State of the Physical, Biological and Selected Fishery Resources of Pacific Canadian Marine Ecosystems in 2014

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by

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ABSTRACT

Fisheries and Oceans Canada is responsible for the management and protection of marine resources on the Pacific coast of Canada. An annual State of the Pacific Ocean meeting is held to review the physical, biological and selected fishery resources and present the results of the most recent year's monitoring in the context of previous observations and expected future conditions. The workshop to review conditions during 2014 took place at the Institute of Ocean Sciences, Sidney, B.C. on March 10 and 11, 2015, with over 100 participants both in person and via webinar. In general, Pacific Canadian waters experience strong seasonality and considerable freshwater influence and include relatively protected regions such as the Strait of Georgia as well as areas fully exposed to the open ocean conditions of the Pacific. The region supports ecologically and economically important resident and migratory populations of invertebrates, groundfish, pelagic fishes, marine mammals and seabirds. Observations of the marine environment in early 2014 identified a large pool of very warm water in the Northeast Pacific Ocean and an area of cooler water along the west coast of North America. By the end of the year the very warm water had moved into the coastal regions with record high temperatures recorded at many locations in the fall. Monitoring of the biological conditions showed the influences of this warm water on marine species composition and distribution. Such observations include a change from cold water to warm water zooplankton taxa from spring to fall 2014 off the west coast of Vancouver island, the second year with no sardines observed in B.C. waters, a record proportion of Fraser River Sockeye Salmon returning via the 'northern diversion' through Johnstone Strait, and mass mortalities of juvenile Cassin's Auklets (a plankton-feeding seabird) in late fall 2014. Warmer than normal weather was experienced in the fall and winter of 2014 along the west coast of British Columbia with less regional snowpack evident in the spring of 2015. A special session at the meeting was convened to examine the emerging issue of ocean acidification. The level of monitoring and research on this subject was considered below that required given the potential risk to the health of the environment and commercial interests. The proposals of groups to advance the work on this subject were discussed.

RÉSUMÉ

Pêches et Océans Canada est responsable de gérer et protéger les ressources marines de la côte ouest du Canada. Une rencontre annuelle sur l'état de l'océan Pacifique a lieu pour réviser les conditions physiques, biologiques, ainsi que certaines ressources halieutiques et pour présenter les résultats des derniers recensements et les mettre en contexte avec les observations précédentes et les conditions futures basées sur les prédictions. Un atelier pour réviser les conditions de 2014 a eu lieu à l'institut des sciences de la mer, Sidney, C.B., les 10-11 mars 2015, avec plus de 100 participants en personne et via webinaire. En général, les eaux canadienne du pacifique ont fait expérience de forte saisonnalité et d'une influence considérable d'apport en eaux douces, incluant des aires relativement protégé comme le détroit de Géorgie ainsi que des aires complètement exposé aux conditions ouvertes du pacifique. La région supporte des populations résidentes et migratoires d'invertébrés, de poissons, mammifères marins et oiseaux de mer qui sont importantes d'un point de vue écologique et économique. Les observations des conditions marines tôt en 2014 ont indiqué la présence d'un grand bassin d'eaux chaudes dans le nord-est de l'océan Pacifique, ainsi qu'une bande d'eaux plus froides le long de la côte ouest de l'Amérique du Nord. Vers la fin de l'année, le bassin d'eaux très chaudes se retrouvait maintenant dans les régions côtières avec des records de températures mesurés à plusieurs sites durant l'automne. Le recensement des conditions biologiques a montré l'influence de ces eaux chaudes sur la composition et la distribution des espèces marines. Ces observations incluent un changement des taxon de zooplancton typiquement retrouvées en eaux froides vers celles retrouvées en eaux chaudes du printemps à l'automne sur la côte ouest de l'île de Vancouver, une deuxième année sans observations de sardines dans ces eaux, une proportion record des saumons sockeye de la rivière Fraser qui a retourné par la diversion du nord à partir du détroit de Johnstone, et une mortalité de masse des stariques de Cassin (une espèce se nourrissant de zooplancton) tard dans l'automne 2014. Des températures plus chaudes que la normal ont été observés pendant l'automne et l'hiver 2014 le long de la côte de la Colombie Britannique, avec moins d'accumulation de neiges évidente pendant le printemps 2015. Une séance spéciale sur l'acidification des océans a été tenue. Le niveau de recensement et de recherche sur ce sujet a été considéré comme étant insuffisant, particulièrement en considérant les risques que cela posent sur l'environnement et les intérêts commerciaux. Des discussions sur les groupes qui peuvent faire des progrès sur ce sujet ont eu lieu.

1. HIGHLIGHTS

- A two day *State of the Pacific Ocean* meeting was held at the Institute of Ocean Sciences in Sidney, B.C, on March 10 and 11, 2015.
- The foremost physical ocean feature of significance was the development and evolution of a large pool of warm water that impacted both the oceanic and coastal waters off Canada's west coast.
- The biological response to this warm water is evident in the presence and distribution of warm water species; the biological impacts are less certain given the extent of the differences in the physical environment from normal conditions.
- A special session on ocean acidification was held to discuss the state of understanding and the plans for research into this subject of emerging concern.

1.1. Northeast Pacific

- Observations of ocean temperatures from satellites, ships and the Argo fleet of profiling floats showed a rapid and unexpected warming of the surface waters in the Gulf of Alaska in October 2013 that continued throughout 2014.
- This pool of warm water, evident to a depth of 100m, in places exceeded 4ºC above normal and is attributed to the unusual positions of the Aleutian Low pressure zone and the North Pacific High pressure zone rather than El Niño conditions that were neutral in 2014.
- Associated with this pool of warm water was a reduced nutrient export from subarctic waters to the Transition Zone Chlorophyll Front leading to a loss of phytoplankton biomass in this critical feeding area and low levels of nutrients in the oceanic surface layer.
- Nutrient renewal from vertical transport was restricted in winters 2013/14 and 2014/15 due to increased stratification.
- Fraser River Sockeye Salmon showed a record high diversion rate with 96% of fish migrating through Johnstone Strait rather than Juan de Fuca Strait. This is one example of how traditional indicators of stock status and ocean conditions must be interpreted with caution when such exceptional marine conditions occur.

1.2. Outer British Columbia coast

- The coastal waters off the west coast of Canada remained relatively cool until September 2014 when water temperatures observed at light stations and coastal weather buoys rose to record levels that persisted into 2015.
- 2014 started off with strongly positive anomalies for the abundance of both sub-Arctic and boreal zooplankton; by late summer southern zooplankton species were predominant.

- Despite anomalously high ocean temperatures the phytoplankton community composition and biomass on the shelf and offshore in May and September 2014 was similar to previous years.
- Cooler ocean conditions and stronger winds along the central B.C. coast in early 2014 resulted in a relatively late spring bloom (15 April) and delayed peak summer zooplankton biomass (second week of May).
- The catch of Smooth Pink Shrimp in bottom-trawl surveys west of Vancouver Island in 2014 was almost twice as high as the previous maximum (data since 1973); for a second consecutive year no sardines were caught by pelagic night trawls or the B.C. sardine fishery.
- The estimated Pacific Herring biomass for 2014 compared to 2013 increased for stocks on the west coast of Vancouver Island, the Strait of Georgia, and the central coast, changed little for the Prince Rupert stocks, and declined for the Haida Gwaii stocks.
- Cassin's Auklets, a plankton-feeding seabird which breeds off northwest Vancouver Island, had a successful breeding season in 2014 but suffered mass mortalities of juveniles in the fall and winter of 2014/15.

1.3. Strait of Georgia

- Salinity and temperature patterns in the Juan de Fuca Strait and Strait of Georgia waters during early 2014 showed little variation from those observed in data collected since 2000.
- Snowpack levels in southwestern B.C. were 50% of normal in early 2014. Fraser River discharge rates at Hope in 2014 were average until May when a two month period of high flow volumes was observed, and river temperatures in July through September were at times 3^{o}C higher than normal.
- Surface water in the Juan de Fuca Strait indicated the influence of warm coastal waters from the west coast of Vancouver Island in the September and October water properties surveys.
- The start of the 2014 spring bloom in the central Strait of Georgia as determined by chlorophyll concentrations measured at the Halibut Bank buoy and on the Queen of Alberni ferry, the biophysical model of the Strait of Georgia, and by MODIS-Aqua satellite data was April 2, March 27 and March 31 to April 6, respectively.
- The 2015 return of Fraser River Sockeye is expected to be close to the cycle average, with a 50% probability at or below 6,778,000 fish, assuming typical ocean survival rates for the period they were at sea.
- Acoustic telemetry array tracking of two-year-old Chilko Lake Sockeye Salmon smolts during their outmigration showed survival rates in 2014 comparable to those in years since 2010. Cumulative smolt survival for the 1000 km outmigration in 2014 was 9% over a median time period of 34 days, consistent with previous years.

1.4. Ocean Acidification

- The term “ocean acidification” describes the process of lowering the pH of ocean water as a result of absorbing carbon dioxide from the atmosphere.
- The Fisheries and Oceans Canada Pacific Ocean Acidification Working Group (POAWG) was formed in 2014 to review ocean acidification globally and regionally, and to establish minimum requirements for monitoring and studying changes in the ocean carbonate system that may impact aquatic species, fisheries, and the aquaculture industry in Pacific Region.
- The water along the outer B.C. coast tends to have high acidity naturally because the subsurface North Pacific waters are ‘old’, i.e. they have been away from the surface for a long time allowing organic matter to accumulate which becomes CO_2 when it decays and so increases acidity.
- In the Strait of Georgia, conditions of low pH, which have persisted since 2009, threaten the viability of commercial scallop aquaculture.
- The impact of ocean acidification on many organisms in BC waters is not well known. Small free-swimming marine snails, called pteropods, are extremely sensitive to ocean acidification conditions, and may be used as an indicator taxon to establish cause and effect relationships between pH levels and biological conditions.
- A time series (1968-2015) of pH measurements has been maintained by the Vancouver Aquarium at the First Narrows section of Burrard Inlet. Interannual variability is evident but in the last several years, a decrease in variability of pH has occurred, centred on a modal pH of 7.6. Measurements in 2014 show elevated pH levels of 7.8 for the first six months, declining to the modal value of 7.6 for the latter part of the year.
- A time series (2001-2011) at the western entrance to Juan de Fuca Strait estimates the mean surface pH to have decreased from 8.3 to 7.7.
- The Canadian Network of Centres of Excellence MEOPAR (Marine Environmental Observation, Prediction, and Response network) has funded projects towards establishing a national ocean acidification program designed to:
    - Develop a 'Climatology' of pH and pCO_2 in Canadian coastal waters
    - Identify key species (and ecosystems) at risk and potential impact on coastal communities and industries
    - Foster strong collaboration with the Department of Fisheries and Oceans (research and management), other Canadian research networks, (e.g. Ocean Networks Canada, ArcticNet), and the international community
    - Develop tools to predict probable extent and impacts on economically and culturally important marine species in Canada over the next few decades.

2. INTRODUCTION

Fisheries and Oceans Canada, Pacific Region, conducts annual reviews of physical, chemical and biological conditions in the ocean, to develop a picture of how the ocean is changing and to help provide advance identification of important changes which may potentially impact human uses, activities, and benefits from the ocean. These reviews take the form of one to two day meetings, usually held in February or March of the year following the year under review. These review meetings began in 2000 to assess conditions in 1999; reports from these reviews are available at

http://www.pac.dfo-mpo.gc.ca/science/oceans/reports-rapports/state-ocean-etat/index-eng.html

or by conducting a web search using the search terms: “DFO, Pacific, Ocean Status Reports”.

Reviews and reports from 2007 to 2013 were conducted under the direction of the Fisheries & Oceans Canadian Science Advice Secretariat (CSAS). In 2014, these State of the Pacific Ocean reviews were moved to a separate process and are now presented as Fisheries & Oceans Canada Technical Reports. The report from 2014 (of conditions in 2013) is available at

http://www.dfo-mpo.gc.ca/Library/353469.pdf

In 2015, the meeting took place on March 10 and 11 at the Institute of Ocean Sciences, in Sidney, B.C. The agenda for the meeting is presented in Appendix 1, and the participants are listed in Appendix 2.

This technical report presents the highlights and summaries of the presentations and discussions at the workshop. These summary reports are not peer reviewed, and present the status of data, interpretation, and knowledge as of the date of this meeting. For use of, or reference to, these individual presentations, please contact the individual authors.

3. OVERVIEW AND SUMMARY

The oceanography of the Northeast Pacific Ocean (Figure 3-1) in 2014 was remarkable because extremely warm water caused changes to marine species composition, distributions and productivity. While cooler water was observed along coastal British Columbia early in 2014 by the end of the year both coastal and ocean water temperatures were up to three degrees Celsius warmer than usual.

Such significant changes to ocean conditions have impacts throughout the marine food web as the supply of nutrients and the presence of prey and predators alter. In 2014 nutritious cold water species of zooplankton were replaced by southern copepods, juvenile Cassin’s auklets (a plankton-feeding seabird) suffered mass mortalities in fall

and winter of 2014, there were large catches of shrimp but no sardines, and almost all the Fraser River sockeye returning to spawn avoided the southern route by swimming via the inside passage northeast of Vancouver Island.

The anomalies observed in 2014 introduce uncertainties into the methods conventionally used to monitor the health of the ecosystem and to forecast the growth and survival rates of fish that are of commercial interest. Additional caution is required in interpreting the usual indices of stock status, and enhanced monitoring is needed to identify further changes as quickly as possible.

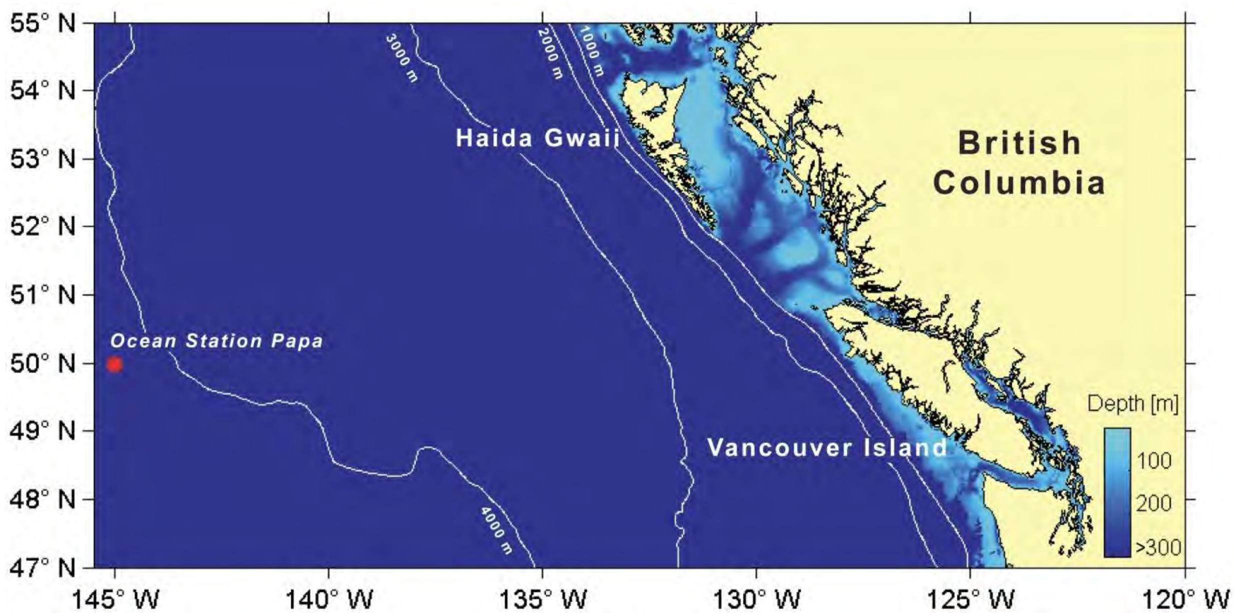

Figure 3-1. Map of Canadian Pacific waters discussed in this report.

3.1. Northeast Pacific

Following seven years of cooler than normal sea surface temperatures (SSTs), satellites and the Argo fleet of profiling floats observed a large pool of warm water in the south central Gulf of Alaska in October 2013. Within a few months temperature anomalies over a 1000 km^2 area in the near surface waters (upper 100m) were greater than 4 standard deviations from the mean (Figure 3-2).

The formation of this pool of warm water is attributed to anomalous large scale weather patterns in late 2013 and early 2014. The North Pacific High pressure zone was situated north of its normal position which reduced the heat flux from the ocean to the atmosphere, and weakened the transport of cooler water from the subarctic regions (Crawford 2015). This 2014 warm water feature is not consistent with the development of warm water events typically associated with El Niño – Southern Oscillation (ENSO).

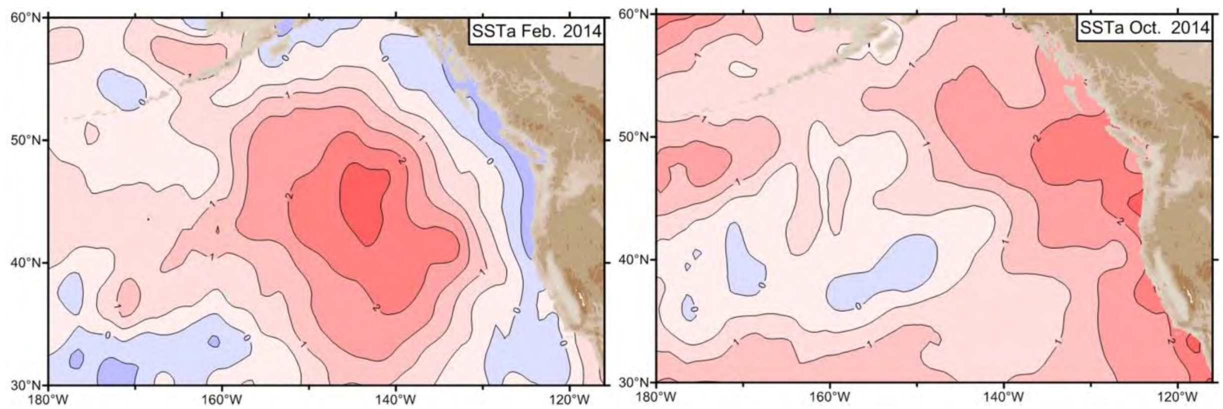

Figure 3-2. Sea surface temperature anomaly maps showing the pool of warm water in the North Pacific Ocean observed at the beginning of 2014 had moved closer to the west coast of North America in the fall and winter of 2014 (Freeland 2015 data source: NOAA, National Oceanic and Atmospheric Administration).

Salinity anomalies were also evident and, as the surface waters became less dense, the increased stratification restricted the 2013/14 wintertime vertical transport of nutrient-rich deeper water into the surface layer and reduced the mixing of warm surface water with cooler deep water. Observations early in 2015 indicated that the resupply of nutrients to the surface was also restricted in winter 2014/15 (Freeland 2015).

The diminished southward transport of nutrient-rich subarctic water led to a 30% decrease of the phytoplankton biomass, and a northward displacement of the Transition Zone Chlorophyll Front, which is important to the feeding patterns, migration routes, and breeding strategies of a wide variety of organisms (Whitney 2015). Ocean sampling of zooplankton off the west coast of Canada identified greater numbers of smaller, warm water copepods and euphausids, while coastal sampling off Vancouver Island revealed energy-rich cold water zooplankton early in 2014 replaced by less nutritious warm water species later in the year (Galbraith et al. 2015).

Sockeye Salmon migrating to the Fraser River to spawn follow either a southern route through Juan de Fuca Strait or a northern route through Queen Charlotte and Johnstone Straits. Observations in 2014 showed the highest diversion rate ever recorded (96%; data since 1953) of returning Fraser River Sockeye Salmon migrating via the “Northern Route”. The SST at Kains Island in May and June has been a primary variable used to predict the northern diversion rate since 1999. However, the anomalously warm Kains SST in May 2014 was followed by a cooler June (due to the onset of coastal upwelling) and resulted in a forecast of 66% northern diversion, a significant underestimate. This illustrates how the usual stock assessment indictors must be interpreted with caution when very unusual ocean conditions occur. Improved methods to forecast the diversion rate are currently being explored as part of a Canadian Science Advisory Secretariat research document (Lapointe et al. 2015).

3.2. Outer British Columbia Coast

Coastal waters along the west coast of North America continued to be cooler than normal until May of 2014 with lower than average wave energy (Gower 2015a). Nearshore observations show that the influence of the expanding pool of warm water on B.C. continental shelf waters was moderated by the summer upwelling of deeper and cooler offshore water. The timing of the Spring Transition (the shift from downwelling to upwelling), and the volume of upwelled water, was near average in 2014 (Hourston and Thomson 2015). In September 2014, at the end of the upwelling season, the Aleutian Low pressure zone expanded and deepened forcing warm surface water onto the coast. A 1500 km wide swath of warm surface water extending from Mexico to Alaska was observed from the autumn of 2014 and continues to be observed in 2015. Mean sea level observations were above average at stations along the coast, but not to the extent experienced during El Niño events (Gower 2015b).

Significant biological events in 2014 reviewed in this report include a very successful breeding season for Cassin's Auklets (in Spring 2014) followed by mass mortalities of juveniles in October to January 2015 (Hipfner 2015). For the second consecutive year there has been no sardine catch along the Vancouver Island coast by the fishery or the DFO night pelagic trawl survey (Flostrand et al. 2015); there were, however, record catches of Smooth Pacific Shrimp in this region (Perry et al. 2015). Zooplankton surveys early in 2014 were dominated by energy-rich northern species which were replaced in late summer and fall with higher abundances, but nutritionally poorer, southern species (Galbraith et al. 2015). Coastal surveys in May and September 2014 identified typical phytoplankton community composition and biomass (Peña and Nemcek 2015).

Estimates of Pacific Herring biomass for 2014 compared to 2013 increased on the west coast of Vancouver Island, the Strait of Georgia, and the central coast. The Prince Rupert stocks remained similar over both years, and the Haida Gwaii stocks declined due to low recruitment and natural mortality. Since the 1970s there had been a decreasing weight-at-age trend for all Pacific Herring stocks which reversed in 2010 and continues to increase in 2014 (Cleary et al. 2015).

While growth rates of juvenile Coho Salmon off the west coast of Vancouver Island are typically poor during warm water conditions (such as those associated with El Niño events), the growth rates in 2014 exceeded all those since observations began in 1998. In contrast, physical indices (Pacific Decadal Oscillation (PDO), North Pacific Gyre Oscillation (NGPO), ENSO averaged over May and September, and the mean SST at Amphitrite point averaged over March and June), predictive of the survival of juvenile Coho Salmon which migrate along the west coast of Vancouver Island, were unfavourable (Trudel et al. 2015). Confirmation of the strength of returning Coho stocks in 2015 will help to distinguish which of these indices (biological growth rate or physical conditions) are the 'better' indicators (at least for 2014). Southern Sockeye stocks with sea-entry into the upwelling regions of coastal waters, such as the Okanagan and Barkley stocks, have been rebuilding since 2009 with record returns in 2014. Conditions at sea-entry in 2013 were favourable for the survival of adults returning in 2015; however juvenile salmon going to sea in spring 2015 encountered very different, and poorer, conditions leading analysts to caution about poorer returns in 2016 and 2017.

Transboundary and North Coast stocks continue to have average to sub-average returns over the past ten years, including 2014, and are expected to remain sub-average through 2015 (Hyatt et al 2015).

Survey data from 34 flights made from September 2012 to March 2015 over the west coast of Vancouver Island reveal Humpback Whales were predominantly sighted on the continental shelf whereas Fin Whales and Blue Whales were predominantly sighted on the continental slope and further offshore. All three species, however, overlapped spatially in the vicinity of Nitinat Canyon and Barkley Canyon (Nichol and Ford 2015).

3.3. The Strait of Georgia

The warm water conditions so influential off the west coast of Canada were not present in the Strait of Georgia until later in 2014. Water temperatures measured at lighthouse stations and with depth profiling instruments during the water properties surveys in April, June, September showed conditions for most of 2014 to be near normal. Temperature profiles taken in Juan de Fuca Strait in September and October 2014 showed the signature of the warm coastal water extending east as far as the southern Strait of Georgia (Chandler 2015a, b).

Snowpack levels in southwestern B.C. were 50% of normal in early 2014 and Fraser River discharge rates at Hope in 2014 were about average until May when a two month period of high flow volumes was observed. River temperatures in 2014 during the summer months were warmer than normal, at times 3 ^{o}C higher than the average temperatures in the 72 year dataset (Gower and Chandler 2015).

The timing and intensity of the spring phytoplankton bloom in the Strait of Georgia is important to the overall productivity of the region, and can significantly influence the growth and survival of organisms throughout the food web, including salmon and herring. Three methods are applied to identify the spring bloom including *in situ* measurements of chlorophyll concentrations in the central Strait, the interpretation of (cloud-free) satellite imagery, and the simulation of physical and biological processes in a mathematical model. Chlorophyll measurements made at the Halibut Bank weather buoy and onboard the Queen of Alberni ferry identify April 2 as the start of the spring bloom (Gower 2015c). March 31 to April 6 was given by Carswell et al. (2015) as the timing based on MODIS-Aqua satellite data. The mathematical model predicted a spring bloom start date of March 27 (Allen and Latornell 2015). The timing of the spring bloom, and the start of the productive season, typically varies from late February (2005) to mid-April (2010) based on data acquired since 2002. In 2014 all three methods provided a similar start date (late March, early April), similar to the timing in 2013 and about average compared to the time series.

Since the record low returns of Fraser River Sockeye in 2009 there have been particularly large returns in 2010 and 2014 for the dominant cycle Late Shuswap stock which has experienced above average escapements and average to above average survival. Assuming typical ocean survival rates the 2015 return forecast indicates a 50% probability the total Fraser Sockeye return will be at or below 6,778,000 (there exists a

one in two chance the return will be at or below this value), which is close to the cycle average (Grant and MacDonald 2015).

A large-scale acoustic telemetry array to track two-year-old Chilko Lake Sockeye Salmon smolts during their initial 1000 km outmigration showed typical survival rates in 2014 when compared to the data collected since 2010. In 2014 there was a 28% survival rate between the northern Strait of Georgia and Queen Charlotte Sound (average since 2010 of 33%); a 57% survival rate between the mouth of the Fraser River and the northern Strait of Georgia, (average 68%); and a 39% rate in the fresh water section of the outmigration (average 32%). Cumulative smolt survival for the entire route in 2014 was 9% taking a median time of 34 days, consistent with previous years (Rechisky et al. 2015).

3.4. Ocean Acidification

A special session on Ocean Acidification was added to the State of the Pacific Ocean meeting to provide a forum to discuss the increasing importance of this issue to the health of the global oceans and the waters off Canada's west coast.

Water along the outer B.C. coast tends to have high acidity naturally because the subsurface North Pacific waters have not been in contact with surface waters and the accumulation of organic matter becomes CO_2 when it decays and so increases acidity (Ianson 2015).

The circulation of water off Canada's west coast is highly dynamic and with terrestrial inputs there is much variability in carbon content and pH, and too few data available to identify spatial and temporal patterns. One relatively long time series (1968-2015) of pH measurements has been maintained by the Vancouver Aquarium at the First Narrows section of Burrard Inlet. Interannual variability is evident but in the last several years, a decrease in variability of pH has occurred, centered on a modal pH of 7.6 (Marliave et al. 2015). Another time series (2001-2011) from Tatoosh Island, at the southern seaward end of the Strait of Juan de Fuca, estimates the mean surface pH to have decreased from 8.3 to 7.7 (Denman 2015). There are few local data to support trend analysis at this time; open ocean observations of the decline in ocean pH in the Northeast Pacific are consistent with the global trend (Wong et al. 2010).

The impact of ocean acidification on many organisms is not well known. Small free-swimming marine snails, called pteropods, provide an important food source for many pelagic fish species and a large fraction of the West Coast population is being affected by ocean acidification (Bednaršek et al. 2014). Because of their extreme sensitivity to ocean acidification conditions, pteropods can be used to establish cause and effect relationships of pH levels with biological conditions such as shell dissolution, shell calcification, changes in vertical distribution, and survival success. Models are being developed to estimate pteropod population survival rates based on future regional ocean acidification scenarios which can be used to determine the level of sampling required to make confident predictions.

Commercial shellfish aquaculture operations in the Strait of Georgia have noticed a decrease in the pH of water they draw from the Strait. Since 2009 this increased acidity has devastated the production of scallop seed and compromised the economic viability to grow and market shellfish (Saunders 2015).

Fisheries and Oceans Canada have established a Pacific Ocean Acidification Working Group (POAWG) to review ocean acidification globally and regionally, and to establish minimum requirements for monitoring and studying changes in the ocean carbonate system that may impact aquatic species, fisheries, and the aquaculture industry in DFO's Pacific Region (Hunter et al. 2015).

The Canadian Network of Centres of Excellence MEOPAR (Marine Environmental Observation, Prediction, and Response network) has funded projects towards establishing a national ocean acidification program designed to:

- Develop a 'Climatology' of pH and pCO_2 in Canadian coastal waters
- Identify key species (and ecosystems) at risk and potential impact on coastal communities and industries
- Foster a strong collaboration with the Department of Fisheries and Oceans (research and management), other Canadian research networks, (e.g. Ocean Networks Canada, ArcticNet), and the international community
- Develop tools to predict probable extent and impacts on economically and culturally important marine species in Canada over the next few decades

3.5. Acknowledgements

The authors and contributors to this Technical Report wish to thank all the officers and crew of the many vessels that have been involved in collecting data and maintaining monitoring stations for these studies. Without their assistance many of the reports in this document would not be possible.

3.6. References

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Individual reports on conditions in the Northeast Pacific

4. GLOBAL TEMPERATURE IN 2014

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4.1. Highlights

- The surface temperature of the earth in 2014 was the warmest of any year since reliable measurement began in 1880 (Figure 4-1).

4.2. Summary

The two panels of Figure 4-1 reveal identical changes in the global surface temperature anomaly from year to year and the highest anomaly in 2014, but the reference years are different. Figure 4-1a presents anomalies relative to an average temperature over the 20th century, which is the period normally selected by NOAA in presenting this time series. Figure 4-1b uses the reference years of 1981 to 2010, which is the range applied to many of the temperature time series that appear later in this report, since most climate agencies use a recent 30-year average to define average conditions. Using a recent 30-year average suppresses the cumulative impact of century-scale climate warming. Instead, most earlier years appear abnormally cold.

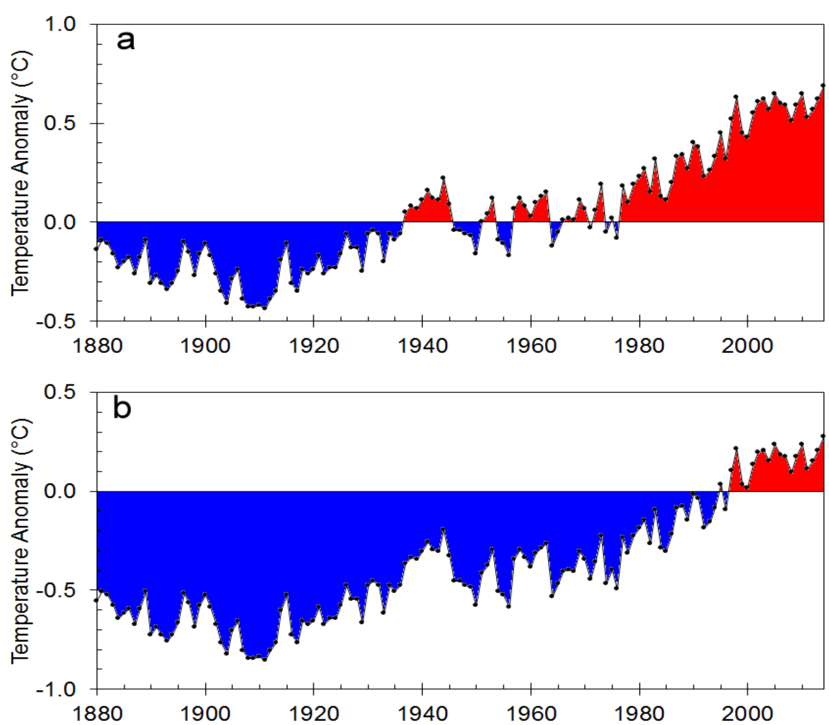

Figure 4-1. Time series of the annual global surface temperature anomaly from 1880 to 2014, (a) with respect to a base period of 1901 to 2000, (b) with respect to the base period 1981-2010. Data source: National Oceanic and Atmospheric Administration (NOAA).

The reference period matters when temperature anomaly in the year 2014 is shown for regions of the earth in Figure 4-2, where the base years are 1981 to 2010. The shading in Figure 4-2 is mostly pink, indicating a warmer global surface than the average over 1981 to 2010, but even warmer shading would be required if the reference years were 1901 to 2000.

Most of the surface of the earth was warmer in 2014 than the 1981 to 2010 base period, especially over the Northeast Pacific Ocean, California, Alaska and Europe. The region of most significant negative temperature anomaly was in eastern to central North America, especially in the winter months of January to March. These regions were hit by another cold winter beginning in late 2014. These cold winters pushed global warming out of the headlines, since these blue regions contain the largest population centres and news agencies of Canada and USA.

The two contrasting temperature anomalies, positive over the northeast Pacific Ocean and negative over eastern North America, are attributed to a large shift in the jet stream, which pushed far to the north of its normal position as it passed over the North Pacific Ocean, then swept southwards over North America carrying cold air masses to the south over eastern Canada and USA.

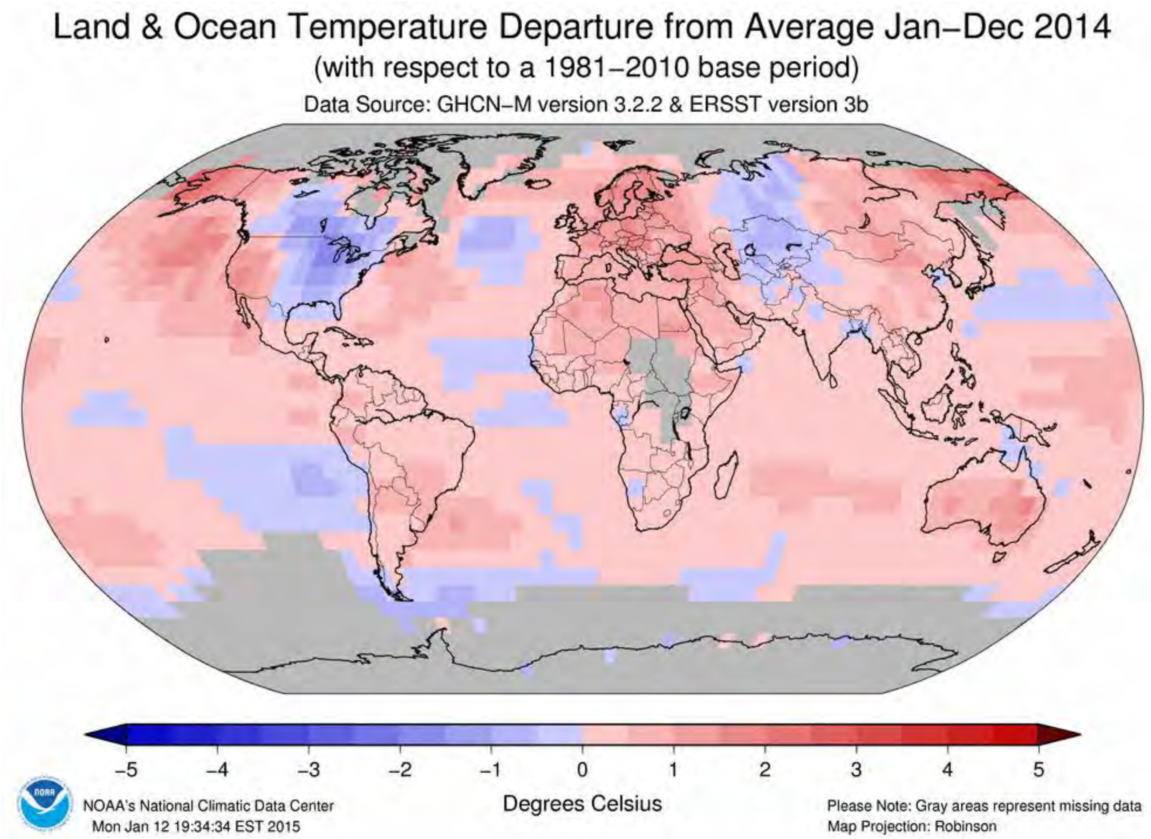

Figure 4-2. Map of the globe showing surface temperature anomalies (°C) in the year 2014. The colour bar at bottom shows the temperature anomaly scale, with pink and red for positive anomalies and relatively warm regions, pale blue and dark blue for negative anomalies and relatively cool regions. Grey areas represent missing data. Source: NOAA. http://www.ncdc.noaa.gov/sotc/service/global/map-blended-mntp/201401-201412.gif

5. NORTHEAST PACIFIC OCEAN: WARMEST EVER IN 2014 AND EARLY 2015

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5.1. Highlights

- In autumn 2013, the North Pacific High Pressure system was farther north than normal and gave rise to the "warm blob"
- Sea temperatures were cooler than normal along the coast in the spring and relatively normal through the summer. In autumn 2014, an unusually large Aleutian Low together with Ekman divergence pushed the blob eastward and very high temperatures persisted on the coast until at least March 2015.
- 2014 is a year of transition; most climate indices shifted from cool over the past several years (2007 to 2013) to warm for British Columbia at the beginning of 2015.
- The Pacific Decadal Oscillation was at its highest value ever recorded in late 2014.

5.2. Summary

After seven years of mainly cool ocean temperatures, surface waters began to warm in 2013, with the most extreme warming arriving in early 2014 in the mid-Gulf of Alaska, as shown by the red region in Figure 5-1a on the right. This feature, labelled the "warm blob", was easily the warmest temperature anomaly ever observed in the region (Freeland 2015), reaching about 4°C above normal temperature and lasting the entire year.

However, cooler than normal seawater persisted along the continental shelf from Mexico to Southeast Alaska in early 2014 (blue region of Figure 5-1a). These relatively cool waters were a remnant of the generally cool conditions along the coast since 2007. It was the warm blob that captured much attention in 2014, but these relatively cool coastal waters protected most marine species on the continental shelf from excessive warming in early 2014.

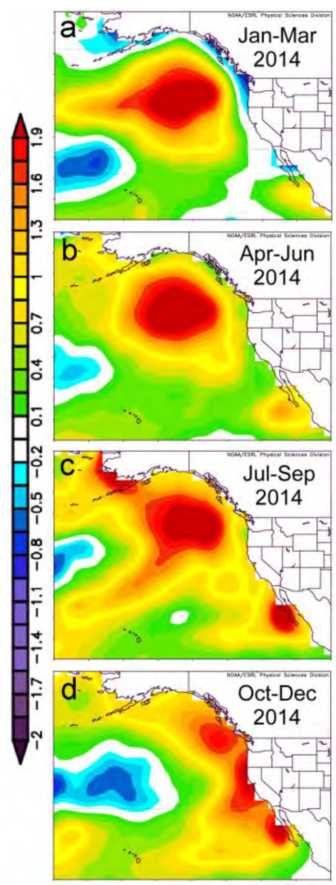

Figure 5-1. Temperature anomalies of the Northeast Pacific Ocean in of each of four seasons through 2014, from winter months of Jan.-Mar. in (a) to autumn months of Oct.-Dec. in (d). Scale of temperature anomalies (°C) is to the left of these four panels. Source: NOAA: http://www.esrl.noaa.gov/psd/cgi-bin/data/composites/printpage.pl

Coastal waters gradually warmed toward near-normal or slightly warmer seasonal temperatures in April to June 2014 (Figure 5-1b), and in July to September (Figure 5-1c). Summer upwelling winds protected shelf waters from the extreme temperatures of the warm blob during the summer.

In the autumn months of October to December 2014 the warm blob moved eastward with autumn storms, bringing extreme warm anomalies to the continental shelf and right to shore. This warm anomaly persisted until at least March 2015, and many daily high temperature records were set at lighthouse stations through the winter of 2014-5 (Chandler 2015). For example, the winter 2014/15 temperature anomaly at Amphitrite Island (southwest Vancouver Island) was the largest of any winter in its 80-year record.

The causes of the warm blob and its eventual eastward drift toward the coast are found in seasonal anomalies in the large scale winds that blow around two main atmospheric features, the Aleutian Low and the North Pacific High (Figure 5-2).

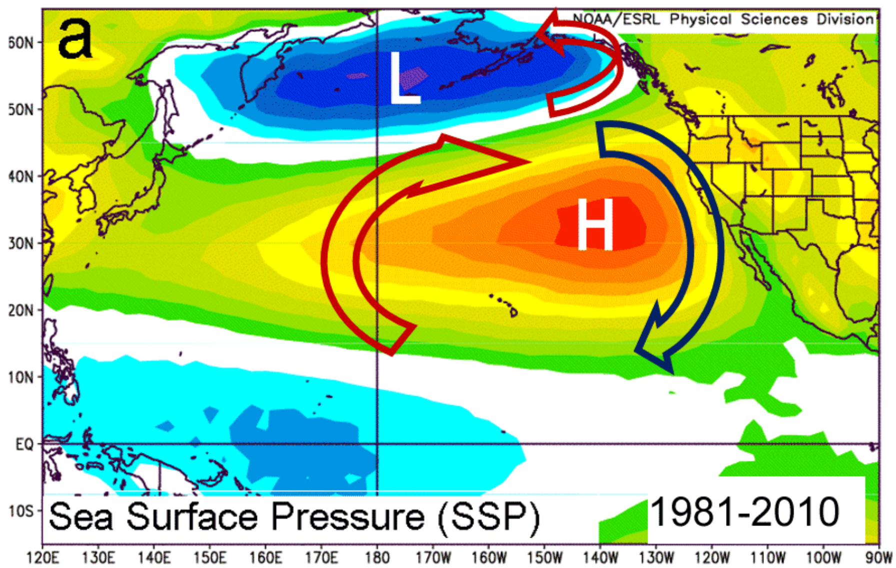

Figure 5-2. Isobars of sea surface pressure representing average conditions from 1981 to 2010. Each colour shade represents a change in air pressure of 1 millibar, with red denoting high pressure, and blue denoting low. H denotes the North Pacific High; L denotes the Aleutian Low. Arrows show directions of prevailing winds around these two pressure systems, with red for warm winds and blue for cool.

The Aleutian Low deepens and expands in area in winter, bringing warm winds and ocean waters from the south toward the B.C. coast. The North Pacific High expands and increases in pressure in summer, bringing somewhat cool winds from the north to the southern B.C. coast and to all regions of Washington south to Mexico. Accompanying these northerly summer winds are cool upwelled waters along the coast.

In general, warm waters lie under the North Pacific High and cool waters under the Aleutian Low. In late 2013, the North Pacific High pushed far to the north of its normal position, and the relatively calm sunny conditions under this anomaly gave rise to the warm blob. This warming was accelerated by an inflow of warm surface water from the south (See Bond et al. 2014, for details)

All this changed in the autumn of 2014, when the Aleutian Low increased in strength and area far past its normal state for autumn and winter, pushing the North Pacific High far to the south. Warm southerly winds of the Aleutian Low blew over the eastern side of the warm blob and the impact of Ekman divergence under these southerly winds pushed the warm blob toward the west coast of North America. In general, an unusually intense Aleutian Low pushes deep-sea waters toward the coast due to Ekman divergence, and also pushes southern, warm coastal waters northward, with this second effect contributing most to coastal warming. However, in late 2014 and early 2015, these offshore waters were much warmer than normal, and both onshore and northward flows contributed to the unusually strong warming of the B.C. coast.

5.3. Weather and ocean conditions represented in climate indices

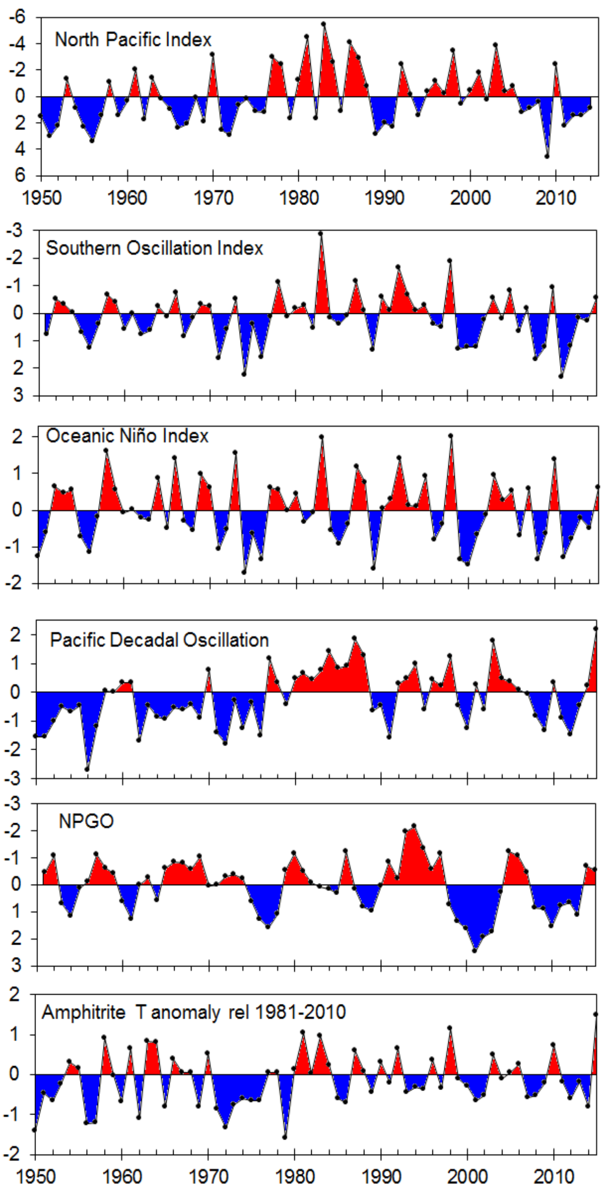

Figure 5-3. Five indices of Pacific Ocean climate plus SST anomaly (°C) at Amphitrite Point. Each data point is an average over the months of November to March, and plotted for the calendar year of March. North Pacific Index is not yet available for 2015. Amphitrite and North Pacific Gyre Oscillation (NPGO) index are missing some data from 2015. Some series are inverted (negative values are above the axes) so that all series are red when coastal B.C. temperatures are anomalously warm.

Figure 5-3 presents five climate indices for years since 1950, as well as the ocean temperature anomaly at Amphitrite Point on the southwest coast of Vancouver Island. Indices are computed for winter months of November to March, partly to allow the most recent observations to appear, and also because winter months tend to be the time of greatest ocean response to El Niño and La Niña events.

Given the extreme warming along the west coast shown in Figure 5-1 in late 2014, it is not surprising that Amphitrite and Pacific Decadal Oscillation are at their highest-ever magnitudes in Figure 5-3, and that all of the series with observations in 2015 are plotted in red in Figure 5-3, indicating ocean and atmospheric conditions normally related to warm waters along the west coast.

It is noteworthy that all of the series of Figure 5-3 are mainly blue over most of the seven winters from 2007 to 2013 (except 2010 representing an El Niño winter), and then shift to red in 2015 following a transition year in 2014. The warming of the 2015 winter was not only strong, but followed almost a decade of generally cool ocean water along the west coast.

Although the North Pacific Index (NPI) has not yet been computed winter 2014-15, it is likely well into the red zone due to intensification of the Aleutian Low. Both the Southern Oscillation Index and the Oceanic Nino Index (ONI) emerged into the red zone in 2015, but just barely. In general, strengthening of the Aleutian Low in winter follows closely a positive value of the ONI and a negative value of the Southern Oscillation, indicating an El Niño on the Pacific Equator and a tropical Pacific air pressure gradient that sets up an oceanic El Niño. The relatively strong Aleutian Low in the 2014/15 winter was accompanied by much weaker-than-normal ONI and Southern Oscillation.

The time series in Figure 5-3 are explained in the next paragraphs. In general, blue regions prevailed prior to 1977, and red regions after then for about two decades until 1998. The Pacific Decadal Oscillation (PDO) shows this pattern best. An exception is the North Pacific Index (NPI) which remained negative (red) through most years from late 1970s through to the mid-2000s. In general, cooling aligns with La Niña (negative ONI), negative PDO, NPGO and NPI, and positive SOI.

5.4. Description of the indices

North Pacific Index (NPI) is the area-weighted sea level pressure over the North Pacific Ocean from 30°N to 65°N and 160°E to 140°W. This index is a useful indicator of the intensity and areal extent of the Aleutian Low Pressure system. The NPI was generally positive (blue) from 1950 to 1976, and generally negative (red) from 1977 to 2005. This change is attributed to strengthening of the Aleutian Low Pressure system in winter after 1977. From 2005 to 2014, the NPI was mostly positive, due to weaker Aleutian Lows. No data are available for 2015, but it is expected to be negative. Monthly time series of this index are provided by the Climate Analysis Section, NCAR at Boulder, Colorado and based on Trenberth and Hurrell (1994) and Wallace and Gutzler (1981). Both monthly and winter-only values are available at: https://climatedataguide.ucar.edu/climate-data/north-pacific-np-index-trenberth-and-hurrell-monthly-and-winter

Southern Oscillation Index (SOI) represents the anomaly of the atmospheric sea surface pressure difference between the island of Tahiti and Darwin, Australia, which usually sets up the El Niño and La Niña ocean responses. A strong positive anomaly is associated with stronger trade winds and positive SOI (blue in Figure 5-3), and generally sets up La Niña. A negative anomaly is associated with weaker trade winds, or even a reversal of wind direction in the tropical Pacific, and negative SOI (red in Figure 5-3), and generally sets up El Niño. SOI is available at: http://www.cpc.ncep.noaa.gov/ data/indices/soi.

Oceanic Niño Index (ONI) is a measure of the anomaly of ocean surface temperature in the central tropical Pacific Ocean, and serves as the official index of the occurrence of El Niño and La Niña episodes as determined by the NOAA Climate Prediction Center (CPC). Although it is computed monthly, each value is based on a three-month period centred over the nominal month. The reference period for computing anomalies is 30 years and is updated every five years. A side effect of this particular reference-year system is to account for climate change and some decadal variability in temperature. ONI is provided by the NOAA's National Weather Service National Centers for Environmental Prediction CPC and available at: http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/detrend.nino34.ascii.txt

Pacific Decadal Oscillation (PDO) is based on analysis of Mantua et al. (1997) and Zhang et al. (1997). It is the first mode of ocean surface temperature variability in the North Pacific Ocean, and is often positive in El Niño years. However, its variability is slower than that of the Oceanic Niño Index, and it is usually a good indicator of temperature patterns that persist for a decade or more. Prior to calculating the first mode of SST variability, the global average temperature for each month is subtracted from the SST at each data location in the North Pacific Ocean. As a result, the PDO time series does not include global warming (or cooling), and instead represents variability and change local to the North Pacific Ocean. The time series is provided at the website of the Joint Institute for Studies of Atmosphere and Ocean of NOAA in Seattle: http://jisao.washington.edu/pdo/PDO.latest

North Pacific Gyre Oscillation (NPGO) is a climate pattern that emerges as the second dominant mode of sea surface height variability in the Northeast Pacific Ocean (Di Lorenzo et al. 2008, 2009). The NPGO closely tracks the second mode of North Pacific SST, also referred to as the Victoria Mode. When positive (the blue intervals in Figure 5-3), the westerly winds over the eastern North Pacific are often stronger than normal, and the west coast of North America and eastern Gulf of Alaska are cool. These conditions have dominated in most winters from 1999 to 2013, but not in 2014 and 2015. The time series is available at this website: http://www.o3d.org/npgo/

Amphitrite Point temperature anomaly time series is based on ocean surface temperatures measured daily at the Amphitrite Point lighthouse since 1934 on the southwest coast of Vancouver Island (Chandler 2015). Base years are 1981 to 2010. Monthly values are provided by Fisheries & Oceans Canada: http://www.pac.dfo-mpo.gc.ca/science/oceans/data-donnees/lighthouses-phares/index-eng.html

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6. THE “BLOB” OR ARGO AND OTHER VIEWS OF A LARGE ANOMALY IN THE GULF OF ALASKA IN 2014/15

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6.1. Highlights

- One year ago I showed evidence of a huge anomaly invading the N.E. Pacific, some have called this “The Blob”.
- The Blob continued to influence the N.E. Pacific through 2014 to the present.
- Onset of The Blob was abrupt.
- It created a mixing barrier in the Gulf of Alaska that restricted nutrient supply to upper layers.

6.2. A Description of The Blob

Figure 6-1 shows plots from the sea surface temperature analyses that derive from NOAA, the so-called Reynolds plots, which do not use Argo data. Figure 6-2 shows data derived exclusively from Argo observations. The two datasets are interesting because they are mutually exclusive but show similar events. The frames in Figure 6-1

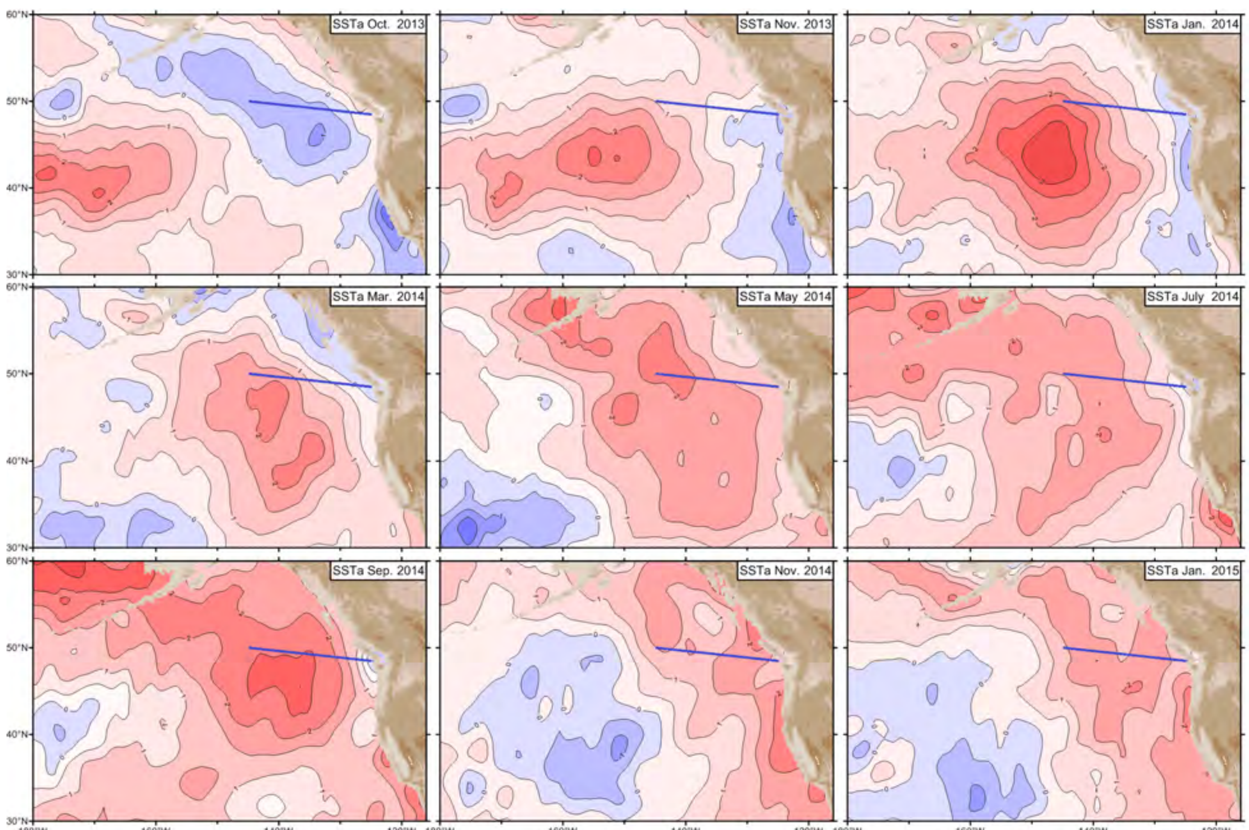

Figure 6-1. Sea-surface temperature anomaly (°C) from October 2013 to January 2015.

are at intervals of 2 months except for the first pair which are consecutive months, to show the sudden onset of this event. The blue line shows the approximate location of Line-P, which are the sections shown in Figure 6-2. One year ago I showed a plot of the sea surface temperature anomaly (SSTa) normalized by standard deviation, this showed the peak anomaly being up to 4.3 standard deviations from the mean which is very large (Freeland 2014). The frames in Figure 6-1 show the sudden appearance of The Blob in the NE Pacific between October and November 2013. The peak development is in January to February 2014. From there it appears to move towards the shore but never really disappears. The ocean remains warmer than usual well into 2015.

The panels in Figure 6-2 are derived by interpolating observations from the global array of floats comprising the Argo array. Essentially, I reconstructed observations at each Line-P station using optimal interpolation to a depth of 1000 decibars, centred on the 15th day of each month and accepting Argo observations into the interpolation from a time window within 10 days on either side of the centre of the time window. The left-hand side of each plot is Station Papa. On the right-hand side are the inshore stations but in an area that has been blanked out. The blanking area is the part of Line-P shallower than 2000 decibars. Since Argo floats profile from 2000 decibars to the surface drawing contours in this area implies extrapolating from inside the Argo array to

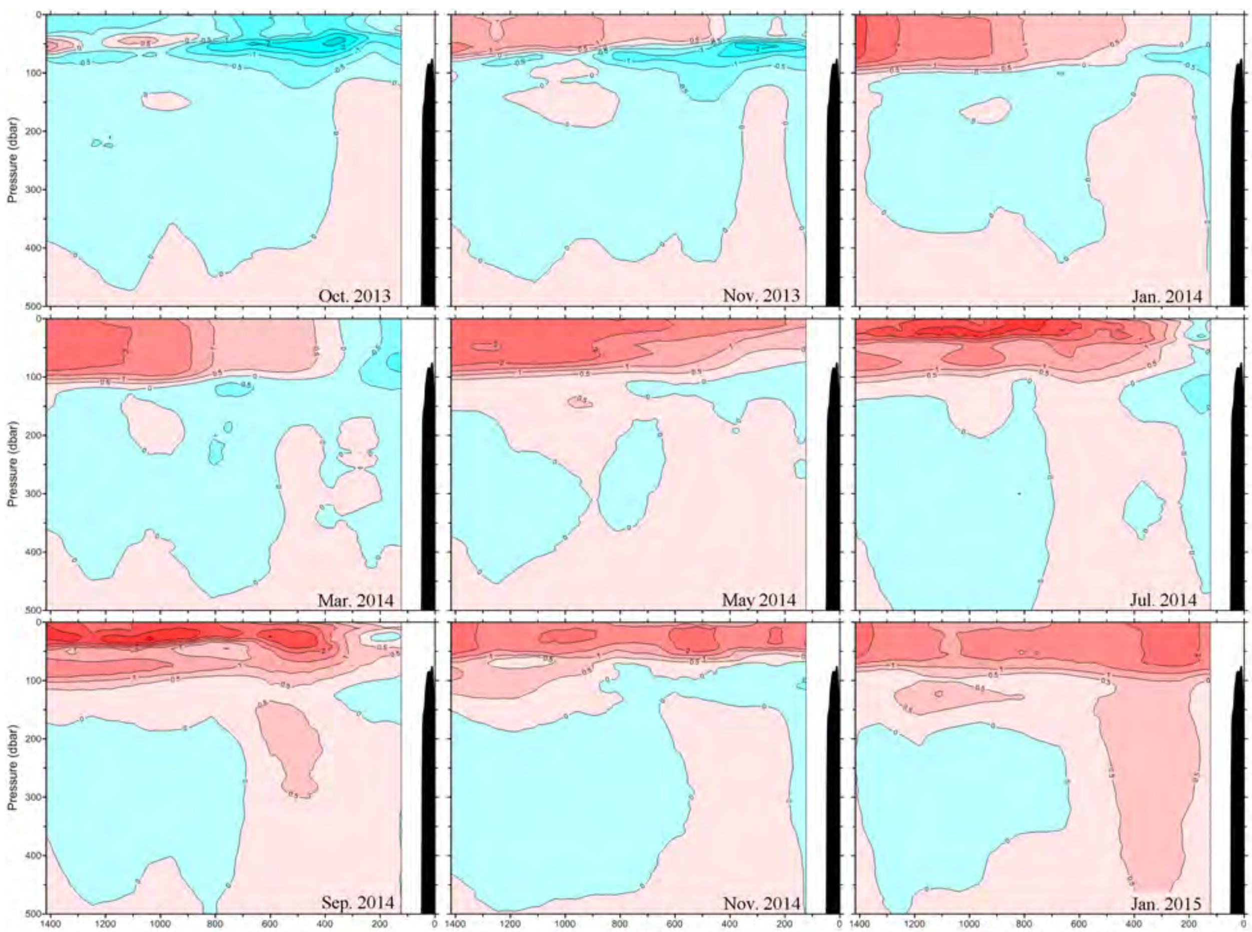

Figure 6-2. Temperature anomalies versus depth (decibars) and distance along Line-P.

the outside. The months chosen match exactly the months used in Figure 6-1. Though a different dataset, and a different approach to mapping the phenomenon, the panels in Figure 6-2 confirm the conclusions made earlier concerning the maps in latitude and longitude (Figure 6-1). Specifically we again see the very abrupt and unanticipated onset of The Blob between October and November 2013. The ocean remains very warm through 2014 and extending into early 2015 with the peak anomalies appearing along Line-P in January to February 2014; but again we see that The Blob never really went away. The diagrams in Figure 6-2 also show that the anomaly, though large, penetrates only to a depth of about 100 metres. Not shown in Figure 6-2 are the salinity anomalies. The optimal interpolation does include salinity and, though not shown here, are inverses of the temperature anomalies. Increased temperature and decreased salinity in surface waters must imply an increased density difference between the surface and deeper waters.

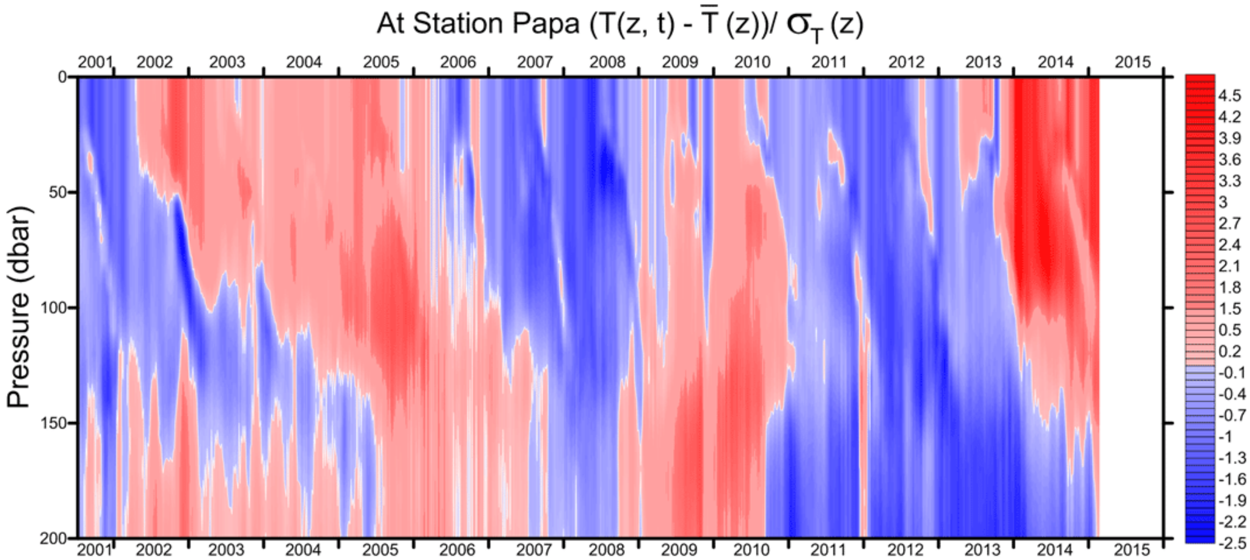

Figure 6-3. Temperature anomaly (°C relative to a 2001-12 average) at Ocean Station Papa.

Computing the sections in Figure 6-2 required interpolations to all of the stations comprising Line-P including Ocean Station Papa. Taking all of the interpolations to Station Papa (also known as P-26) from the start of Argo to the present time allows us to create the view in Figure 6-3 showing normalized temperature anomalies versus depth and time from 2001 to the present. The temperature anomalies are the observed temperatures minus the mean state computed from mid-2001 to December 2012 and then standardized by the seasonally and depth-varying standard deviation computed over the same period. This clearly demonstrates that The Blob is by a large margin the biggest event in the NE Pacific since the Argo array began. The deviations from normal are large, more than 4 standard deviations from the mean and extend down to 100 decibars (metres) though in 2015 this plot suggests some deeper penetration is occurring. Again we see the very abrupt onset in very late 2013. Salinity deviations are not shown, but during this period are the inverse of temperature anomalies.

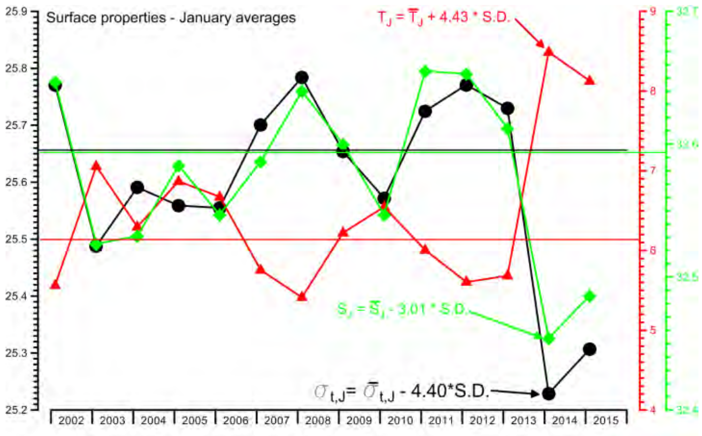

Figure 6-4. January temperature (red series), salinity (green series) and density (black series) observations at Station Papa from 2002 to 2015.

Figure 6-4 is an alternate view of the data presented in Figure 6-3. Again it presents the near-surface Argo interpolations to Ocean Station Papa, but now including the salinity observations and the derived water density (σ_t) observations. This shows the dramatic deviation from normal in surface temperature in January 2014 of 4.43 standard deviations (the red line and triangles). Also shown are the equivalent salinity observations (green line and lozenges) showing a peak deviation in January 2014 of -3.01 standard deviations. Both the high temperature and low salinity act to decrease the near-surface density which we see in the black line and circles peaking in January 2014 with a deviation 4.4 standard deviations below normal. This surface density is very low. Since the anomaly penetrates only down to 100 decibars the observations imply a large increase in density between the surface and deeper waters.

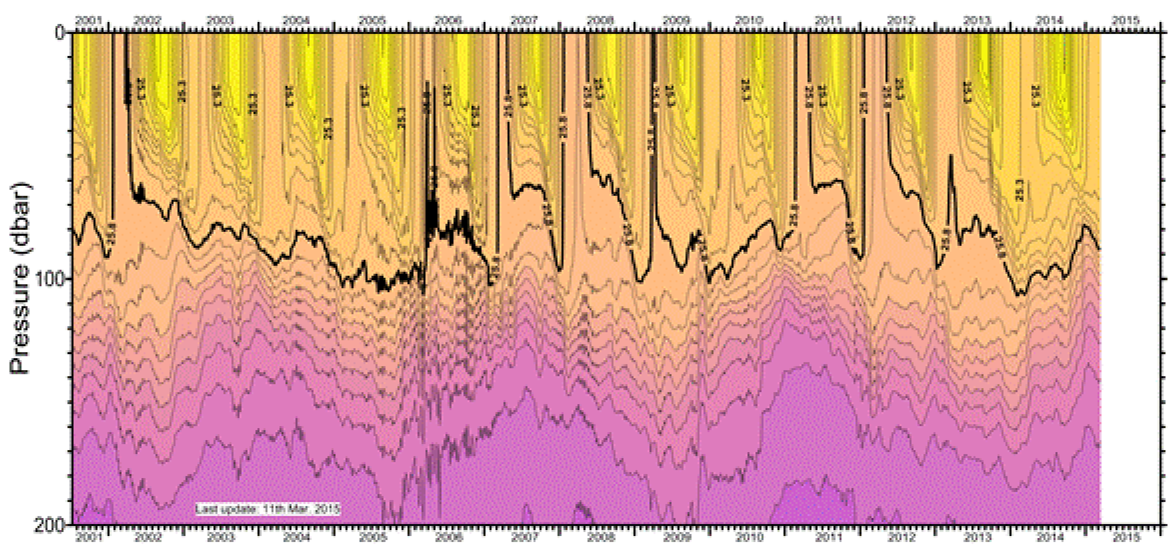

Figure 6-5. Density (σt) versus depth at Ocean Station Papa at 5-day intervals from 2001 to the present, interpolated from Argo observations. The bold line represents the 25.8 σ_t surface.

In Figure 6-5 the point about increased density contrast is made very clear. It shows a contour plot of density surfaces versus depth and time. Every winter storms occur in the NE Pacific that create turbulence and stir up the ocean. This causes deep water to be mixed upwards towards the surface increasing the density of near-surface waters. The highlighted contour in Figure 6-5 shows the density surface 25.8 σ_t. This is raised to the

surface (indicating sufficiently deep mixing) only 1 out of every 2 winters. Before The Blob occurred we can see that at the height of winter in the ocean when mixing is to its maximum depth there is no more than one contour separating this bold contour from the surface. However, in the winters of 2013/14 and 2014/15 there are 4 contours separating 25.8 σ_t from the surface. Another view of the stratification (shown at the State of the Ocean meeting but not included here) shows that by the time the meeting took place in March 2015 re-stratification had begun. It would take a huge winter storm to supply energy sufficient to penetrate this extreme stratification, and since seasonal re-stratification has begun (clear at the time of the State of the Ocean Meeting) it now seems apparent that this will not happen before winter 2015/16.

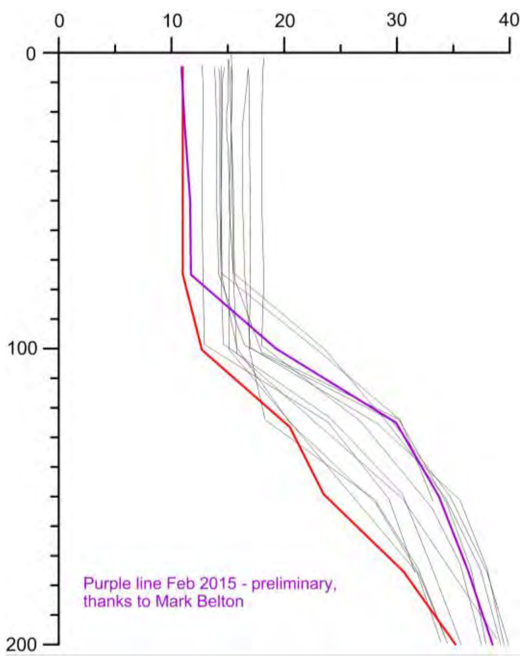

Figure 6-6: Nutrients (nitrate + nitrite; x-axis in µmol/L) in the near-surface waters (y-axis in metres) at Station Papa 2001 to 2015 in winter (Jan/Feb of each year). Red line is from 2014; purple line from 2015 (preliminary data).

Since vertical mixing is weak, the extremely strong stratification must be affecting the supply of nutrients. One of the primary nutrients is plotted in Figure 6-6 versus depth which shows plots for all observations in January or February at Station Papa from 2001 to the present time. The 2014 observations, which are final, are shown in red. In purple are preliminary observations from February 2015. The nitrate supply in early 2014 and 2015 appears to be lower than anything seen since 2001. The nutrient concentrations near the surface can increase if a large storm occurs. As things stand in March 2015, a massive storm would be needed which mixes the ocean down to 128 metres in order to get the surface nutrients back to the long-term normal. Since restratification has begun it is clear that such an event is unlikely before the onset of winter 2015/16. Since mixing with deeper waters is the only known source of nutrients to the upper ocean, it is evident that nutrients will remain in poor supply at least until next winter and possibly beyond.

Other indicators show that the North Pacific Current is significantly to the south of its normal position. The North Pacific Current splits into two branches as it approaches the N. American coast with part of the water flowing into the Gulf of Alaska and part forming the California Current. All three currents are near their normal current strength.

6.3. References

Freeland, H. 2014. Something odd in the Gulf of Alaska, February 2014. In Perry, R.I. (Ed.). State of the physical, biological and selected fishery resources of Pacific Canadian marine ecosystems in 2013. Can. Tech. Rep. Fish. Aquat. Sci. 3102: vi + 136 p. Available online: http://www.dfo-mpo.gc.ca/Library/353469.pdf

7. WINDS, WAVES AND SST FROM WEST COAST WEATHER BUOYS

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7.1. Highlights

Winds

- The average wind speed for the winter Oct 2013 to Mar 2014, as measured by Nomad and 3-metre buoys, was lower than in any other year since 1995.
- The Nomad weather buoys offshore and the smaller buoys near shore both show higher winds in 1998 to 2011 than in earlier or later years.
- This period of higher wind gives an apparent increasing trend in wind speed which is now diminishing.

Waves

- The average significant wave height (SWH) for the winter Oct 2013 to Mar 2014, as measured by exposed 3-metre buoys, was the lowest so far measured (since 1990). As measured by Nomad buoys, further offshore, they were second lowest since 1988.
- The Nomad weather buoys show a slow decrease in measured SWH by about 10% in the 28 years of measurements.
- The smaller buoys near shore show no long-term trend.

SST

- The weather buoys near the coast show a negative anomaly early in 2014, increasing to a warm anomaly of about 1.5 to 2 °C by late 2014.
- At the location of the Nomad buoys, further offshore, the anomaly appears to have arrived earlier and to be slowly increasing through 2014.
- The data records from these buoys (most start about 1990) are still too short to show long-term warming.

7.2. Environment Canada Weather Buoy data

Hourly wind, waves and SST data from the Environment Canada meteorological buoys are available from the Oceanography and Science Division (OSD) of DFO (http://www.meds-sdmm.dfo-mpo.gc.ca/). The monitoring network consists of three offshore Nomad buoys (46184, 46004 and 46036), six 3-meter discus buoys along the shelf (46205, 46208, 46147, 46207, 46132 and 46206, from north to south) and eight 3-meter discus buoys in coastal waters (46145, 46183, 46185, 46204, 46131, 46146, 46181, 46134) (Figure 7-1).

7.3. Winds

The average wind speeds are plotted for the three Nomad buoys in Figure 7-2 and for the six smaller buoys closer to the coast in Figure 7-3. Anomaly plots in both figures show a tendency for winds to have been on average 0.4 m/s higher from 1998 to 2011 compared to measurements before and after those years. This has caused an apparent rising trend for data up to 2011, which is diminishing as more recent data are included.

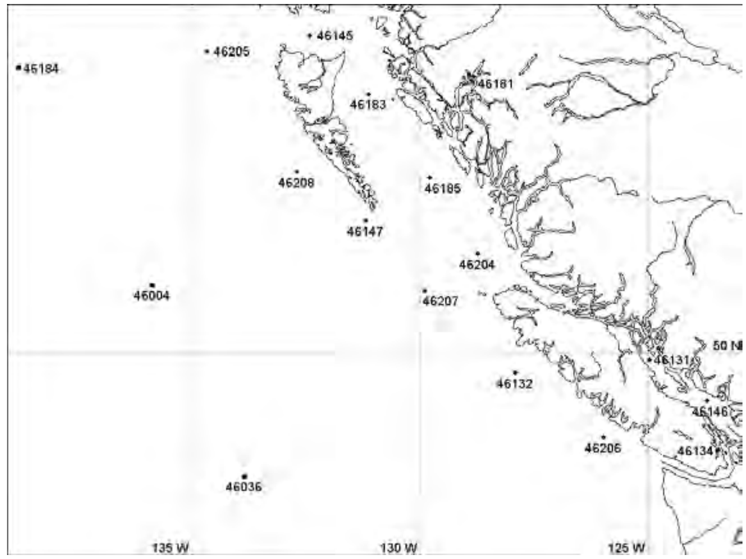

Figure 7-1. Location of the 17 meteorological buoys off the B.C. coast.

Winds are taken from anemometer #1 when available, otherwise from anemometer #2. Both are at a height of about 5 m. Months with less than 300 hourly measurements are ignored. Months in which instruments show an unexpected number of low measurements, are ignored.

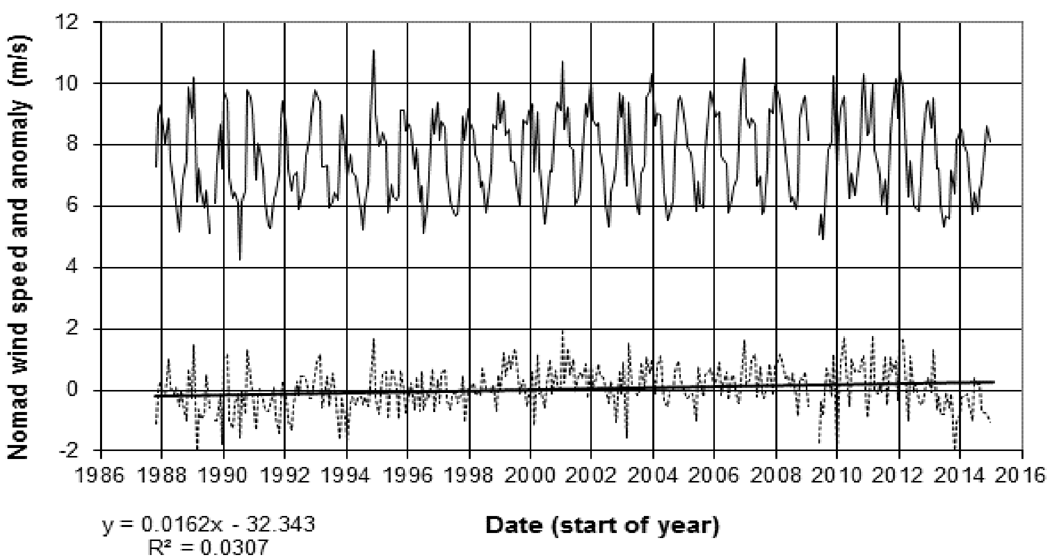

Figure 7-2. Monthly average wind speeds (solid line) and anomalies (dotted) averaged for the three Nomad ODAS buoys 46184, 46004 and 46036 in the west coast meteorological network, located about 400 km west of the B.C. coast.

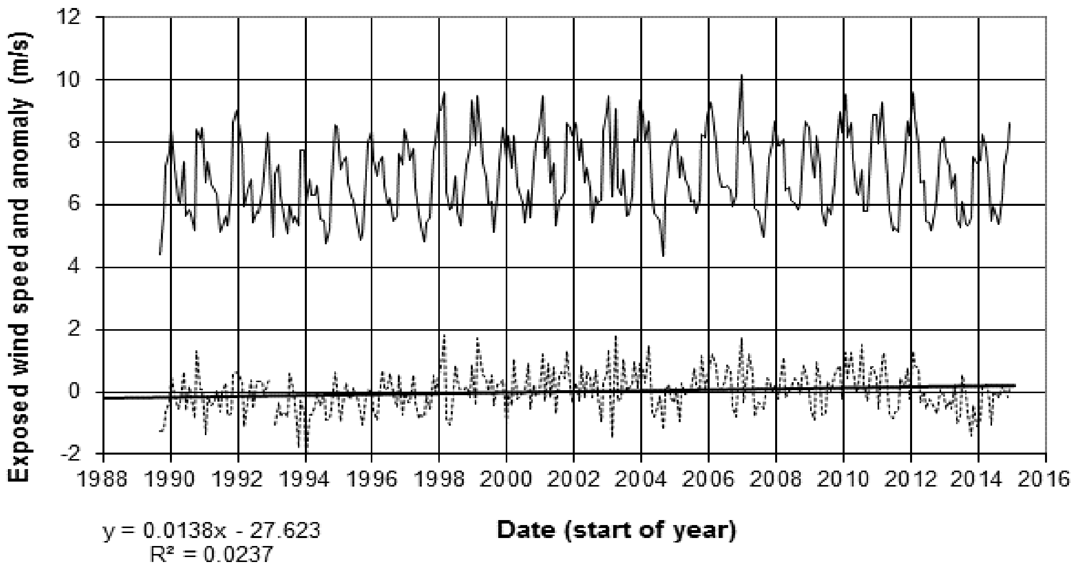

Figure 7-3. Monthly average wind speeds (solid line) and anomalies (dotted) averaged for the six 3-metre ODAS buoys 46205, 46208, 46147, 46207, 46132 and 46206 in the west coast meteorological network, located in a northwest to southeast line along the exposed B.C. west coast.

7.4. Significant wave heights

The average significant wave heights are plotted for the three offshore Nomad buoys in Figure 7-4. The anomaly plot for the offshore buoys in Figure 7-4 shows a decreasing trend in wave height ($p=2.10^{-5}$ assuming monthly means are independent). This represents about a 10% reduction over 26 years, but may also be influenced by decadal cycles seen in the data series (Figure 7-4). The same time series for the six smaller buoys closer to the coast shows no such trend (Figure 7-5). Neither the offshore or shelf buoys show the significant wave height patterns observed for wind speeds from these buoys. The difference in patterns for wind and waves suggests that wave measurements may be dominated by swell waves generated elsewhere.

Months with less than 300 hourly measurements are ignored. High values, for example in February of 1998 and 1999, are confirmed by 3 and 8 operating buoys, respectively.

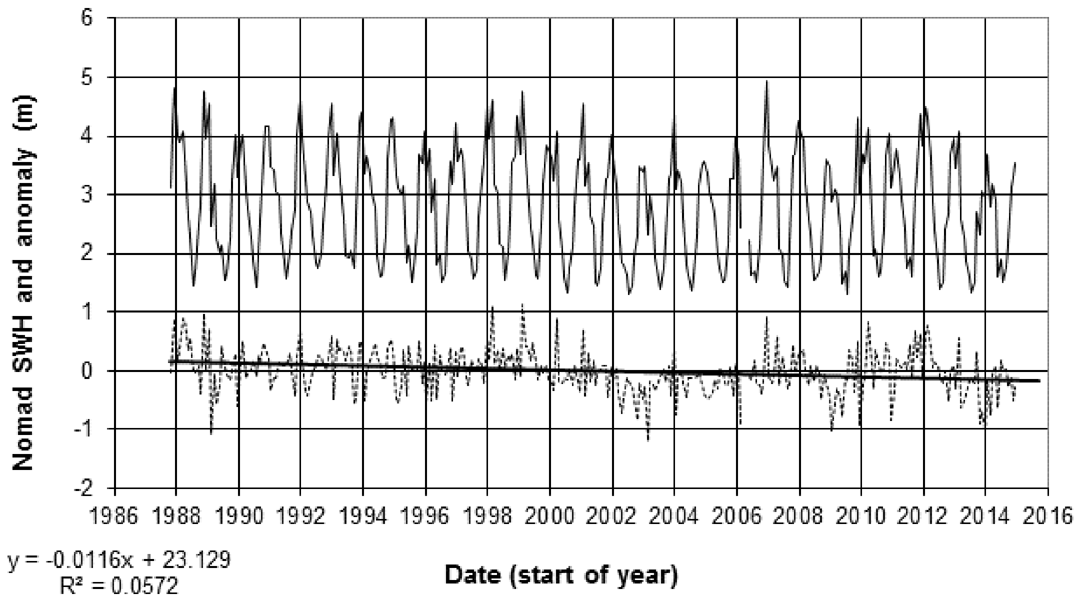

Figure 7-4. Monthly average significant wave heights (solid line) and anomalies (dotted) averaged for the three Nomad ODAS buoys 46184, 46004 and 46036 in the west coast meteorological network, located about 400km west of the B.C. coast.

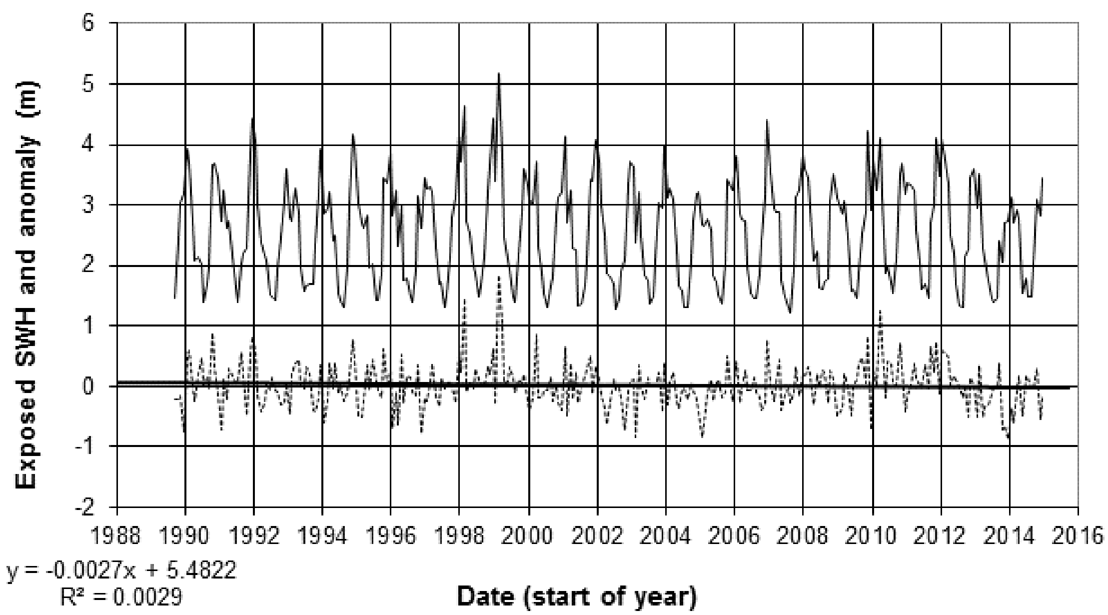

Figure 7-5. Monthly average significant wave heights (solid line) and anomalies (dotted) averaged for the six 3-metre ODAS buoys 46205, 46208, 46147, 46207, 46132 and 46206 in the west coast meteorological network, located in a northwest to southeast line along the exposed B.C. west coast.

7.5. SST

The sea surface temperature (SST) data records are plotted in Figure 7-6 for all buoys. Nomad buoys (only 46184 giving temperature), show a warm anomaly of about 1 ^oC increasing to 1.5 ^oC in 2014. Coastal buoys (46205 down to 46146) show a strongly rising anomaly during the year. Months with less than 300 hourly measurements are ignored.

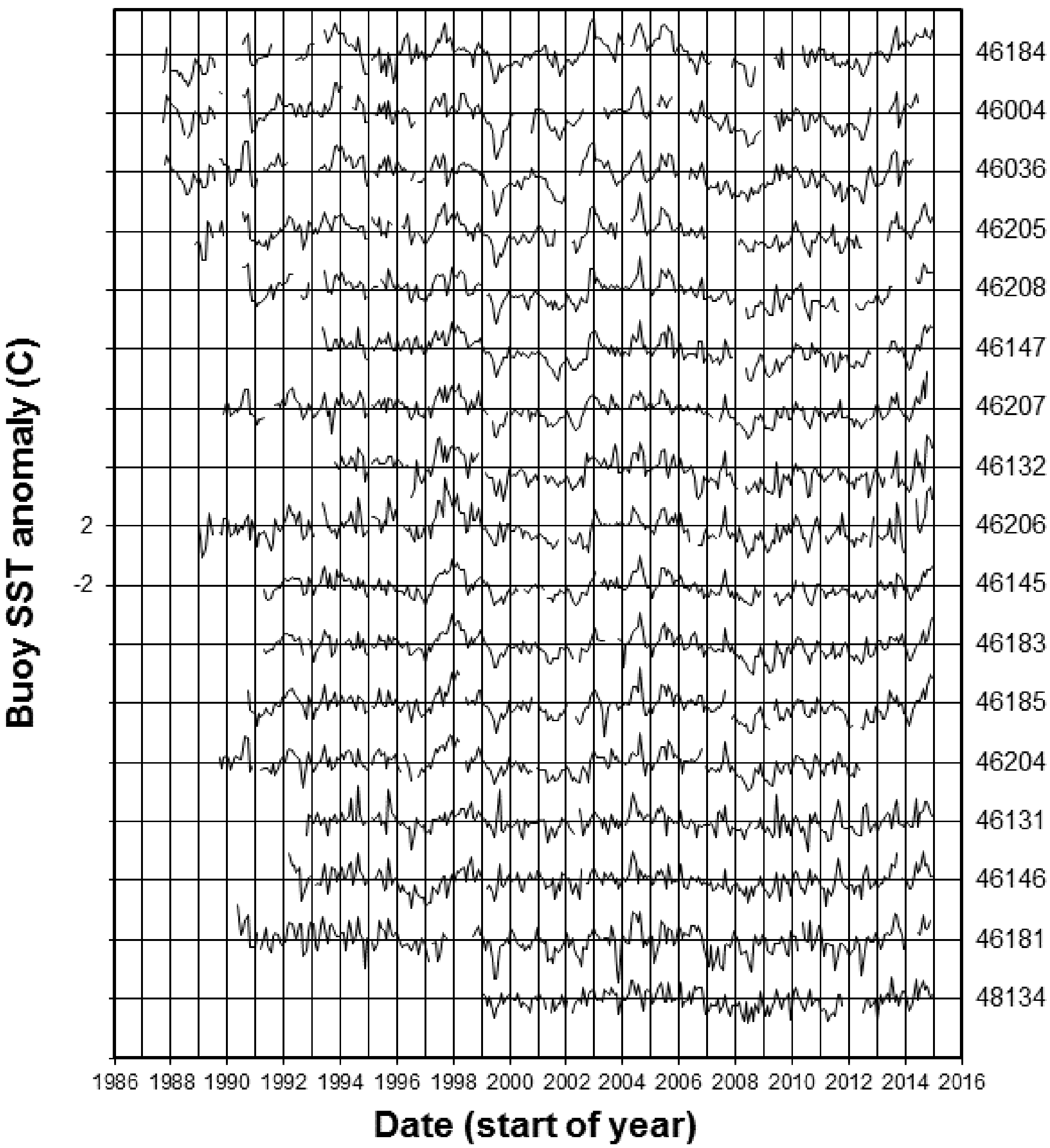

Figure 7-6. Monthly average temperature anomalies for the 17 ODAS buoys in the west coast meteorological network. Nomad buoys 46184, 46004 and 46036 are located about 400km west of the coast. Buoys 46205 down to 46206 are located north to south, close to the coast. Buoys 46145 down to 46146 are located in the more sheltered waters of Hecate and Georgia Straits. The last two buoys are in Douglas Channel and Saanich Inlet, respectively.

8. 2014 CONDITIONS ALONG LINE P AND THE COAST OF VANCOUVER ISLAND

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8.1. Highlights

- Persistent anomalously high surface water temperature throughout most of 2014 seaward of the shelf.
- Warm water extended nearly to shore by September but has shallowed significantly.
- High oxygen and chlorophyll-a (and associated fluorescence) near coast by September.

8.2. Summary

Line P is a series of oceanographic stations extending from the mouth of the Juan de Fuca Strait, south of Vancouver Island, to Ocean Station Papa at 50°N 145°W, in the Pacific Ocean. (Figure 8-1). The Line P time series is one of the longest oceanographic time series in the world, with data going back to 1956. Fisheries and Oceans Canada visits Line P three times per year, usually in February, June, and August.

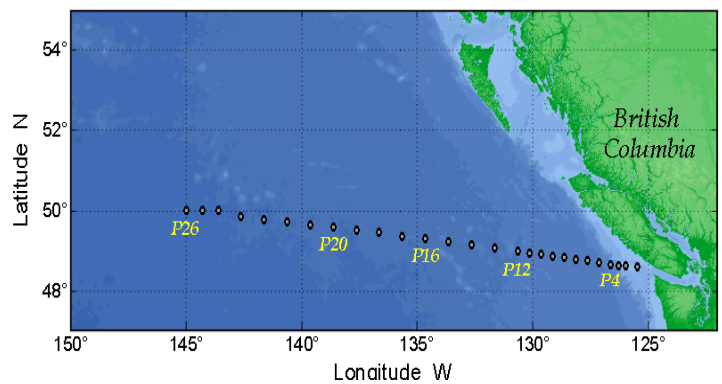

Figure 8-1. Line P and Station Papa (P26).

The La Perouse program is a series of sampling lines on the west coast of Vancouver Island (WCVI), ranging from the mouth of the Juan de Fuca Strait in the south to Cape Scott in the north (Figure 8-2). The program started in the late 1970s and is now sampled twice per year, in late May and early September.

The main story of 2014 is the strong and widespread temperature anomaly that has been sitting in the Gulf of Alaska since the last few months of 2013. At the same time, however, cold waters were trapped along the coast of Vancouver Island in the early half of 2014. Figure 8-3 shows the temperature anomaly along Line P during each of the three 2014 cruises, calculated with respect to the 1981-2010 climatology.

The "blob", a warm surface anomaly covering the Gulf of Alaska, is clearly visible in these figures; the anomaly was situated offshore during the winter of 2014 (February), and it was at its deepest then too, reaching down to 100 dbar. In June the warm waters were shallower but were also present closer to the coast. By August, only the top layer of the NE Pacific was warm, although the surface anomaly reached its maximum value

of 4.5 °C. Also of note is the cold water trapped along the coast in February 2014 (Figure 8-3A), with the cold anomaly reaching -2.4 °C – balancing the +2.4 °C warm anomaly for the same month. As the year progressed and the warm water made its way towards the coast, the cold coastal surface waters slowly disappeared but were still present below the mixed layer depth.

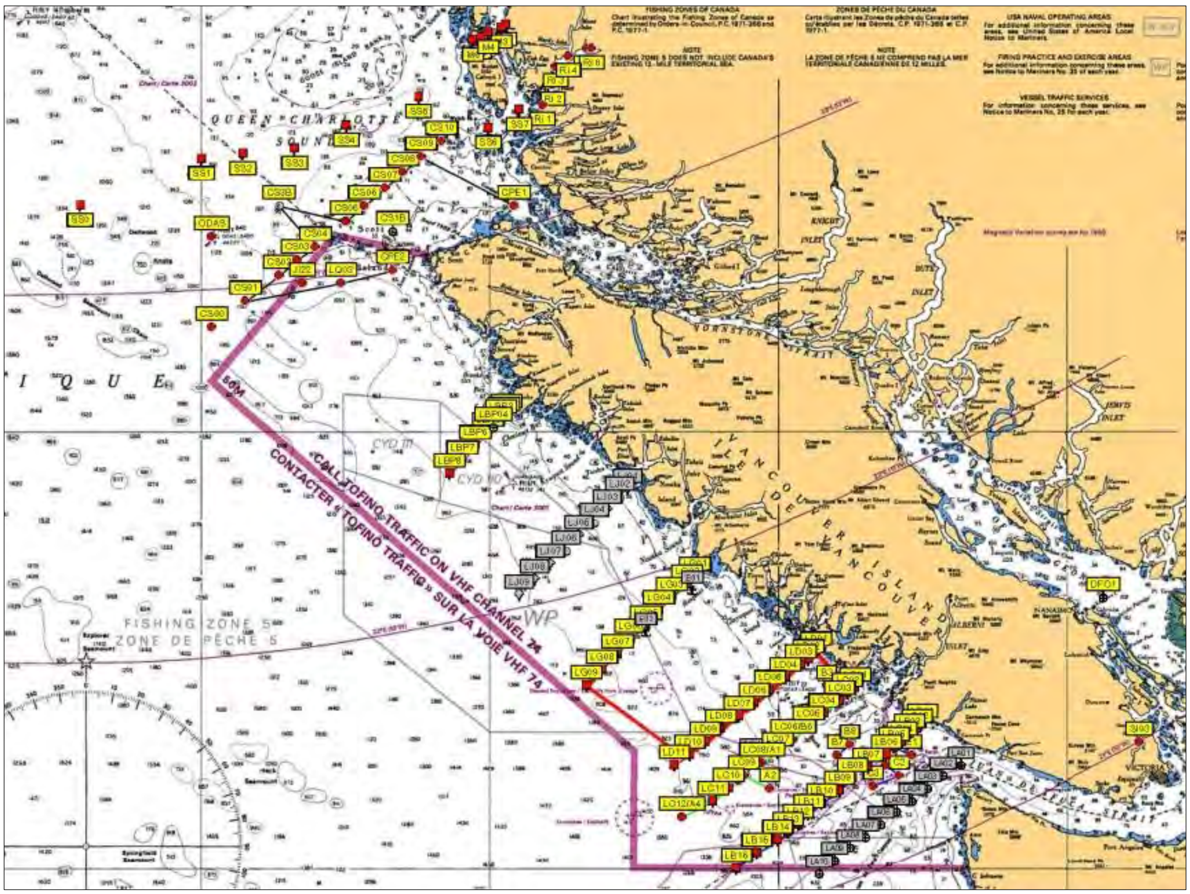

Figure 8-2. La Perouse stations along the West Coast of Vancouver Island

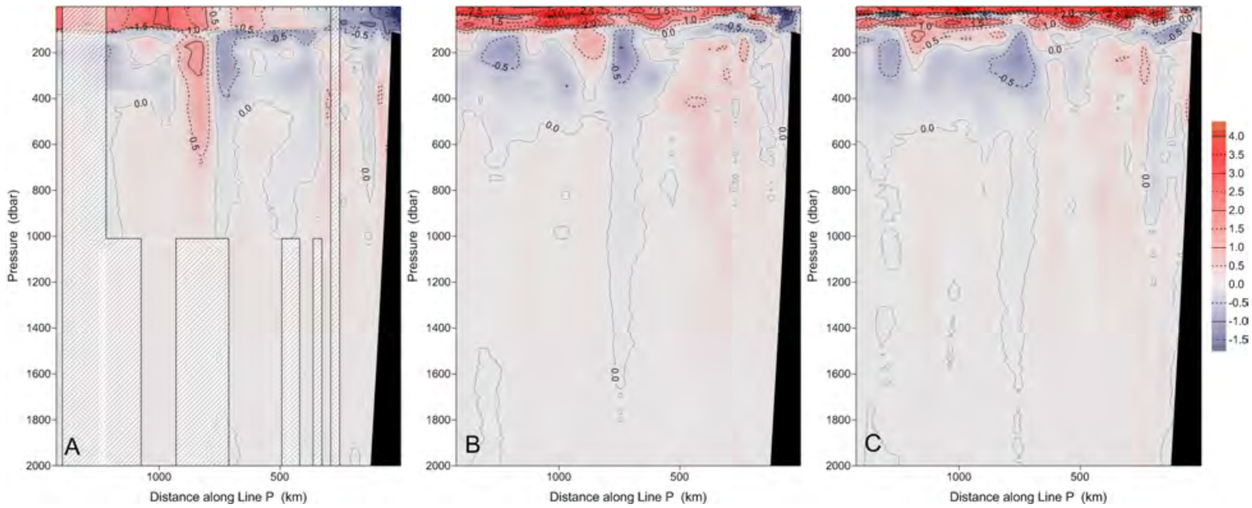

Figure 8-3. Temperature anomaly along Line P in February 2014 (panel A), June 2014 (panel B) and August 2014 (panel C) with respect to the 1981-2010 averages. All three panels are on the same scale of temperature anomaly. The shaded areas in panel A represent the sections with no data, only interpolation.

The onshore movement of the 'blob' was obvious by September 2013, with coastal temperatures well above those seen in 2012 (Figure 8-4). The uniformly warm surface waters may be a result of the weak upwelling in 2013 (Dewey et al. 2015). Sea surface temperatures remained high through early 2014 but appeared to have returned to more 'normal' levels by September 2014.

Another interesting event of 2014 is the very intense phytoplankton bloom that occurred along the southern end of WCVI at the end of the summer. Dissolved oxygen values reached the high level of 9.1 ml/l at station P2 (399 µmol/kg) whereas five samples of chlorophyll-a ranged from 40 to 49 mg/m³ between 5 and 15 dbar at the same station (Figure 8-5). This event was still present although less pronounced along the coast two weeks later during the La Perouse cruise:

Oxygen levels in the La Perouse area are normally lower on the bank. In September an anomalous 'plume' of low-oxygen water rose to within 25 dbar of the surface well offshore, perhaps the result of an eddy or jet associated with the bank, or a particularly strong upwelling event (Figure 8-6).

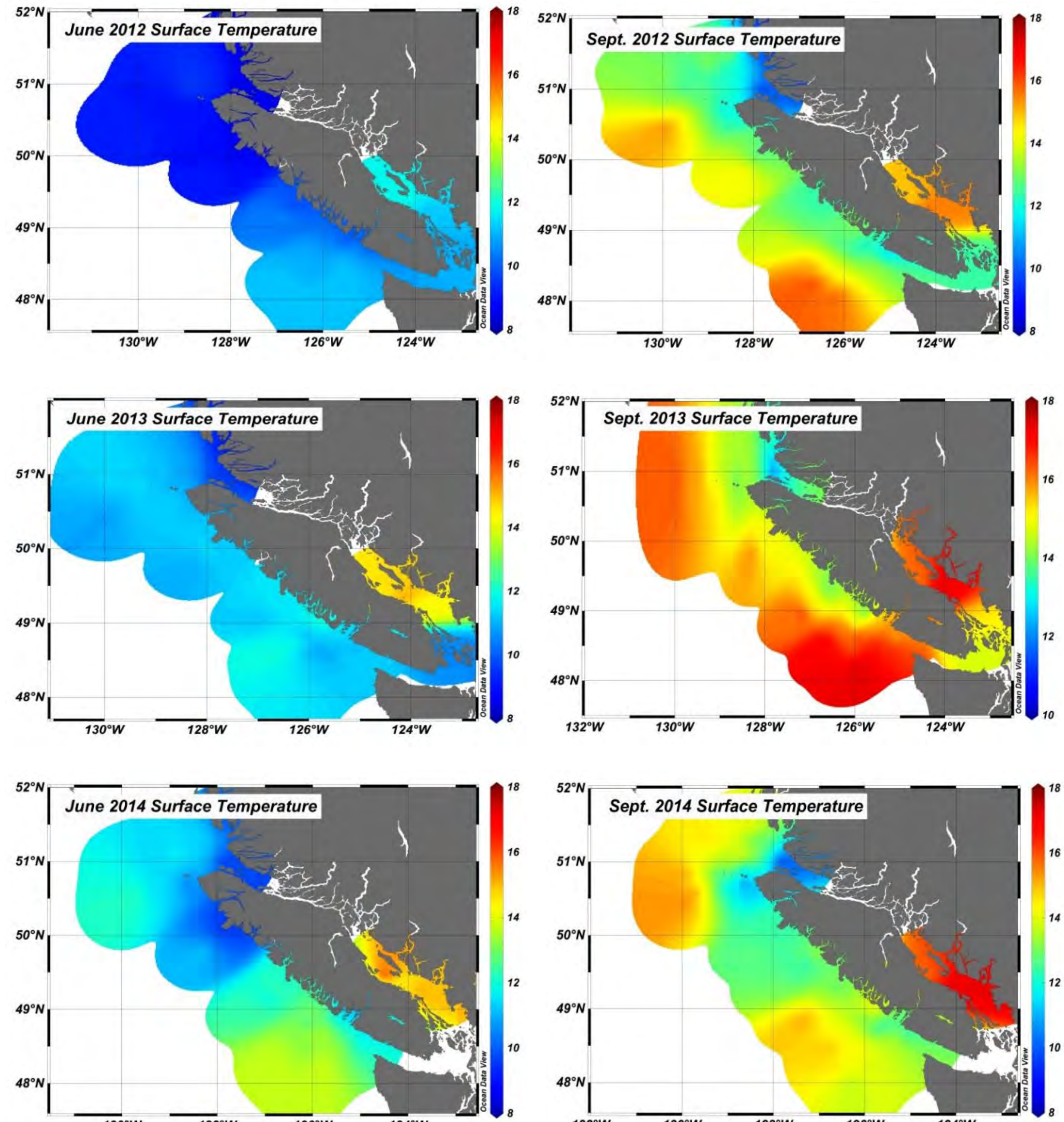

Figure 8-4. Surface Temperatures over the study area 2012-2014.

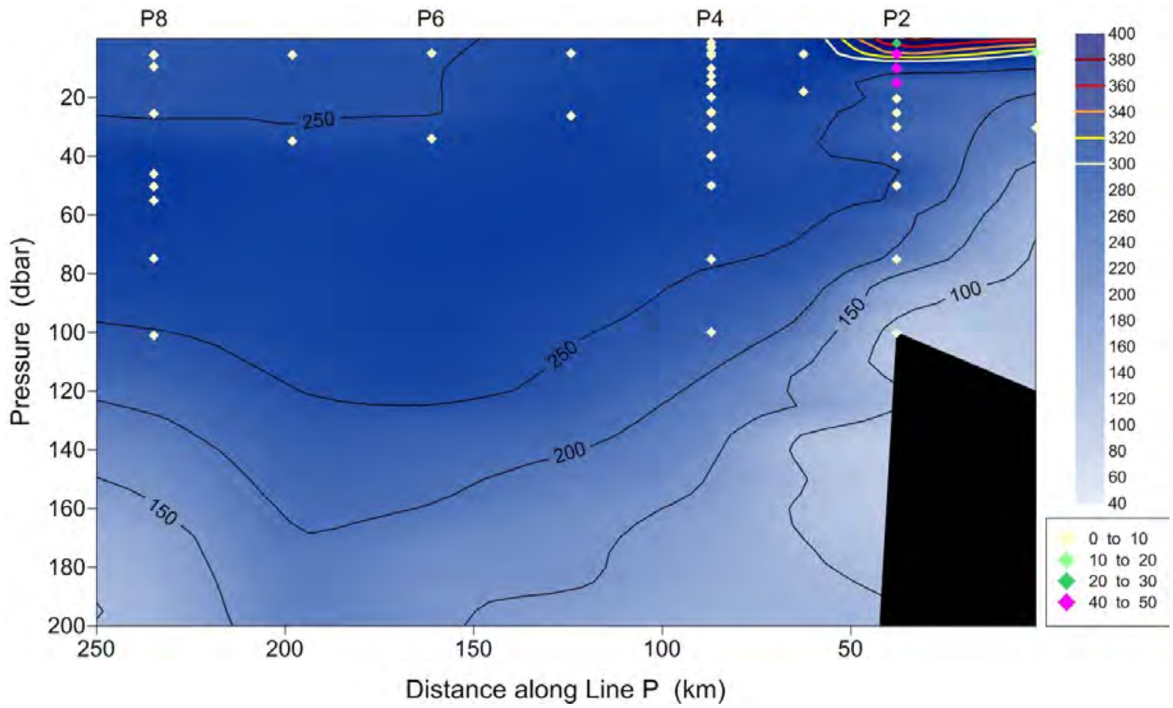

Figure 8-5. Contours of dissolved oxygen along Line P from stations P1 to P8. The lozenges represent the extracted Chlorophyll-a in mg/m³. The high values of dissolved oxygen and chlorophyll a are clearly visible at Station P2.

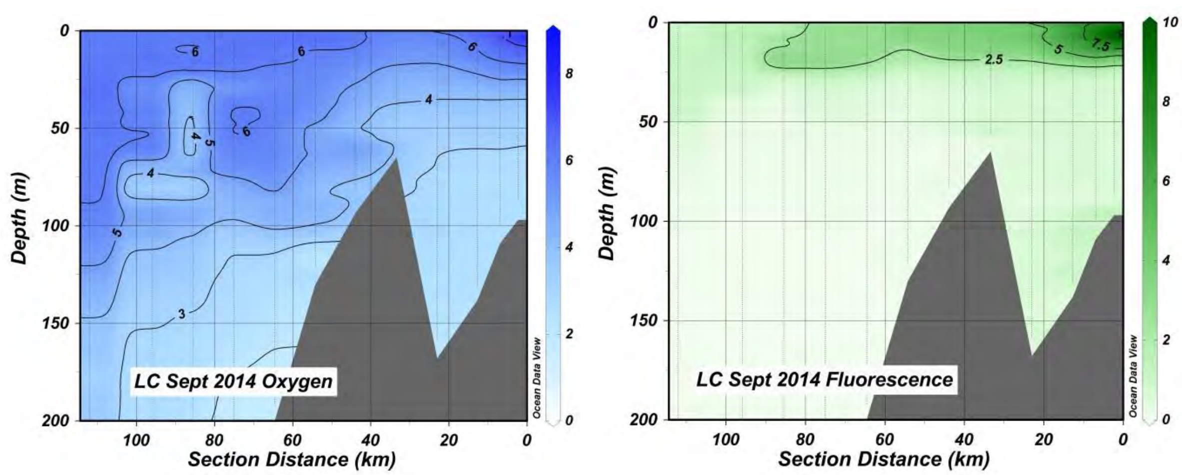

Figure 8-6. Dissolved oxygen and fluorescence along LC line.

8.3. References

Dewey, R., Sastri, A., and Mihaly, S. 2015. The 2014 perspective from Ocean Networks Canada. In: Chandler, P.C., King, S.A., and Perry, R.I. (Eds.). State of the physical, biological and selected fishery resources of Pacific in 2014. Can. Tech. Rep. Fish. Aquat. Sci. 3131 (this volume).

9. IMPACTS OF THE 2013-2014 WARM ANOMALY ON PHYTOPLANKTON BIOMASS IN THE NE PACIFIC

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9.1. Highlights

- The 2013-14 warm anomaly in the NE Pacific reduced nutrient export from the subarctic to subtropics between at least 130 and 170 °W, resulting in a 30% decrease in chlorophyll a in the transition zone (35 to 45 °N). This loss of biomass is expected to impact the many species accustomed to feeding in this productive area in winter.
- Satellite data suggest spring growth of phytoplankton was weak in the vicinity of Station P (50 °N, 145 °W). From May through November, phytoplankton biomass was near normal. Line P nutrients suggest anaemic diatom growth (an apt term, suggesting iron deficiency) which should impair the growth of larger zooplankton (see Batten 2015).

9.2. Impacts of the warm anomaly

In a recent paper, I outlined how strong southerly and weak westerly winds persisted from October 2013 through January 2014 in the NE Pacific, creating a warm region of water covering 1.5 million km^2 (Whitney 2015). Since westerly winds force the export of nutrients from the subarctic to subtropical ocean in winter, any weakening of these winds will result in lower chlorophyll levels (i.e. reduced phytoplankton biomass).

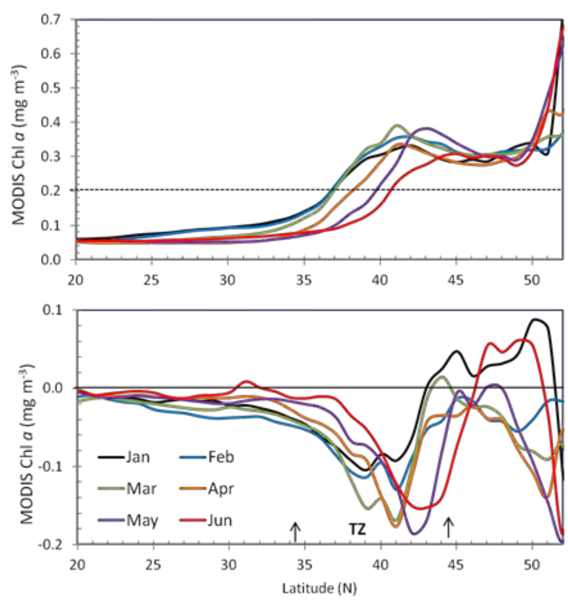

Figure 9-1. Chlorophyll and chlorophyll anomalies between 130 and 150 °W. The upper panel shows average chlorophyll levels (2003-2013) over winter and spring months. The lower panel plots the anomalies measured in 2014. Arrows show the extent of the Transition Zone (TZ; figure from Whitney 2015).

A region of high winter productivity is typically found across the North Pacific, south of the subarctic current in winter (south of 45 °N; Figure 9-1). This region, called the Transition Zone Chlorophyll Front (TZCF), was strongly impacted through winter and spring of 2014. Between 130 and 170 °W, the TZCF lost ~30% of its chlorophyll from January through June 2014. The region of maximum chlorophyll was displaced about 300 km to the north in January and February.

An analysis of chlorophyll levels in winter over the period of SeaWiFS and MODIS satellite

coverage (1997 to the present) suggests the loss of chlorophyll in 2014 was a unique event, but was also part of a longer term trend towards lower chlorophyll in the subtropics (Whitney 2015). Decreasing ocean productivity in the eastern TZCF can be expected to stress many organisms using this area as a preferred winter feeding area (e.g. tuna and other fish, turtles, pinnipeds, albatross, squid and sharks). The stress could be especially acute for nesting animals along the North American and Hawaiian coasts who depend on a stable food supply to nurture their young.

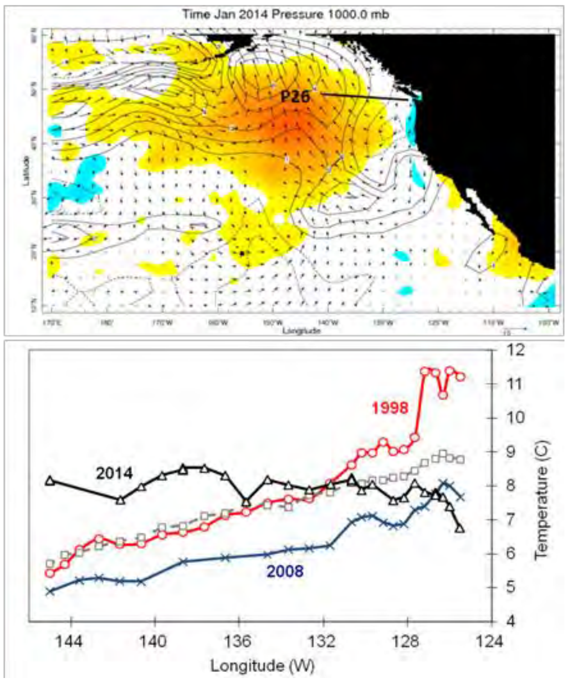

Figure 9-2. The location of Line P is shown with respect to the SST anomaly recorded in January 2014 (upper panel). Arrows show the direction of the wind anomalies. The lower panel shows winter temperatures along Line P for previous cold (2008) and warm (1998) years, the winter average (1988-2008, in grey) and 2014.

In the subarctic Pacific, warm winter waters can be expected to increase the stratification of the upper ocean, resulting in a weakened supply of nutrients (including iron) to the mixed layer. At their furthest western extent, Line P surveys sample the iron poor, high-nutrient, low-chlorophyll (HNLC) waters of the subarctic, providing seasonal measurements of nutrients which can be used to roughly assess changes in primary productivity. Surface sampling from 1988 to 2008 provide a baseline with which to assess the impacts of the 2014 warm anomaly. Surface seawater temperature (SST) varies considerably between cold winters like 2008 and warm events such as 1998 El Niño. In 2014, warm waters in the subarctic had an offshore origin, rather than along shore as occurs during an El Niño (Figure 9-2). Compared to typical winter SST, waters along the western portion of Line P were 1-2 °C warmer, with Station P being 2.4 °C warmer than normal (also salinity was below the winter average by 0.2, likely due to increased ocean stratification and weakened surface water transport to the subtropics).

Nutrient drawdown by phytoplankton fuels the growth of both small algae and larger algae including diatoms which require dissolved silicate to form frustules. Nitrate removal from the surface ocean is often equated to new production, or the production of biomass supporting both animal life and the vertical export of particles to the deep ocean (the two means of carbon and nutrient export from the upper ocean). However, a portion of the nitrate drawdown (~3 µM; Whitney 2011) remains in the surface layer as dissolved organic nitrogen, ammonium and small particles. Thus, silicate becomes an important nutrient to track, since it correlates well with the production of more readily exported carbon (large phytoplankton).

In 2014, both nutrients had higher removal rates from the surface layer than the 1988-2008 average from near the coast to 140 °W (Figure 9-3). By August, nitrate depletion

extended westward as far as the previous extreme observed during warm 1994. High nutrient, low chlorophyll waters (HNLC), a signature of iron deficiency, were only observed in the last few stations along Line P. In this region, nitrate drawdown was near typical but silicate removal was the weakest yet observed. Because sampling in HNLC waters in February was incomplete (only P26), June data have been added to nutrient plots to help resolve the uptake of silicate. These data suggest weak silicate drawdown (~2 µM) west of 142 °W. Diatom growth must have been paltry in 2014, something also observed in CPR sampling (Batten 2015).

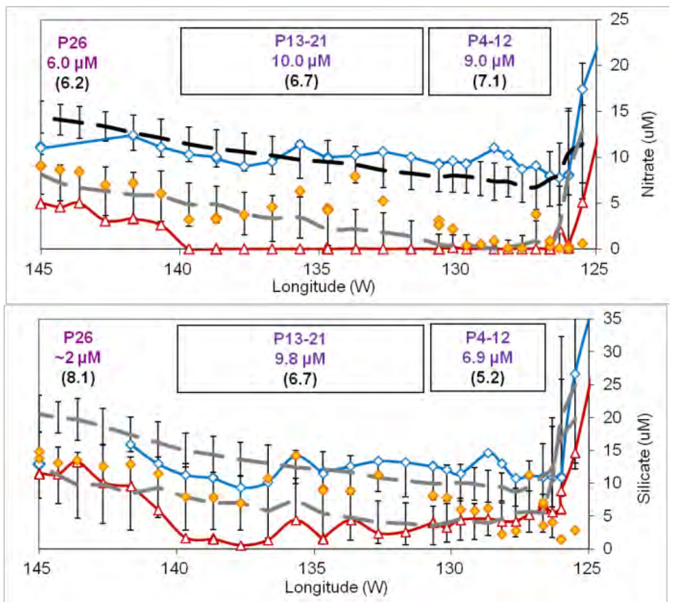

Figure 9-3. Nitrate and silicate in surface waters along Line P. Dashed black (February) and grey (Aug/Sep) lines show the 1988-2008 averages (error bars, 1 sd). Surveys in 2014 occurred Feb 11-20 (blue), June 9-19 (orange) and Aug 21-30 (red). At the top of each panel, nutrient drawdown averages are given for the 20 year average (black) and 2014 (purple) for a range of stations whose extent is indicated by the width of the text boxes. Thanks to Marie Robert and the Line P program for providing data.

Satellite data from the Station P region (49 to 51 °N, 144 to 146 °W; Figure 9-4) confirm that phytoplankton biomass was low in 2014, especially in spring. Chlorophyll *a* seldom shows much increase in this region, unless iron levels are increased by natural (volcanic ash, mesoscale eddies) or human means (SERIES experiment in 2002). Decreases occurred along Line P or in a north-south direction generally due to the influences of subtropical waters. In the late winter and early spring of 2014, chlorophyll and particulate inorganic carbon (a measure of the abundance of calcareous plankton, mainly coccolithophores) both remained near the lowest levels measured by MODIS until May 1. Chlorophyll levels returned to near normal through the summer, and did not appear to be decreasing in November when satellite data were lost due to sun angle and clouds. Warm waters may have inhibited a spring accumulation of biomass (e.g. spring growth may not be observed due to grazer control of phytoplankton growing slowly because of iron limitation) but extended the growing season in the fall.

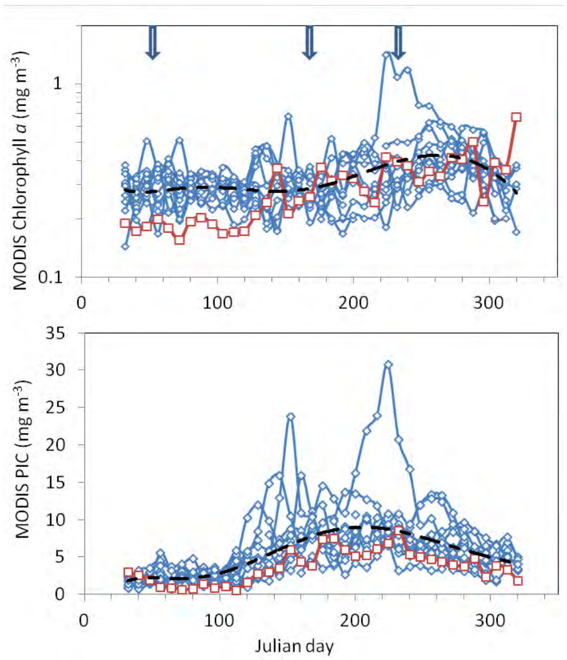

Figure 9-4. MODIS satellite chlorophyll a (upper panel, log scale) and particulate inorganic carbon (PIC, lower panel) for the region 49 to 51 °N, 144 to 146 °W) from 2003 to 2014 (highlighted in red). Arrows indicate when Station P was sampled in 2014. Polynomial fits to all data (dashed black lines) show the typical annual trend.

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10. OFFSHORE PLANKTON INDICES FROM CONTINUOUS PLANKTON RECORDER SAMPLING

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10.1. Highlights

- Diatoms (the larger cells that are caught by the CPR) were very low in 2014. The positive PDO value would have predicted high numbers (but low numbers are consistent with observations by Whitney 2015).
- Zooplankton seasonal timing was early and the season was unusually long.
- Summer 2014 zooplankton composition was biased towards small copepods (as expected), and also high numbers of euphausiids.
- Warm water copepods were more numerous in 2014 than recently (with the highest mean abundance since 2006).

10.2. Sampling

Sampling from commercial ships towing a Continuous Plankton Recorder (CPR) occurs approximately monthly 6-9 times per year between March and October in the off-shore NE Pacific (Figure 10-1). Each CPR sample contains the near-surface (about 7 m depth) plankton from an 18.5 km transect, filtered using 270 μm mesh, and afterwards analysed microscopically to give taxonomically resolved abundance data. Data to June 2014 have been finalised at the time of writing, while samples for July to Sept 2014 are still only partially analysed. Several indices are now routinely updated and are summarized here.

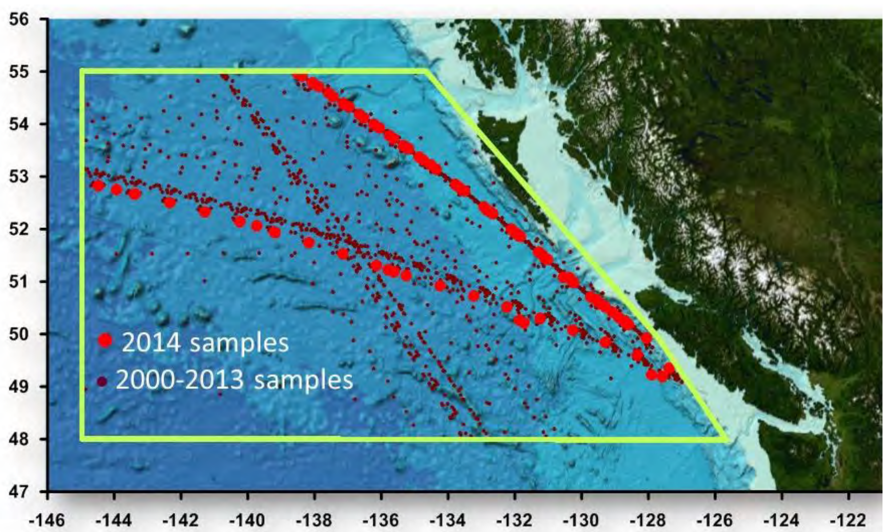

Figure 10-1. Map showing the location of the historical (2000-2013) samples used in this report and those collected in 2014.

10.3. Plankton indices

10.3.1. Diatoms

The CPR retains larger, especially chain forming, diatoms and an annual index of abundance is calculated. Although these larger cells may not be the major component of the phytoplankton community in the offshore, nevertheless changes in the index from year to year should reflect real changes in the lower trophic level ecosystem. From 2000 to 2013 the annual diatom abundance anomaly showed a positive, significant relationship with the Pacific Decadal Oscillation (PDO) index, with diatoms being more abundant in warmer, PDO positive years (r^2=0.47, p<0.01). However, in 2014 the number of diatoms in CPR samples was very low in each sampled month and this relationship no longer applied (Figure 10-2).

The low abundance of diatoms in 2014 is consistent with findings by Whitney (2015a) for the transition zone further south, and for the Station P region which had low nutrients and low chlorophyll levels in spring. Whitney (2015b) speculates that the warm anomaly offshore reduced nutrient export causing a reduction in phytoplankton growth and biomass.

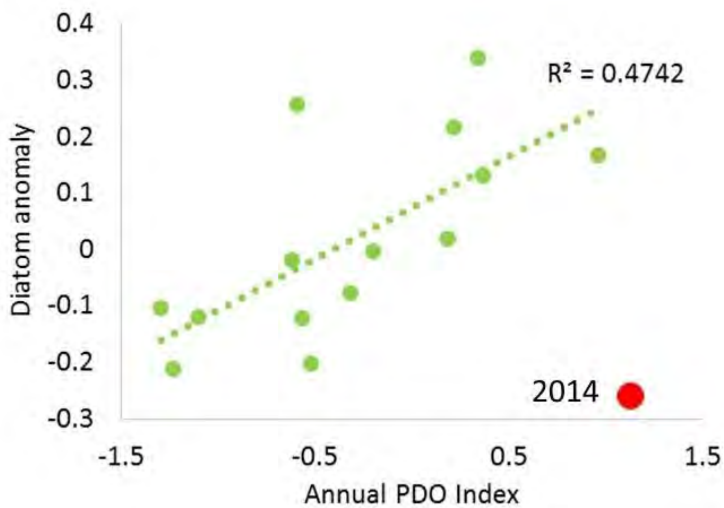

Figure 10-2. The relationship between the annual PDO index and annual diatom abundance anomalies from 2000 to 2013. The 2014 point is indicated in red.

10.3.2. Zooplankton Biomass

The estimated annual anomaly of mesozooplankton biomass was slightly positive for 2014, but not exceptional. The largest monthly value occurred in April, rather than May and indices of seasonal timing (day of the year when the 50th percentile of cumulative biomass was reached) also showed that the season mid-point was relatively early. This was consistent with the warm, positive PDO values (developmental rates of the zooplankton proceed faster in warmer conditions). An index of season length, taken as the number of days between the 25th and 75th percentiles, was the longest yet recorded for the time series in 2014. This was unexpected since warm years usually show a shorter season, and as yet we have no explanation.

10.3.3. Zooplankton community composition.

The zooplankton data were subdivided into broad taxonomic groups. Small copepods (< 2 mm) are significantly positively correlated with the PDO, being more abundant in warm years (r^2=0.36, $p<0.01$) while large copepods (> 2 mm) are the reverse, being negatively correlated with the PDO (r^2=0.24, $p<0.05$) and more abundant in cold years. As expected, the relative abundance of small copepods in 2014 was quite high (Figure 10-3) while large copepods were quite low. Also notably high was the abundance of euphausiids in 2014.

Copepods are generally identified to species during sample analysis, or at least to genus, allowing the tracking of a group of warm water copepod species which show a positive, significant relationship with the PDO (r^2=0.29, $p<0.02$). The abundance of this group has been zero, or extremely low, in recent years but numbers increased in 2014 and had the highest value since 2006. The high PDO value would have predicted an even higher abundance, which may still materialize once data have been finalized for the year.

In summary, the CPR data show some results that are consistent with the warm, PDO positive conditions in 2014 such as an early zooplankton season, a bias towards smaller copepods and an increase in warm water taxa, but some results are not as expected. The low number of diatoms and the unusual length of the zooplankton season may indicate oceanographic processes that are unique to the anomalous pool of warm water that did not originate from an El Niño (e.g. see Whitney 2015b).

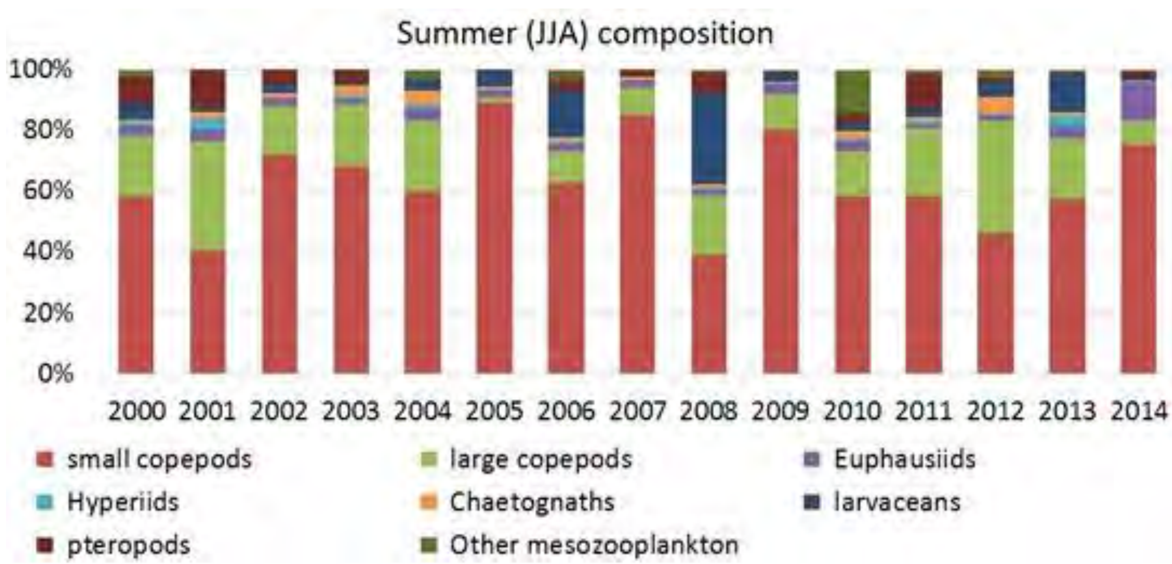

Figure 10-3. The relative contribution of broad taxonomic groups of zooplankton to the summer community in each year.

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Whitney, F.A. 2015. Anomalous winter winds decrease 2014 transition zone productivity in the NE Pacific. Geophys. Res. Lett. 42: 428–431. doi:10.1002/2014GL062634.

See http://pices.int/projects/tcprsotnp/default.aspx for data, updates and more information.

11. FRASER RIVER SOCKEYE DIVERSION RATE; 2014 THE HIGHEST ON RECORD

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11.1. Highlights

- 96% of the 2014 Fraser River Sockeye return migrated via Johnstone Strait in 2014, the highest annual value on record (dating from 1953).
- A dramatic shift (increase) in the fraction of fish migrating via Johnstone Strait occurred in 1978, coincident with the ocean regime shift of winter 1976-77.
- Annual variation in diversion rates has been correlated with both open ocean and coastal sea surface temperatures, ocean currents, and variation in the earth's geomagnetic field.
- New models for forecasting diversion rate are being developed as part of a Canadian Science Advisory Secretariat report.

11.2. Summary

Adult Sockeye Salmon take one of two migration routes on their journey homeward to the Fraser River. Some fish return from the north, migrating via Johnstone Strait, while others migrate via Juan de Fuca Strait, the southern boundary between Vancouver Island in British Columbia and the Olympic Peninsula in Washington State (Figure 11-1). The fraction of fish that migrate via the northern route through Johnstone Strait is called the northern diversion rate, or simply the diversion rate.

For the period 1953-1997, diversion rate estimates were largely driven by the relative magnitude of catches taken from areas along each migration route. These estimates were derived from a variety of run-reconstruction techniques used by the International Pacific Salmon Fisheries Commission (IPSFC), 1953-1985, and the Pacific Salmon Commission (PSC), 1986-present (McKinnell et al. 1999, Starr and Hilborn 1988, Cave and Gazey 1994). McKinnell et al. (1999) found that approach route catches accounted for 93% of the variation in the diversion rate estimates derived by these methods during the period 1977-1997. This result is not surprising given the relatively high fractions of the run harvested in marine areas during this period when the mean annual exploitation rate was 68% (PSC, unpublished data). More recently, marine exploitation rates have decreased and the mean annual exploitation rate was 22% over 1998-2011 (PSC, unpublished data). Estimates of diversion rate over this latter period are more dependent on the relative catches in marine area test fisheries (e.g. Putnam et al.

2014). The resulting daily diversion rate estimates can be quite variable because test fisheries harvest much smaller fractions of the total return (annually 1-2%). However, the variability in annual estimates is buffered from this source of error because annual estimates are the cumulative sum of daily abundance estimates migrating via each route. Because of their dependence on catches (either from commercial or test fisheries), diversion rates tend to be more accurately estimated when the migration is strong through one approach or the other (i.e. >60% or <40%), and much less precise when relatively equal fractions of the fish are migrating via each route. For a quantitative evaluation of sources of error in diversion estimates see McKinnell et al. (1999).

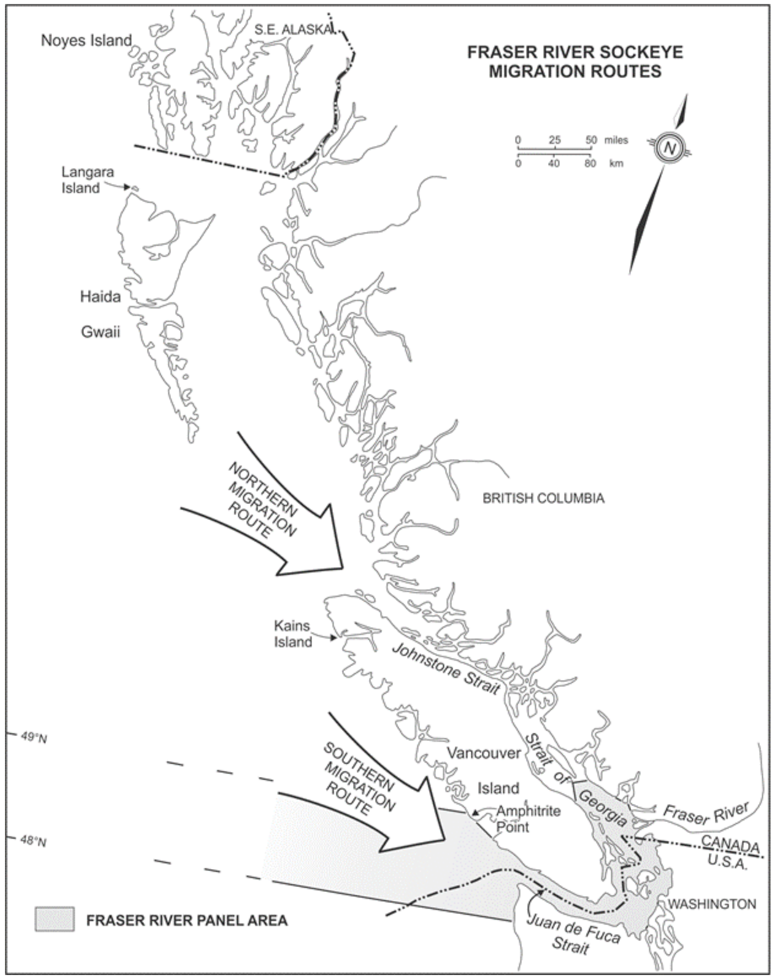

Figure 11-1. The migration routes of adult Sockeye returning to the Fraser River. The Fraser River Panel area are waters that are managed by the PSC.

During the 1953-1977 period annual estimates of diversion were generally low and the mean was 16% (Figure 11-2). Annual diversion rates increased and were much more variable post-1977 and the mean was 51% over 1978-2014 (Figure 11-2). This increase in diversion rate resulted in a decrease in the fraction of Fraser Sockeye caught in “Convention” waters (i.e. equivalent to the Fraser Panel Area shown in Figure 11-1) that were under the control of the IPSFC (through 1985) and now the PSC (1985-present) (Roos 1991), thus complicating the bilateral management of the resource. Consequently, management is now coordinated through multi-agency actions in both Panel (PSC) and non-Panel (largely DFO) area waters through the 1985 Pacific Salmon Treaty. The diversion rate in 2014 (96%) was the highest on record.

In addition to varying inter-annually, the diversion rate generally increases during each year (Figure 11-3), with some of the earliest migrating populations migrating primarily via Juan de Fuca Strait (e.g., Early Stuart sockeye). The rapid increase in the 2014 diversion rate was also anomalous (Figure 11-3).

Hypotheses about causal mechanisms and attempts to predict the diversion rate by relating it to various environmental factors began in the 1960's (see McKinnell et al. 1999 for a review). Research efforts intensified following a period of increasing diversion rates that culminated with a then record 80% diversion in 1983 (IPSFC 1984). The anomalously high diversion rate in 1983 was attributed to an El Niño event that elevated sea surface temperatures (SST) along the northwest Pacific coast (IPSFC 1984). A significant correlation (*r* = +0.70, *N* = 31) was found between the mean spring SST (March to May in the year of return) from shore station (lighthouse) observations at Langara and Kains Islands (Figure 11-1) and the diversion rate over the period 1953-1983. The magnitude of the correlation increased to +0.94 when the analysis was restricted to the most recent years of the period, 1973-1983 (IPSCF 1984). The pattern of improved correlations and dramatic shift in diversion rate post-1977 was hypothesized by McKinnell et al. (1999) to be related to a "change in the state of nature" that researchers now commonly refer to as the ocean regime shift of the winter 1976-1977 (Ebbesmeyer et al. 1991, Hare and Mantua 2000). Subsequently, most investigators have restricted their data sets to this post-1977 period.

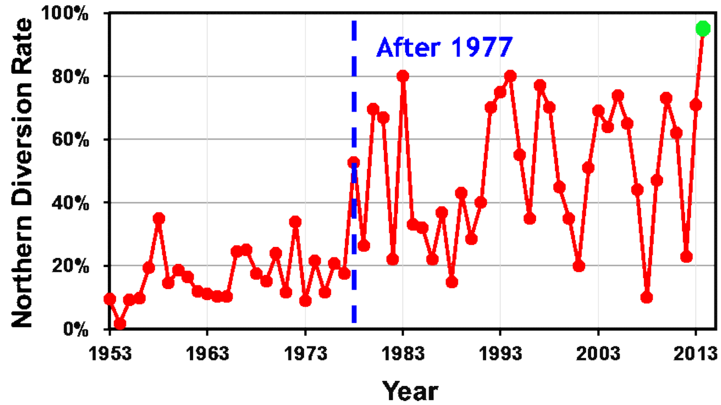

Figure 11-2. Time series of annual northern diversion rates for Fraser River Sockeye Salmon. Values to the right of the blue dashed line denote the post-1977 period. The green circle at far right denotes the 2014 estimate (96%).

Under the terms of the 1985 Pacific Salmon Treaty between the United States and Canada, the responsibility for forecasting diversion rate lies with Canada, or more specifically DFO. Building on the earlier efforts of the IPSFC, McKinnell et al. (1999) related annual estimates of diversion rate to mean monthly SST taken at Kains Island Lighthouse (Figure 11-1) over the period 1977-1997. Positive correlations were found between the SST at Kains and diversion rate for each month in the year of return except October, with monthly correlations peaking in the April-June period. Strongest correlations occurred in June when *r* = +0.85 (McKinnell et al. 1999). Correlations decreased substantially for the months of July-September despite the fact that Fraser Sockeye migrations to the south coast occur during this latter period, suggesting that conditions at Kains Island were not driving the migration pattern; rather that Kains Island temperatures were simply indicative of earlier, more seaward oceanographic conditions (McKinnell et al. 1999). Nevertheless, SST at Kains Island in May and June has been the primary variable used to predict the northern diversion rate since 1999.

In 2014, May SST at Kains Island was anomalously warm resulting in a forecast of 66% diversion (Folkes 2014). However, June SST values were similar to May and nearer normal for the time of year, resulting in a forecast diversion rate of only 34% (Folkes 2014). The combination of May and June SST values generated a forecast for 50%

diversion (95% PI ± 31%; Folkes 2014). The low forecast diversion relative to the observed value of 96% and the relatively large prediction interval is likely due to a combination of factors. First, although SSTs at Kains Island are strongly correlated with open ocean SSTs in the Gulf of Alaska, that correlation can break down depending on the timing of the spring transition which typically results in cooling of coastal waters in association with local upwelling (McKinnell et al. 1999). Thus, even though the Gulf of Alaska was anomalously warm for most of the winter through the summer months of 2014 (i.e. the "warm blob" phenomenon, see Freeland 2015, and Crawford 2015), those conditions appear to have generated warming at Kains in May, but were overridden by the spring transition/upwelling events in June. Second, SST is likely only a surrogate for a variety of factors that are most causally linked to the fish's migration behavior.

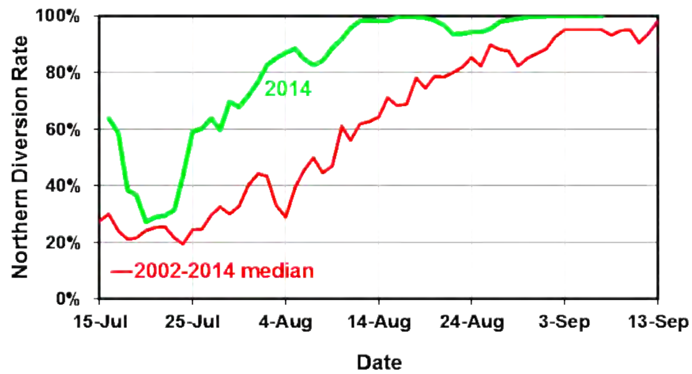

Figure 11-3. Time series of daily northern diversion rates for Fraser River Sockeye Salmon. Red line connects the median daily diversion rates for the period 2002-2014. Green line denotes daily estimates for 2014.

For example, Putnam et al. (2014) hypothesized that Fraser sockeye diversion behaviour is linked to variations in the earth's geomagnetic field near the areas around Haida Gwaii and Vancouver Island. Using data from the full time series (1953-2012), they found that the variation in the geomagnetic field alone explained 23% of the variation in sockeye diversion rate, while offshore SST explained 13% (relative to 62% in the full multiple regression model). They attributed this effect to "geomagnetic imprinting" (Putnam et al. 2014). Although we agree that the geomagnetic field may play a role, whether this can be attributed to "imprinting" is unclear. This is because the vast majority of Fraser Sockeye juveniles appear to migrate northward along the continental shelf through Johnstone Strait, while the path of returning adults varies independently (Groot and Cooke 1985). Furthermore, Putnam et al. (2014) did not quantify intra-annual variation in the geomagnetic fields, which would be necessary to explain the increasing within-year trends in diversion rate shown in Figure 11-3.

Revised methods to forecast diversion are current being explored as part of a Canadian Science Advisory Secretariat research document (Folkes et al. in prep). Seven distinct types of environmental data were gathered for exploration in this work: Fraser river discharge, relative sea level, SST, sea surface salinity, wind stress, ocean current velocity, and earth magnetic field estimates. Initial models were based on single variable relationships (either linear regression, or generalized additive models). Time lags back to 18 months prior to return migration, combined with averaging windows ranging from 3-89 days and a 1°x1° (latitude, longitude) spatial grid were used to construct averages for the explanatory variables. Most of the "high seas" environmental time series were estimated by satellite telemetry, thus limiting some data sets to the post 1981-1982 period. Other data streams, not constrained by those sources, had

longer time series. “Best” model selection was based on qualifying criteria: $r^2 > 0.5$; Bonferonni adjusted p value < 0.05; and number of years > 16. Multivariate linear regression models were constructed by stepwise regression from the qualifying single variable models. The performance of all qualifying multivariate and single variable models were evaluated retrospectively to determine the top models. Results to date suggest that the best models for forecasting diversion rate are related to SST and current velocity. The statistical models based on geomagnetic data did not meet the initial selection criteria of $r^2 \geq 0.5$, and thus were not assessed in the performance evaluation.

The migration routes of Fraser River Sockeye are undoubtedly related to factors that affect ocean distribution and nearer shore migration behaviour. Oceanographic variables appear to act as surrogates for some of these factors, while others may be related to geomagnetic and olfactory clues. However, there are additional sources of variation in annual estimates of Fraser River Sockeye diversion rates. For example, several Fraser Sockeye stocks cycle in their relative abundance and vary in their return timing (Walters and Staley 1987, Blackbourn 1987). This fact, coupled with the relatively consistent increasing trend in diversion rate within a year, means that some portion of the inter-annual variation in diversion rate is likely attributable to inter-annual variation in stock abundance and timing. More detailed stock specific diversion rate information being compiled by Pacific Salmon Commission should help further elucidate causal mechanisms for the variation in diversion rate.

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Individual reports on the outer British Columbia Coast

12. WIND-DRIVEN UPWELLING/DOWNWELLING ALONG THE NORTHWEST COAST OF NORTH AMERICA: MAGNITUDE AND TIMING

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12.1. Highlights

- After about a decade of stronger than average upwelling-favourable winds along the northwest coast of North America, upwelling-favourable winds returned to near-average conditions in 2014. This suggests a return in 2014 to conditions of average upwelling-induced coastal productivity.
- The winters of 2009/10 through 2011/12 had stronger than average downwelling, a result of a more intense and/or eastward shift (toward the North American coast) of the Aleutian Low and associated storm tracks. In contrast, there was weaker than average downwelling over 2012/13 to 2013/14 due to a less intense and/or westward-shifted Aleutian Low. The winter of 2014/15 experienced near-average downwelling up to January, 2015.
- The timing of the Spring Transition – the seasonal shift from generally downwelling conditions along the northwest North American coast in winter to upwelling in summer – displays considerable interannual variability. In years when the Spring Transition is late (such as 2005) marine productivity is generally poor. In 2014, the Spring Transition timing was near average, suggesting upwelling-based productivity was near average.

12.2. Upwelling Magnitude: The Upwelling Index

Due to their link to offshore surface Ekman transport and compensating onshore transport at depth, the duration and intensity of upwelling-favourable (northwesterly) winds are good indicators of coastal productivity. To gauge low-frequency variability in coastal productivity, we have summed upwelling-favourable-only wind stresses by month along the west coast of North America from 45°-60°N latitude (Figure 12-1) from the NCEP/NCAR Reanalysis-1 analyses (Kistler et al. 2001). Figure 12-2 shows the monthly mean integrated upwelling anomalies smoothed using a five-year running mean over the period 1948-2014. The regime shift in the late 1970s appears as a sharp transition from stronger-to-weaker-than-average upwelling-favourable winds. Upwelling-favourable winds have been stronger than average throughout the 2000s. In previous State of the Pacific Ocean Reports (e.g., Irvine

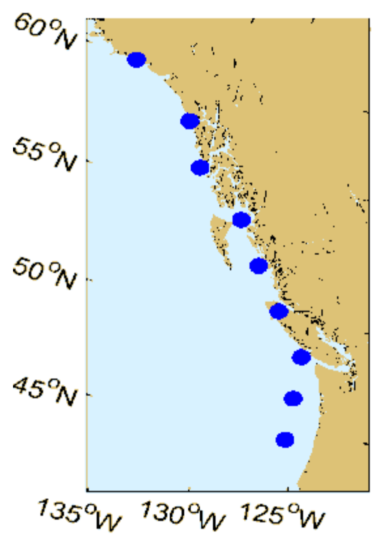

Figure 12-1. NCEP/NCAR Reanalysis-1 coastal surface wind stress grid locations.

and Crawford 2013), we speculated that a repeat of the mid 1970s regime shift to weaker-than-average upwelling appeared imminent, and Figure 12-2 indicates a weakening to near-average upwelling near the end of the time series. An examination of the unsmoothed series reveals stronger-than-average upwelling-favourable winds persisted through most years up to and including 2013 (Figure 12-3). Over 2014 upwelling-favourable wind stress was average, such that the upwelling anomalies were near zero.

12.3. Downwelling Magnitude: The Downwelling Index

We have also examined the downwelling-favourable winds by considering only the poleward component of the alongshore wind stress; anomalies of the monthly poleward sums are shown in Figure 12-4. Here, the regime shift in the late 1970s is characterized by a latitude-dependent transition. Southward of 48ºN, the transition is to weaker downwelling (shifting from average to below-average), whereas northward of this latitude the transition is to stronger downwelling (changing from below average to stronger than average). The major El Niños of 1982/83 and 1997/98 are characterized by stronger than average downwelling throughout their duration. The anomalies of largest magnitude and greatest spatial extent are positive; they occurred over 1998 to 2012 and extended over the range of latitude from 45-60ºN. A more detailed (non-filtered) examination of the last nine years (Figure 12-5) shows wintertime downwelling-favourable wind stress anomalies were either near zero (2008 and 2009) or stronger than average (2007, 2010-2012). Downwelling transitioned to near- or below-average in late 2012 and remained so through 2014.

As indicated by Figure 12-5, the downwelling index reaches its highest magnitude during winter when storms are strongest and most frequent. Stronger than average downwelling during the winters of 2007 and 2010 were due to an eastward shift of the Aleutian Low and associated storm tracks. In 2010, stronger downwelling was also due to the Aleutian Low being more intense. Thus, variations in the downwelling index are due to variability in the Aleutian Low, consisting of a combination of east-west shifts of the centre of the Low and variations in its strength and associated storm tracks. An eastward shift and/or intensification of the Aleutian Low leads to stronger than average downwelling, while a westward shift and/or weaker Aleutian Low leads to weaker than average downwelling. Over the winter of 2013-14 downwelling was far below average due to a much weaker Aleutian Low, while conditions were near average over the beginning of the 2014-15 winter (see also Dewey et al. 2015).

Both upwelling and downwelling indices are positive through much of the 2000s (Figures 12-2 and 12-4), suggesting an overall increase in wind speed and wind stress, regardless of wind direction. This may be due to overall shifts in the locations and/or strength of the dominant surface wind circulation patterns in winter and summer (Aleutian Low and North Pacific High). While the effects on upwelling and alongshore advection are dependent on the wind direction, the effects on mixed-layer depth and Ekman pumping by the generally positive wind stress curl in the Gulf of Alaska in winter should be mainly related to wind strength. In the short-term, variations in the surface wind circulation patterns were likely a factor in setting up the large positive SST

anomalies in the Gulf of Alaska in 2014 (Freeland 2015). However, the long-term effects in the northeast Pacific of changes in scalar wind properties is unclear, but could impact overall productivity.

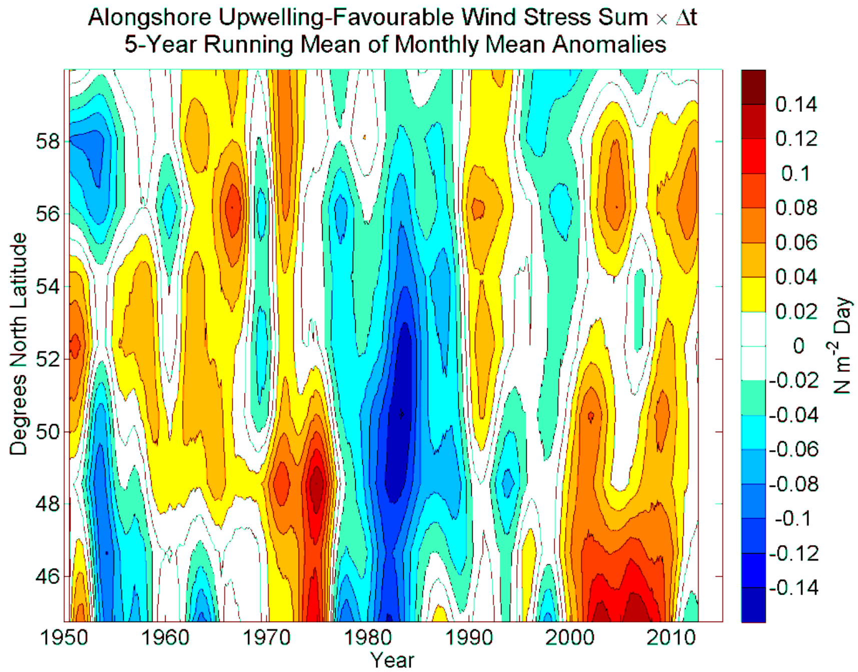

Figure 12-2. Five-year running means of monthly mean anomalies of monthly sums of alongshore upwelling-favourable (equatorward) wind stress at coastal grid points from 45-60° N.

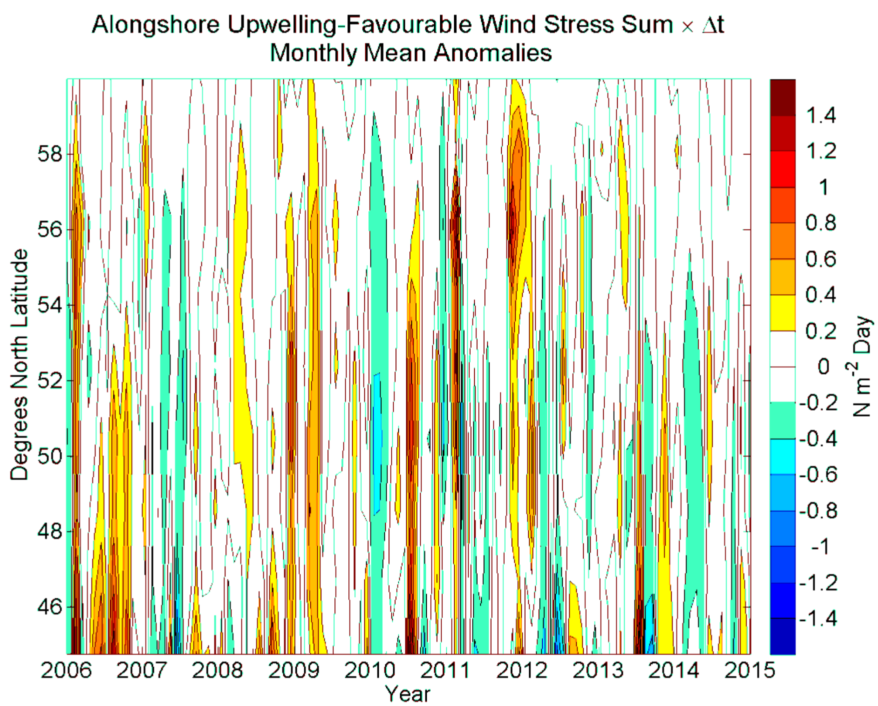

Figure 12-3. Recent (2006 to 2014) non-filtered monthly mean anomalies of monthly sums of alongshore upwelling-favourable (equatorward) wind stress at coastal grid points from 45-60° N.

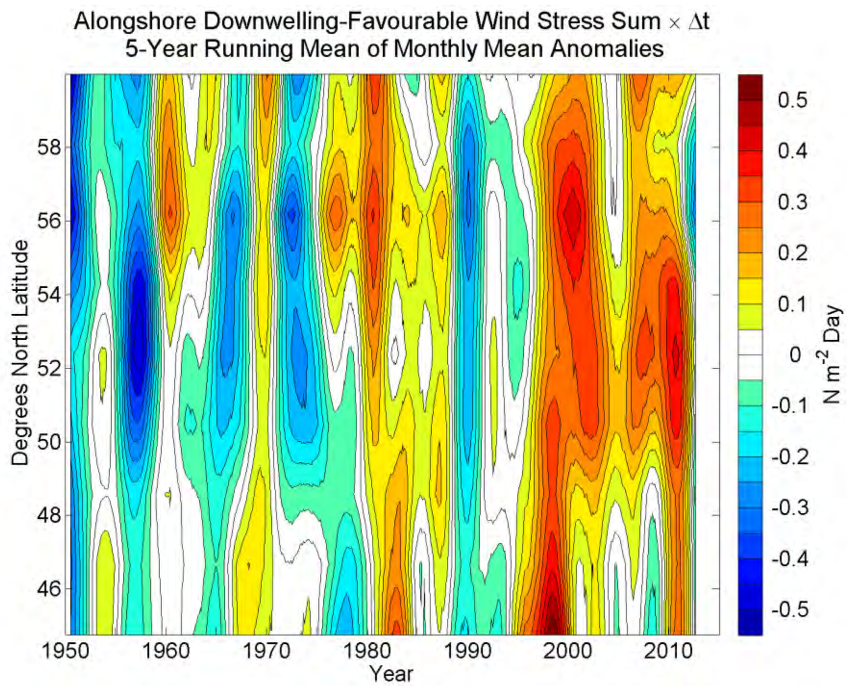

Figure 12-4. Five-year running means of monthly mean anomalies of monthly sums of alongshore downwelling-favourable (poleward) wind stress at coastal grid points from 45-60° N.

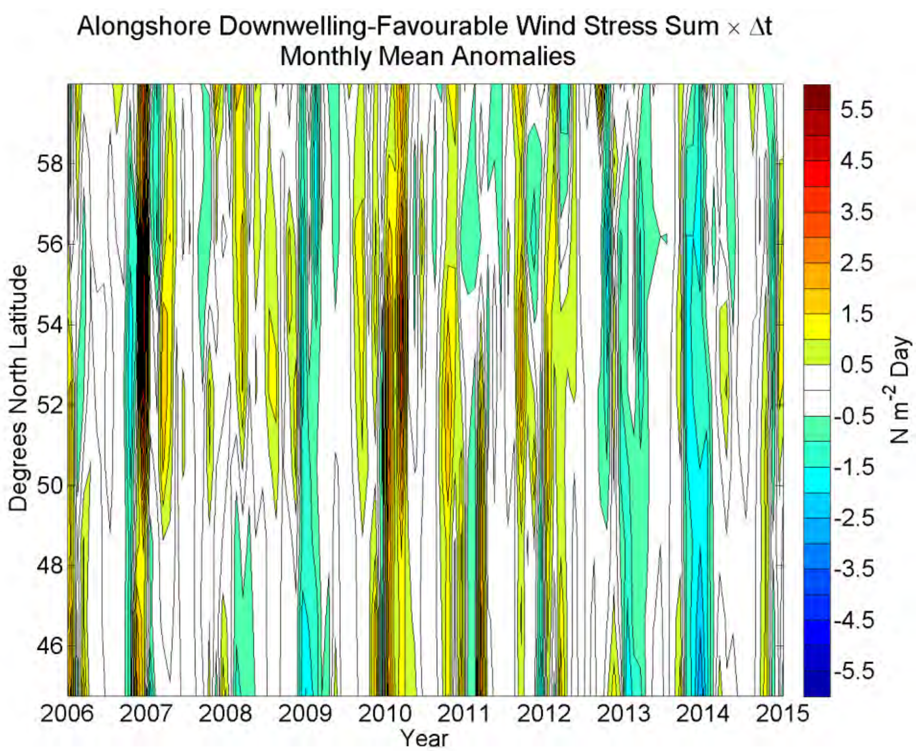

Figure 12-5. Recent (2006 to 2014) non-filtered monthly mean anomalies of monthly sums of alongshore downwelling-favourable (poleward) wind stress at coastal grid points from 45-60° N.

12.4. Upwelling Timing: The Spring Transition

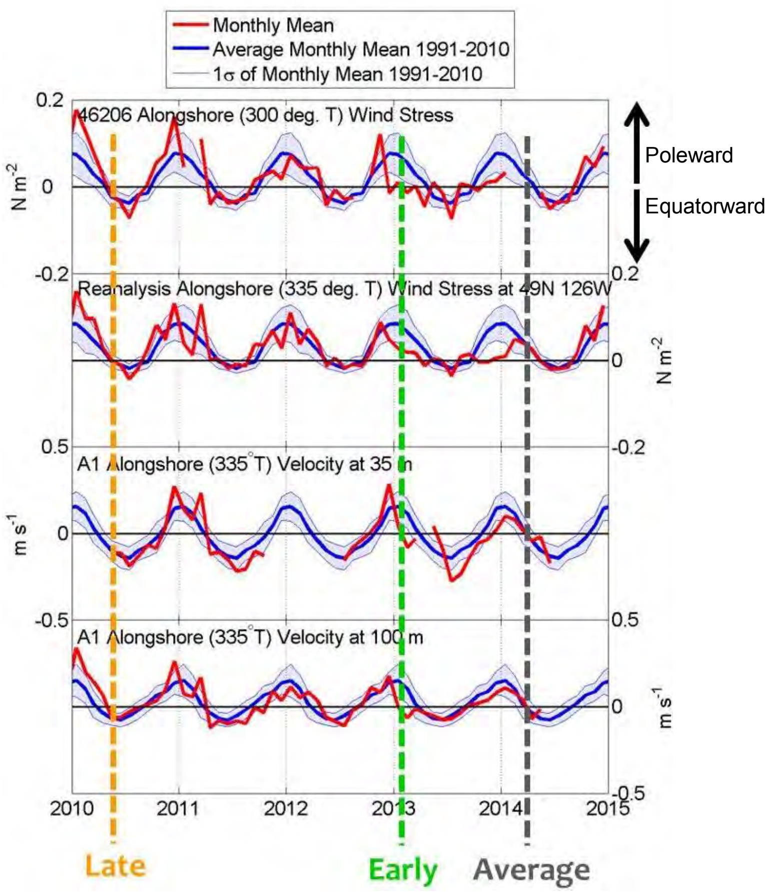

Figure 12-6. Along-shore flow off the west coast of Vancouver Island: wind stress at meteorological buoy 46206 and Reanalysis-1 grid point 49N126W and current velocity at 35 and 100 m at mooring A1. Positive flow is poleward (downwelling-favourable) and negative flow is equatorward (upwelling-favourable) as indicated by the arrows. The Spring Transition timing from downwelling to upwelling conditions was later than average in 2010, early in 2013, and about average in 2014.

Along the northwest coast of North America, biologically productive upwelling conditions are predominant in summer, while downwelling predominates in in winter. This is primarily due to the link between surface winds in the along-shore direction and the associated cross-shore Ekman transport of near-surface waters. Due to storms in the Gulf of Alaska in winter (the Aleutian Low), along-shore winds along the northwest coast of North America are predominantly poleward, which leads to onshore transport of surface waters and downwelling. In summer, the North Pacific High is the dominant atmospheric circulation feature which results in equatorward winds, offshore transport, and upwelling. The shift from downwelling in winter to upwelling in summer occurs in spring when along-shore winds change from mainly poleward to mainly equatorward, and is referred to as the Spring Transition. The reverse process occurs in fall and is called the fall transition. The winds drive a similar seasonal cycle in the alongshore coastal currents which are also poleward in winter and equatorward in summer. This is illustrated in Figure 12-6 for locations off the west coast of Vancouver Island (Figure 12-7).

The timing of the Spring Transition, or onset of seasonal upwelling, varies from year to year (Thomson et al., 2014). In years such as 2010 and 2005 when the Spring Transition was relative late, marine coastal productivity across trophic levels from plankton to fish to birds was generally average to below average, and was particularly poor in 2005 (DFO 2006). In years when the Spring Transition was early such as 2013, productivity was generally average to above average (e.g. Perry 2014). As shown in

Figure 12-6, the 2014 Spring Transition timing was near average, suggesting spring productivity was also about average. However, Figure 12-6 also shows that poleward alongshore winds and near-surface currents have been much weaker than average since early 2013 (see also Dewey et al. 2015), and this scenario of multi-year weak poleward flow is unprecedented in the meteorological buoy wind stress and mooring current velocity time series which both began in the late 1980s. These unusual conditions over the winters of 2012/13 and 2013/14 may also have had an effect on coastal upwelling-based productivity in 2014.

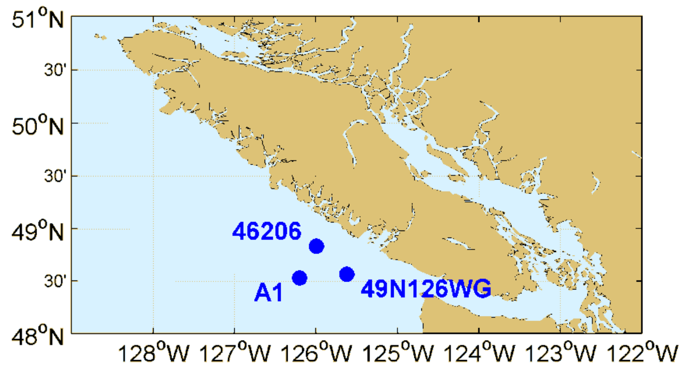

Figure 12-7. Station locations of meteorological buoy 46206, current meter mooring A1, and Reanalysis-1 49N126WG grid point.

12.5. Acknowledgements

NCEP/NCAR Reanalysis-1 wind stress provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at http://www.esrl.noaa.gov/psd/. A literature reference for these data is given below.

12.6. References

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13. SEA LEVEL IN BRITISH COLUMBIA, 1910 TO 2014

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13.1. Highlights

- Sea level is continuing to rise at Prince Rupert and Victoria.
- High sea level in December 2014 was due to warm seas and unusual weather in the Pacific Ocean.

13.2. Summary

The Canadian Hydrographic Service monitors sea levels along the B.C. coast. The records show annual deviations from a long-term average at three ports (Figure 13-1). Both Tofino and Victoria have records that began in 1910, while the record at Prince Rupert began in 1912.

Average sea level in 2014 was above the century-long trend at each of the three ports. These higher levels are due to stronger winds from the south in the autumn of 2014, associated with a low pressure system west of British Columbia during this period.

The linear trend at each port is (in cm/century):

Prince Rupert	+11
Victoria	+6
Tofino	-16

Tectonic motion is lifting the land at Tofino faster than sea level is rising, so that local sea level is dropping at an average rate of 16 cm per 100 years.

The next Cascadia Subduction Zone earthquake could drop the land at Tofino and along the nearby west side of Vancouver Island by as much as a metre, and also send a major tsunami to the B.C. coast.

Global sea levels rose by 17± 5 cm in the 20th century. The Intergovernmental Panel on Climate Change (IPCC 2014) predicts sea level to rise from 26 to 55 cm to 45 to 82 cm depending on levels of CO_2 emissions over the 21st century, but recent observations of ice melt in Greenland and Antarctica suggest these projections might be too low. Therefore, we can expect to observe greater rates of sea level rise in British Columbia in the future than we saw in the 20th century.

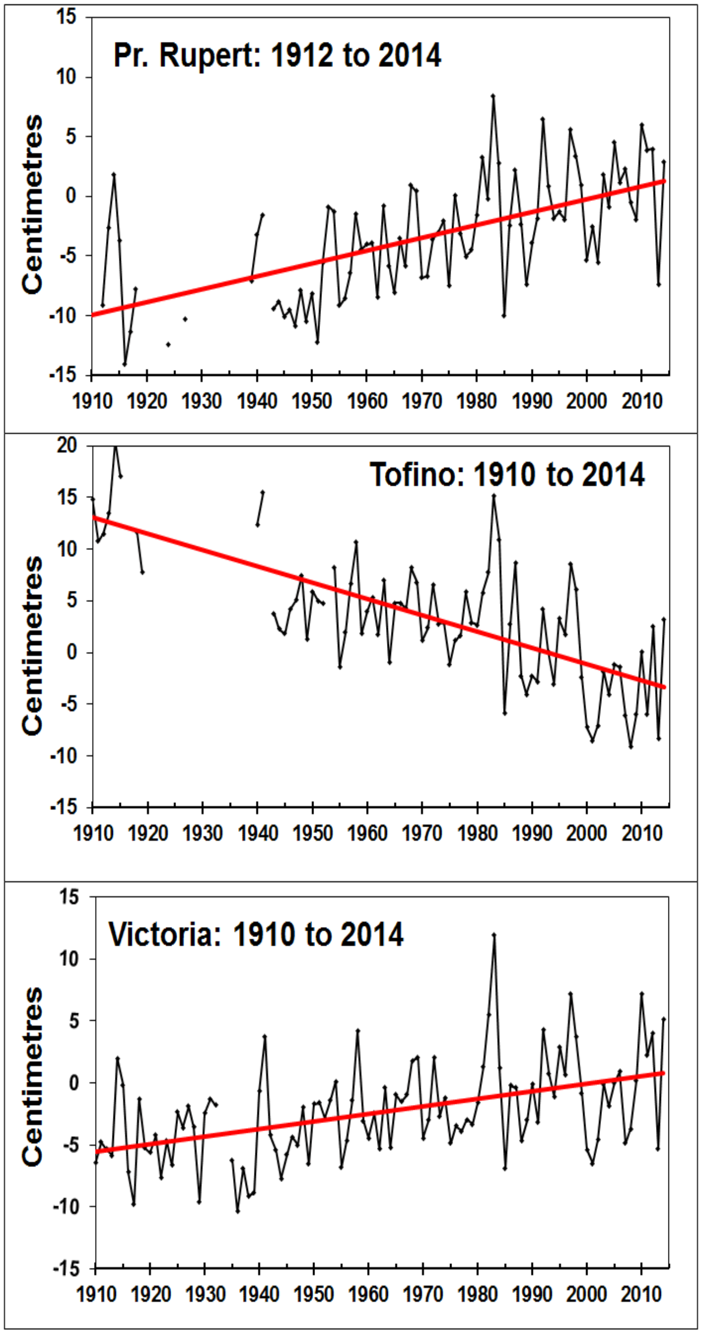

Figure 13-1. Graphs of annual-average sea level anomalies at three British Columbia ports. Reference years are 1981 to 2010. Average linear trends are plotted as red lines.

13.3. References

IPCC. 2014. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (Eds.)]. IPCC. Geneva, Switzerland, 151 p.

14. INTERANNUAL VARIABILITY OF SEA LEVEL AT TOFINO

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14.1. Highlights

- Sea level at Tofino continues a long-term downward trend (due to rising land) at about 1.4 mm/year.
- The tide gauge at Tofino shows a rise of about 20 cm at the times of the El Nino events in 1982/3 and 1997/8, but only a relatively small height increase due to the warm SST anomaly affecting B.C. coastal temperatures in 2014.

14.2. Summary

The sea level record from the Tofino B.C. tide gauge (http://www.meds-sdmm.dfo-mpo.gc.ca/) shows short-term sea level rise of about 20cm at the times of the 1983 and 1998 El-Nino events (Figure 14-1), but no significant rise associated with the warm water "blob" affecting B.C. coastal waters in 2014 (Figure 14-2).

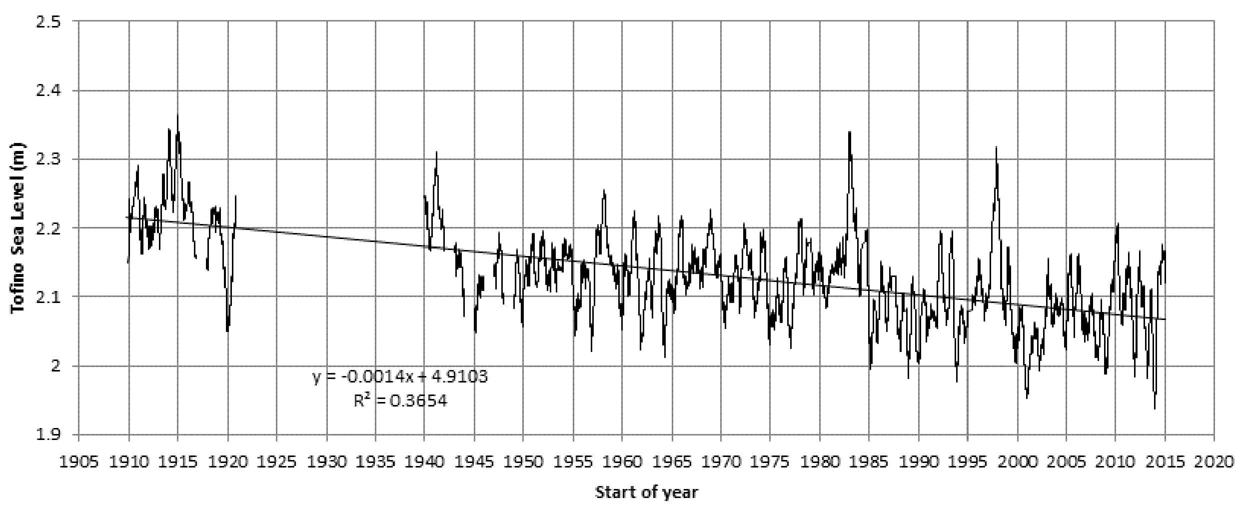

Figure 14-1. Daily average sea levels measured at Tofino B.C. (CHS station 8615) with annual, 6-month and 4-month cycles subtracted, smoothed with a 5-month running mean. Rising land level (post-glacial rebound) causes a long-term relative sea level decrease of 1.4 mm/year, which is expected to continue until the next major subduction earthquake.

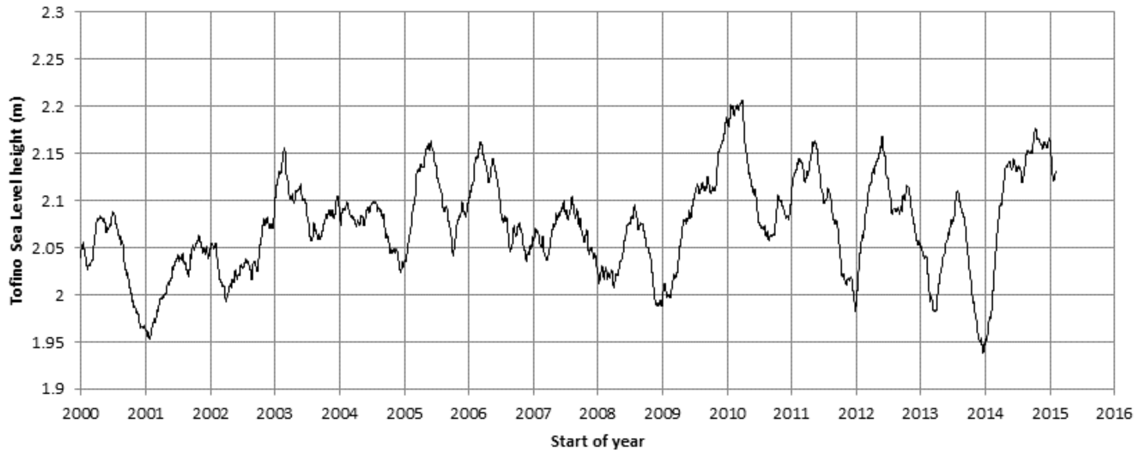

Figure 14-2. Data from Figure 14-1 since the year 2000. The warm SST event observed in 2014 gives no clear sea-level rise comparable to El-Ninos at the starts of years 1983 and 1998 (Figure 14-3). A moderately strong El Nino caused a 10cm peak rise at the start of 2010.

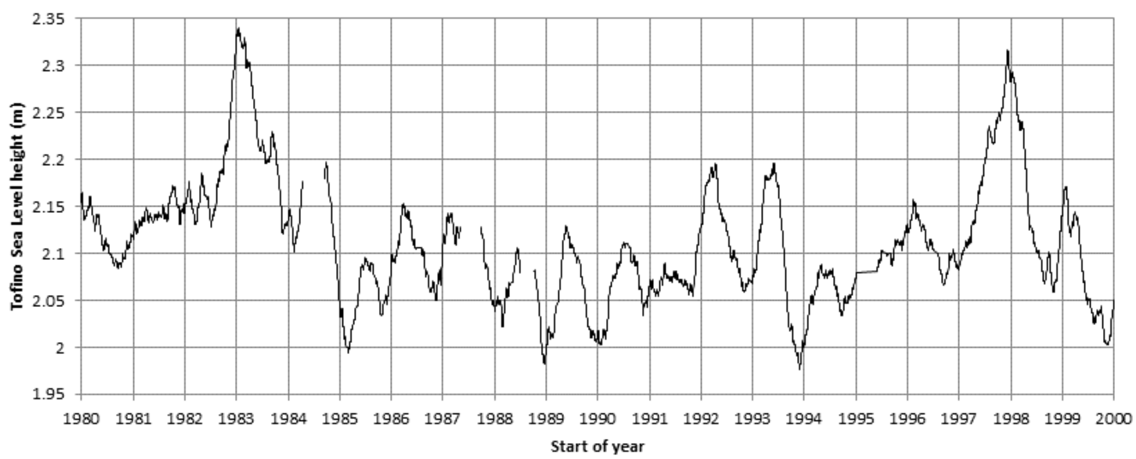

Figure 14-3. Data from Figure 14-1. Daily average sea levels measured at Tofino B.C. (CHS station 8615) with annual, 6-month and 4-month cycles subtracted, smoothed with a 5-month running mean. Rising land level (post-glacial rebound) causes a long-term relative sea level decrease of 1.4 mm/year, which is expected to continue until the next major subduction earthquake.Figure 14-1 from 1980 to 2000. El-Ninos caused 20cm peak high sea levels in January 1983 and December 1997.

15. SEA SURFACE TEMPERATURE AND SALINITY TRENDS OBSERVED AT LIGHTHOUSES AND WEATHER BUOYS IN BRITISH COLUMBIA, 2014

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15.1. Highlights

- Average daily SST at most shore stations were warmer in 2014 than 2013 and warmer at all stations than the 1981-2010 average.
- Shore stations and ODAS buoys showed a similar pattern of cooler temperatures until May, intermittent warm and cold anomalies during the upwelling season, and significantly and continuing warmer than normal SSTs since September.
- Salinity at most shore stations showed little variation from the 30-year average.

15.2. Summary

Two sources of data are used to describe changes in sea surface conditions in the coastal waters of B.C. in 2014. As part of the DFO Shore Station Oceanographic Program sea surface temperature and salinity are measured daily at 12 shore stations, at the first daylight high tide. Most stations are at lighthouses (Figure 15-1), with observations taken by lighthouse keepers using thermometers and hydrometers or a handheld electronic instrument (YSI Pro 30). The buoy data are provided by Environment Canada from a network of ODAS (Offshore Data Acquisition Systems) buoys that collect weather data hourly.

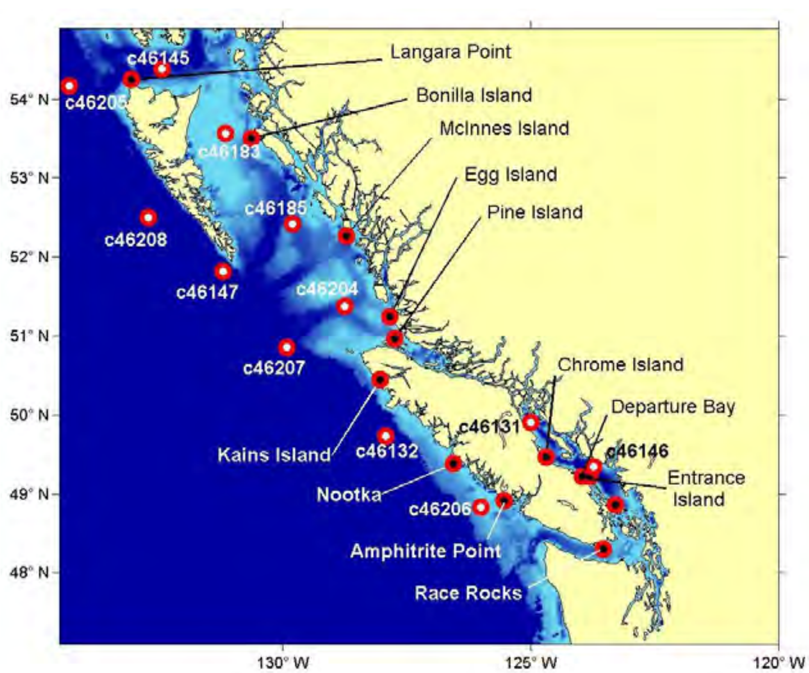

Figure 15-1. Red dots with black centres show the locations of 12 stations in the present shore station network. Red dots with white centers show the locations of 12 weather buoys in the Canadian weather buoy network. See Table 15-1 for details.

Table 15-1. The number of years of data from each shore station and ODAS buoy shown in Figure 15-1.

Shore station	Years of data
Departure Bay	101
Race Rocks	94
Nootka	81
Amphitrite Point	81
Kains Island	78
Langara Point	79
Entrance Island	79
Pine Island	78
McInnes Island	61
Bonilla Island	55
Chrome Island	54
Egg Island	45

Buoy ID	Buoy location	Years of data
c46146	Halibut Bank	23
c46131	Sentry Shoal	23
c46206	La Perouse	27
c46132	South Brooks	21
c46207	East Delwood	26
c46147	South Moresby	22
c46208	West Moresby	25
c46205	West Dixon	25
c46145	Central Dixon	24
c46204	West Sea Otter	26
c46185	South Hecate	24
c46183	North Hecate	24

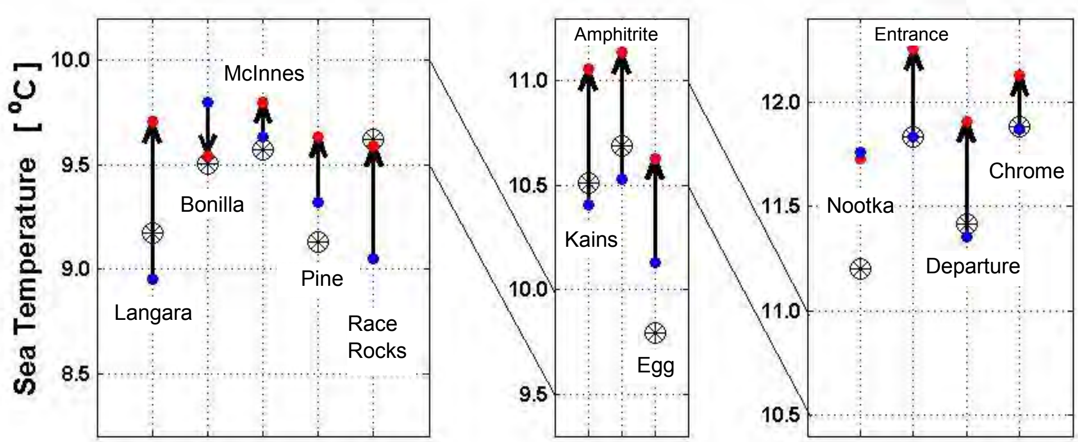

Figure 15-2. The average sea surface temperature in 2013 (blue dots) and 2014 (red dots) from daily observations at shore stations along the West Coast of Canada. Note: the temperature range is the same in each panel, but the temperature values vary; cooler in the left panel and warmer in the right. The crossed circles represent the mean annual temperature based on 30 years of data (1981-2010).

The observations at shore stations show the average daily sea surface temperature (Figure 15-2) was warmer in 2014 than in 2013 at all stations with the exception of Nootka (almost no change) and Bonilla Island (due to a cool spring and summer). Of those stations that experienced warming the average increase in temperature was 0.48 °C (standard deviation of 0.19 °C). The average daily SST at all stations (except Race Rocks) was greater than the thirty-year average (1981 – 2010).

Of those ODAS buoys that experienced warming (6 buoys of 8 with sufficient data; Figure 15-3) the average increase in temperature was 0.58 °C (standard deviation of 0.25 °C).

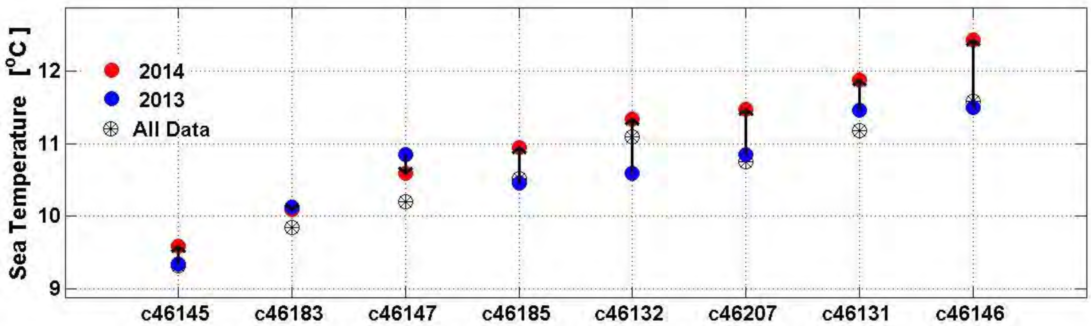

Figure 15-3. The average sea surface temperature in 2013 (blue dots) and 2014 (red dots) from hourly observations at weather buoys along the West Coast of Canada. Note: at four buoys there were insufficient data available to make the comparison between years. The crossed circles represent the mean annual temperature based on all years of data.

The timing of sea surface temperature warming at the lighthouse stations and the ODAS buoys in 2014 followed a similar pattern; cooler temperatures until May, intermittent warm and cold anomalies during the upwelling season, and significantly and continuing warmer than normal SSTs since September. Figure 15-4 illustrates this pattern with data from the Kains Island lighthouse station and ODAS buoy c46132 (South Brooks).

The salinity conditions at most shore stations showed little variation from the 1981-2010 climatology (Figure 15-5). The decrease in salinity at Nootka is within the annual variability typical at this location, and the 2014 observations show conditions closer to the long-term normal salinity.

Assuming a linear change over the entire data record, the time series of temperature at all of the B.C. shore stations show a warming trend at a 95% confidence level. Figure 15-6 shows this warming at representative stations for each of three regions (North and Central Coast, the West Coast Vancouver Island, and the Strait of Georgia). The right panel of Figure 15-6 shows the variation in time of the SST trend using data up to the year shown on the x-axis. The 2014 conditions were sufficiently warmer than 2013 to influence the SST trend which, since 2005, had shown long-term warming, but at a decreasing rate. The observations of warmer water in 2014 have resulted in a positive rate of SST warming. A similar trend analysis applied to the salinity data (Figure 15-7) shows a continuing long-term trend toward less saline conditions.

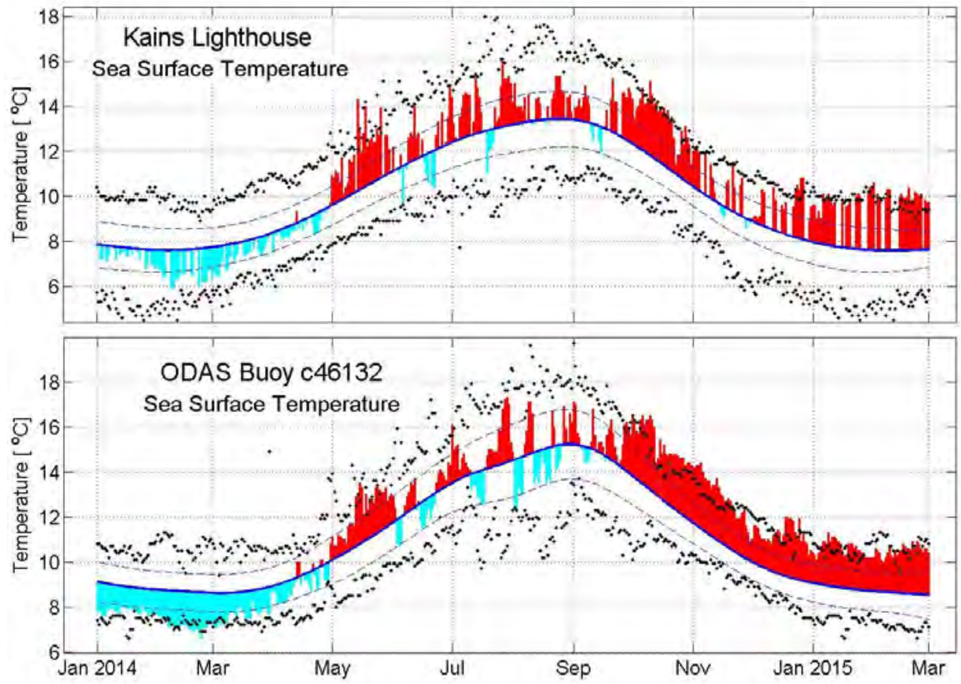

Figure 15-4. Time series of daily SST, blue areas represent temperatures that are below normal, red areas represent temperatures that are above normal. Normal (blue line) refers to the average of all observations and the dashed blue lines show one standard deviation from the average. The black dots show the maximum and minimum temperature observed for each day of the year.

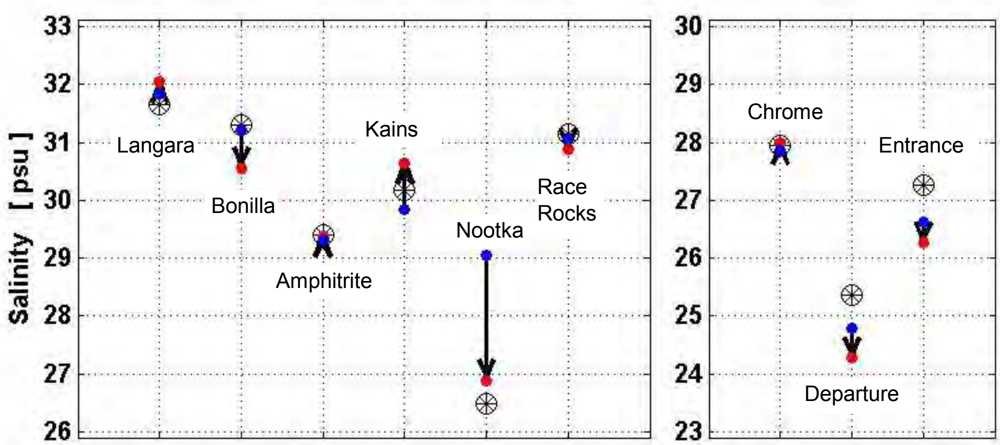

Figure 15-5. The average sea surface salinity in 2013 (blue dots) and 2014 (red dots) from daily observations at shore stations along the West Coast of Canada. Note: the salinity range is the same in each panel, but the salinity values vary; saltier in the left panel and fresher in the right. The crossed circles represent the mean annual salinity based on 30 years of data (1981-2010).

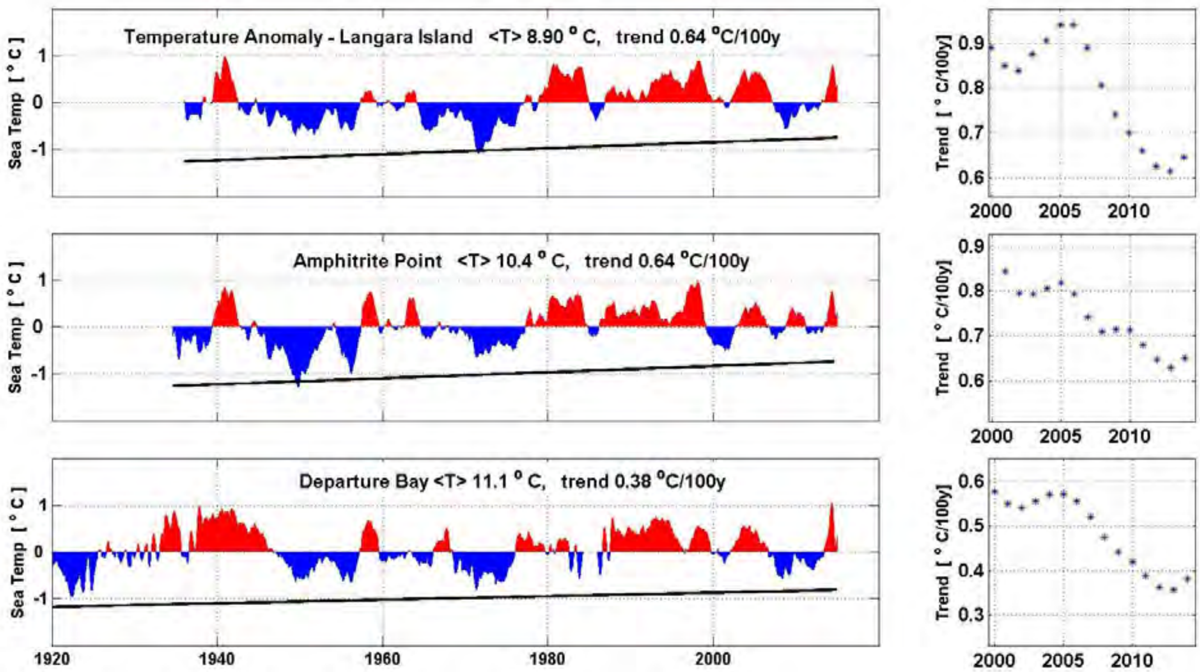

Figure 15-6. Time series of daily temperature observations, averaged over 12 months, at stations representing the North and Central Coast, West Coast Vancouver Island and Strait of Georgia. Positive anomalies from the average temperature of the entire record <T> are shown in red, negative in blue. The panel to the right shows the slope of the trend lines calculated using only data up to the year shown on the x-axis.

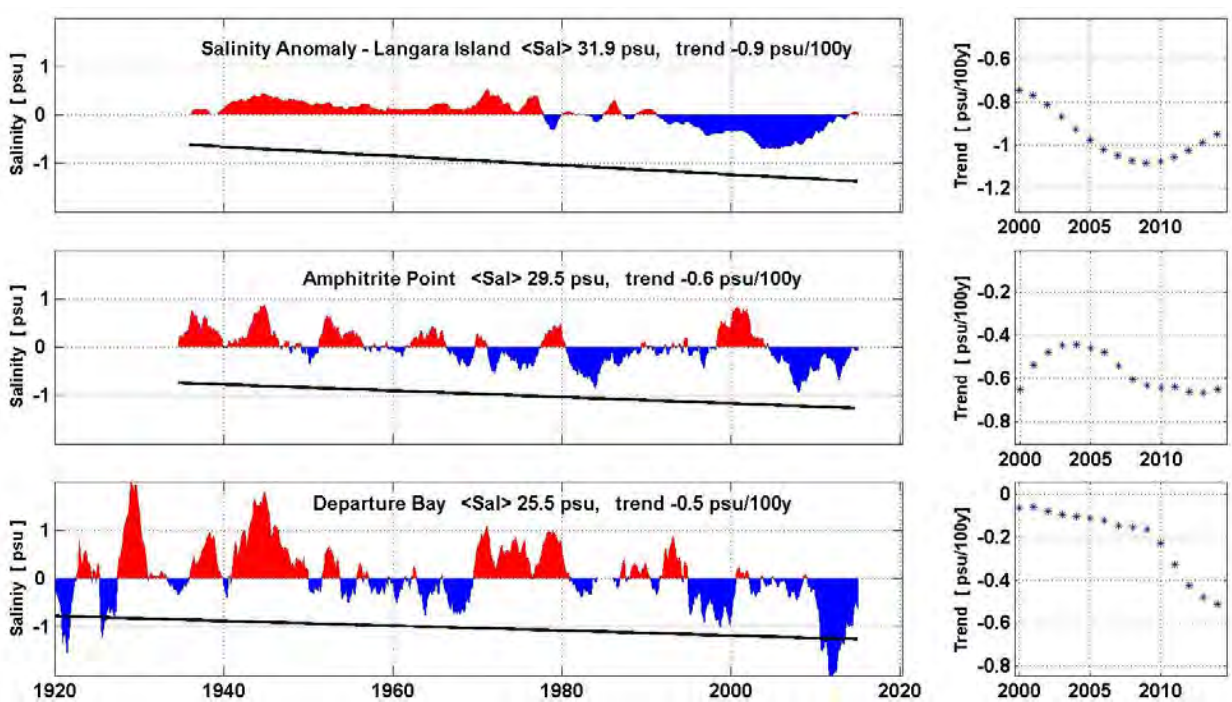

Figure 15-7. As in Figure 15-6 for long-term time series of daily salinity observations.

16. TRENDS IN OXYGEN CONCENTRATION ON THE B.C. SHELF

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16.1. Highlights

- Oxygen concentration in subsurface waters on the B.C. shelf declined from the 1980s, reached a minimum in 2006 to 2009, but has increased slightly in recent years (2010 to 2014).

16.2. Summary

Oxygen concentration (O_2) in subsurface waters of British Columbia has been declining since about 1980. We monitor this decline by measuring O_2 at Station LB08 on the continental shelf of southwest Vancouver Island (Figure 16-1). O_2 decreases with increasing depth, and is normally lowest in mid to late summer due to upwelling winds of this season. In addition to this seasonal cycle, O_2 at any depth generally decreases toward the south, reaching a minimum near Station LB08. Very low O_2 is also found near-bottom in some inlets that have very slow water exchange with outside waters.

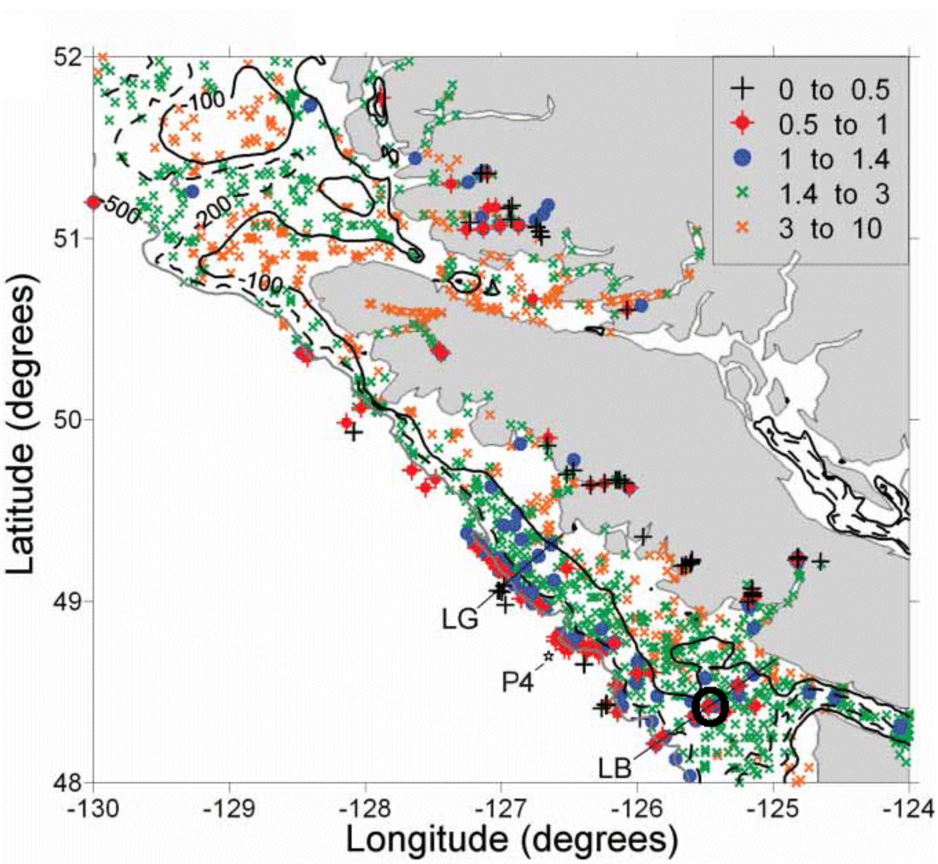

Figure 16-1. Oxygen concentration (O_2) in millilitres per litre (ml/L) in summer within 20 metres of the ocean bottom for regions of the continental shelf of Vancouver Island where bottom depth is less than 1000 metres. Each symbol represents a measurement by DFO research programs. The black O denotes the location of station LB08. Source: Crawford and Peña (2013).

The decline in O_2 since 1980 has not been steady in time, reaching a minimum in 2006 to 2009 in late summer from days 230 to 280 (Figure 16-2). This minimum is also present in May near day 140. There is a slight trend for observations in the years 2010 to 2014 to reveal somewhat higher O_2 than for the period 2006 to 2009. Decreasing O_2 in subsurface waters is normally accompanied by increasing acidity. Both trends are of great concern to marine life.

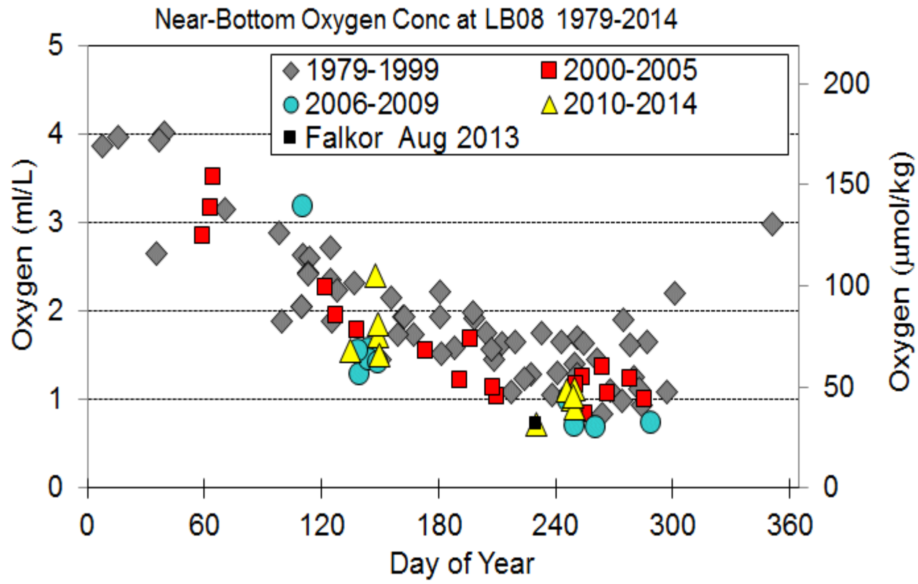

Figure 16-2. Oxygen concentration (ml/L and µmol/kg) near ocean bottom at station LB08. Each symbol represents a measurement by DFO research programs. Figure is based on Crawford and Peña (2013).

16.3. References

Crawford, W.R., and Peña, M.A. 2013. Declining oxygen on the British Columbia continental shelf, Atmosphere-Ocean, 51(1): 88-103. DOI: 10.1080/07055900.2012.753028.

17. THE 2014 PERSPECTIVE FROM OCEAN NETWORKS CANADA

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17.1. Highlights

- Anomalous upwelling along the south coast of B.C. in 2013 can be used as a proxy for wind conditions that helped establish the NE Pacific warm conditions for 2014.
- Warm surface conditions were detected near shore by the fall of 2014.
- The start of the 2014 spring bloom in the southern Strait of Georgia was detected via ferry monitoring on April 1-2. Peak biomass was measured on April 9, 2014.

17.2. Warm Northeast Pacific Conditions

The surface waters of the Northeast Pacific started warming in 2013, peaked in 2014, and now, in early 2015, remain significantly warmer than at any time over the last few decades (Figure 17-1). By January 2014, the area and intensity of this warm anomaly had reached its maximum. Freeland (2014) constructed a map of sea surface temperature anomaly (SSTa) for January 2014 (using the Reynolds SST dataset) showing a region of warm temperature anomalies exceeding 4 standard deviations above the mean. He achieved the same result when using independent Argo float data (Freeland 2015). The area exceeding 3 standard deviations covered an area of more than 1000 km^2. To put this in perspective, such an anomalous event would be expected less than once per millennium (<0.1%). By the fall of 2014, this warm pool of surface water had shifted eastward from the central Gulf of Alaska, and by late 2014 and into early 2015, was blanketing the entire west coast of North America. Although the extent and nature of the mechanisms and dynamics responsible are still being

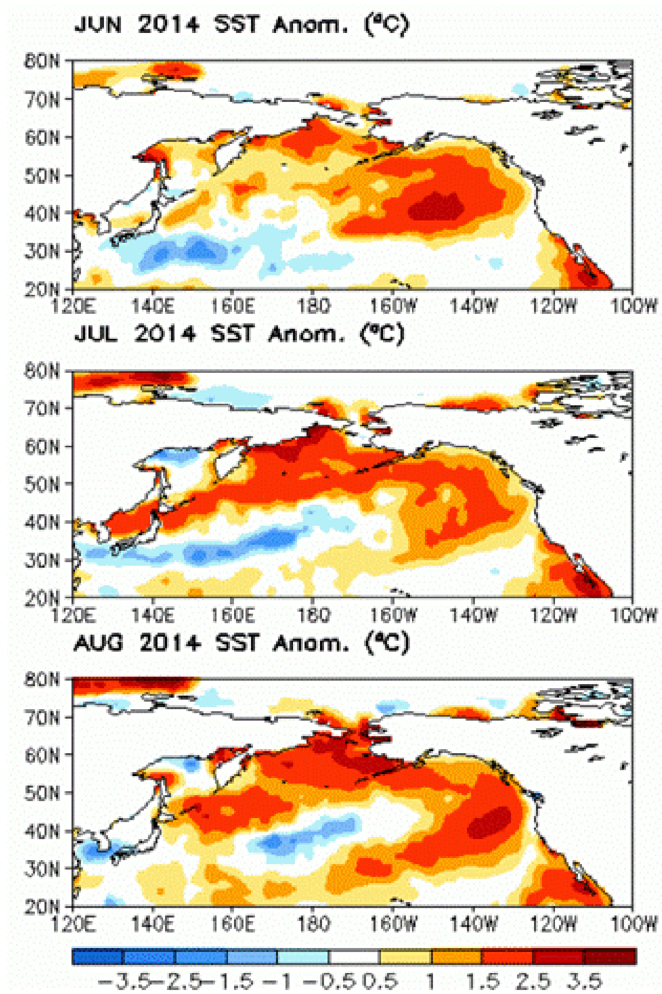

Figure 17-1. Monthly SST Anomaly maps generated on-line at NOAA's Earth System Research Laboratory site.

assessed, there is a growing consensus as to some of the contributing factors that may have led to the development of these warm Northeast Pacific conditions. It is quite safe to state that the Northeast Pacific warming that peaked in early 2014 is not associated with the equatorial El Nino/La Nina phenomena, nor does it appear to represent patterns associate with either the Pacific Decadal Oscillation or North Pacific Gyre Oscillation.

Several variations seemed to have conspired to contribute to the development of the anomalously warm surface waters of the Northeast Pacific in 2014 (Figure 17-1). Starting as early as the winter of 2012-13 and continuing into the winter of 2013-14, the Aleutian Low had become particularly weak, in that both the intensity and extent of the low atmospheric sea surface pressure were significantly diminished (as posted by Dewey 2015). This had at least three significant consequences. First, the weaker winds resulted in weaker Ekman export of the surface waters from the Gulf of Alaska. Second, the combination of weak mean winds and fewer storms limited the vertical mixing, which failed to mix the warm surface waters downward and the cool, nutrient rich water upward. Thirdly, the weaker Aleutian Low to the west was accompanied by a persistent North Pacific High over western North America, which acted as a ridge to block storms and reduced the strength of westerly winds which further export nutrient rich waters from the Gulf of Alaska (Whitney 2015). Subsequently, by early 2014, the surface waters of the Northeast Pacific had become anonymously warm, exceeding in spatial extent and magnitude any record in the last few decades.

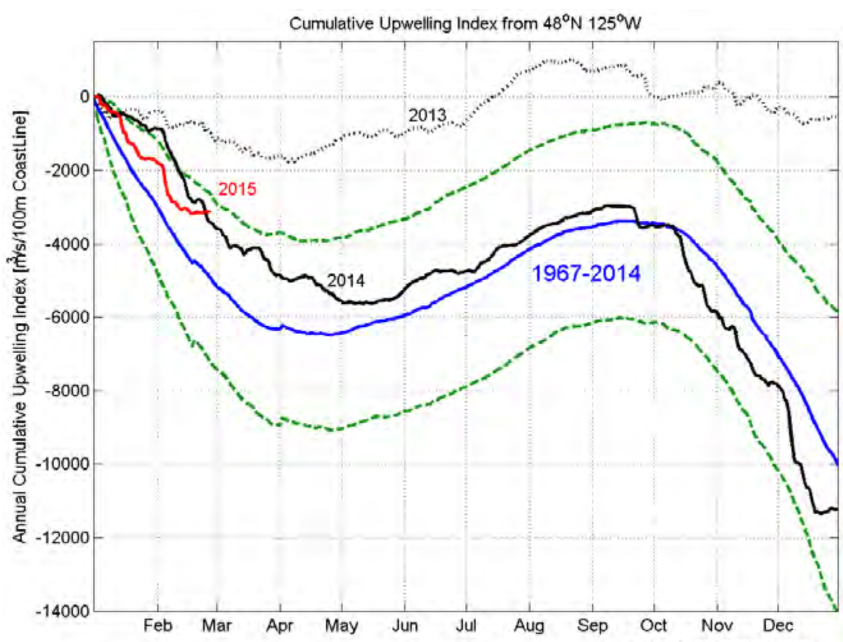

Figure 17-2. Cumulative Upwelling index from west of Vancouver Island, as downloaded from NOAA's Pacific Fisheries Environmental Laboratory.

As a proxy to demonstrate how anomalous the Northeast Pacific winds were in 2013, which contributed to the development of the warm conditions in 2014, we present the upwelling index for the west coast of Vancouver Island (Figure 17-2). When the Aleutian Low is present (winter), the winds along the west coast of Vancouver Island blow northward (south wind), pushing surface waters towards the coast and depressing the deeper cool nutrient rich waters (downwelling). When the North Pacific High develops (summer) the winds are primarily southward (north wind), and Ekman transport pushes warm surface water offshore, elevating the deeper nutrient rich waters (upwelling). The Bakun upwelling

index is a measure of the net volume transport of surface water per unit length of coastline and is derived directly from the along-shore component of the wind. Figure 17-2 shows the cumulative upwelling index for the last 46 years. In a typical year, there is a net downwelling (negative upwelling) of the order 10,000 m^3/100m of coastline, representing the dominance of the Aleutian Low from late September through to May each year. The Aleutian Low was so weak throughout 2013, that the net downwelling for the year was only 500 m^3/100m of coastline, representing the weakest downwelling winds in the 46 year record (5% of the typical 46 year mean).

17.3. Warm Waters Approach B.C. Coast in Fall of 2014

The warm offshore surface waters shown in Figure 17-1 started to shift eastward towards the coast of B.C. in mid-September 2014, when the along-shore winds became downwelling favourable (Figure 17-2). The permanent Ocean Networks Canada (ONC) installation at the entrance to Barkley Sound (Folger Passage) detected this transition, and then proceeded to record the warmest conditions in this relatively short record (Figure 17-3). By early November, the water temperatures at 100m depth had reached 12.5 °C, 1.5 °C warmer than any other part of the time series, and remained high until early February, when they dropped to more seasonal, but still warm (11 °C) values (Figure 17-3).

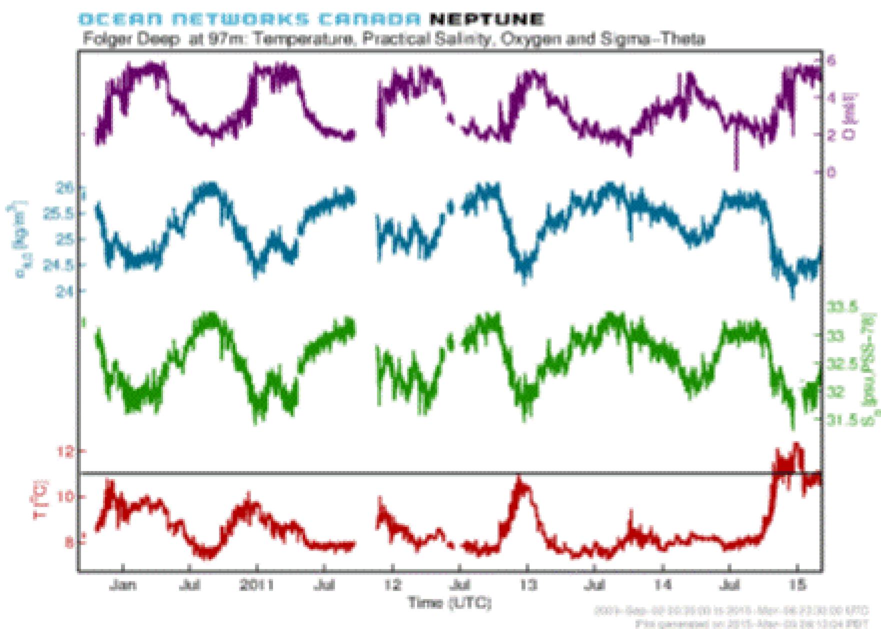

Figure 17-3. Time series of Temperature, Salinity, σ_θ, and dissolved Oxygen from Ocean Networks Canada's Folger Passage installation at 100 m depth.

Further into the Salish Sea, where ONC's cabled instruments are mostly bottom mounted at depths between 100-300 m, the warm waters were not detected (Saanich Inlet, Figure 17-4). A consistent signal that did define 2014 within the Salish Sea was the steady long warming trend representing the "summer" of 2014, which started as early as March and progressed well into October (Figure 17-4).

Although it may be too early to tell, the warm conditions within the Salish Sea (trailing ends of the time series presented in Figure 17-4) have persisted well into March 2015, representing the longest period of late fall warm conditions at depth in the 9 year observatory record.

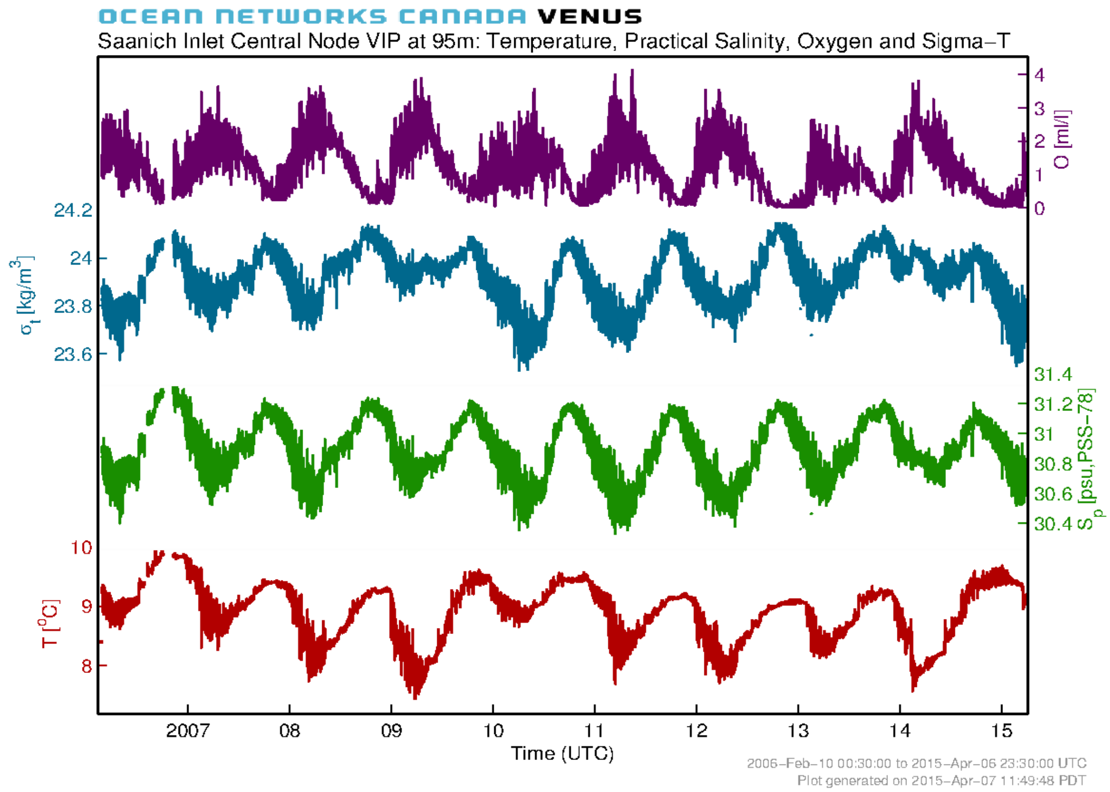

Figure 17-4. Nine year time series of Temperature, Salinity, σt, and dissolved oxygen from Ocean Networks Canada's Saanich Inlet installation at 95 m depth.

17.4. 2014 Spring Bloom in the Strait of Georgia

The development of the spring phytoplankton bloom in the southern Strait of Georgia was monitored via high resolution sea-surface measurements of chlorophyll fluorescence. Underway sea-surface measurements were made every 10 seconds during each of 8 daily cross-Strait trips by BC Ferries vessel, *Queen of Alberni*, transiting between Duke Point (on Vancouver Island) and Tsawwassen. The spring phytoplankton bloom was first detected along-route on April 1-2, 2014 (Figure 17-5). Peak chlorophyll fluorescence was measured April 9, 2014, making the 2014 spring phytoplankton bloom relatively late when compared to the long term (modelled) mean date of March 25 (Allen and Wolfe 2013). The later relative timing of the 2014 spring bloom is consistent with recent (2009-2011, 2013) observations and model predictions of peak biomass.

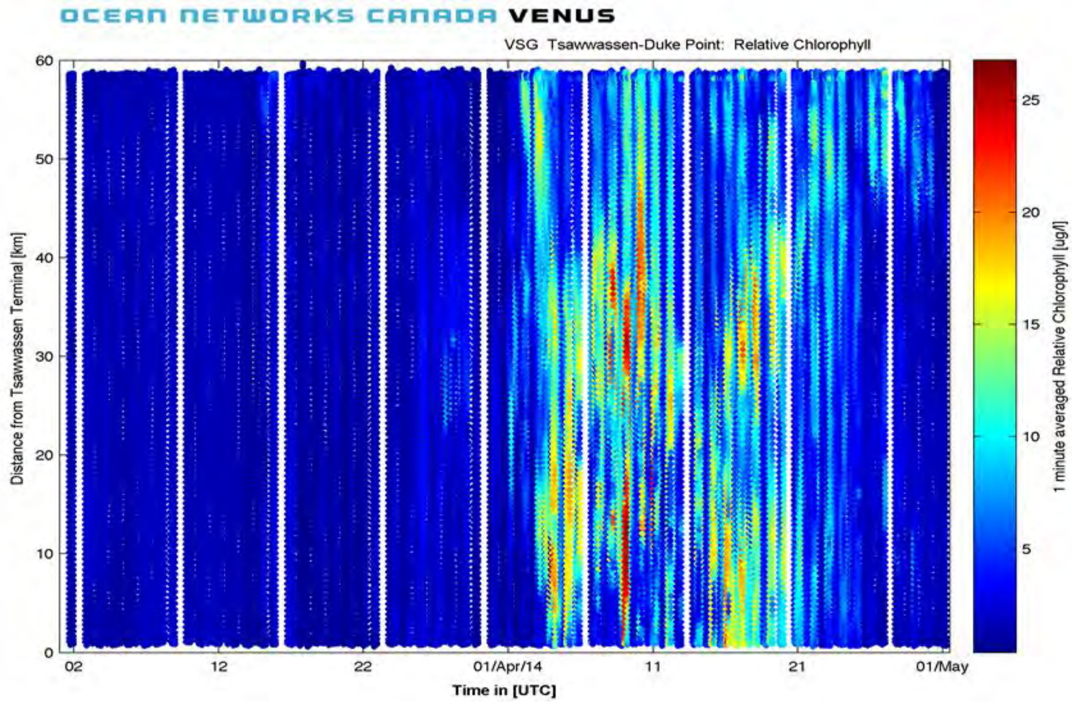

Figure 17-5. Time series of surface chlorophyll fluorescence (mg/m^3) measured en-route by instruments on board the BC Ferries, Queen of Alberni transiting between Tsawwassen (0 km) on mainland B.C. to Duke Point terminal (~60 km) on Vancouver Island. The spring phytoplankton started April 1-2, 2014 with relatively similar phytoplankton biomass measured both inside and outside of the Fraser River plume. The date of peak biomass was April 9, 2014.

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18. PHYTOPLANKTON IN THE WATERS OFF THE WEST COAST OF VANCOUVER ISLAND

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18.1. Highlights

- Despite anomalously high temperatures, phytoplankton community composition and biomass in May and September 2014 was generally similar to previous years at stations on the shelf and offshore.
- During the May 2014 survey diatoms were dominant at most stations along the coast except off North Vancouver Island where cryptophytes and dinoflagellates were higher compared to previous years.
- In September 2014, and similar to previous years, diatoms dominated the phytoplankton biomass on the continental shelf.

18.2. Summary

Phytoplankton abundance and community composition are key factors influencing trophic processes and biogeochemical cycles in coastal regions. Concentrations of nutrients, chlorophyll-*a* (“chl”, an indicator of phytoplankton biomass) and phytoplankton pigments are measured on 10-day cruises twice a year in late May to early June and early September. Sampling is carried out along a series of transects on the west coast of Vancouver Island, extending from the mouth of the Juan de Fuca Strait in the south to Cape Scott in the north (Figure 18-1). Sampling for phytoplankton pigments along these lines started in 2011. Phytoplankton pigments are used to estimate the abundance of phytoplankton groups using a factor analysis algorithm (CHEMTAX) that calculates concentrations based on biomarker pigments.

Nutrient and chl concentrations are highly variable over the study area. On the continental shelf, nutrient concentrations are usually lower in May compared to September. In general, chl is usually high (> 5 mg/m^3) on the continental shelf off southern Vancouver Island where blooms of phytoplankton (>20 mg/m^3 chl) are often observed in May and/or September. On average, diatoms dominate phytoplankton biomass along the continental shelf although dinoflagellates are found to occasionally dominate in September (Figure 18-2). Diatoms-2 (e.g. *Pseudonitzschia spp.*) seem to be more abundant at the northern lines (BP and CS) than farther south where diatoms-1 (e.g. *Chaetoceros spp*.) are more abundant.

In 2014, high chl concentrations (>10 mg/m^3) were observed near shore during the September survey (Figure 18-1), particularly at Line C where a bloom of diatoms occurred (Figure 18-2). As in previous years (with the exception of 2011), diatoms dominated phytoplankton biomass on the continental shelf in September. During the May 2014 survey, diatoms were dominant along the coast, except at Line C and BP

where the relative abundance of cryptophytes and dinoflagellates were higher compared to previous years.

At stations beyond the continental shelf, chl and nutrient concentrations are usually lower than on the continental shelf (Figure 18-3). In this region, phytoplankton community composition is more diverse and variable than inshore with dinoflagellates, diatoms, haptophytes and cryptophytes dominating at times and far fewer diatoms than seen on the coast. In 2014, several phytoplankton groups were abundant in this region during the May and September surveys. In general, the phytoplankton community was similar to previous years with dinoflagellates being more abundant than diatoms (Figure 18-3).

Persistent anomalously high surface temperature waters were observed throughout most of 2014 offshore along Line P but warm water extended nearly to shore by September 2014 (Yelland and Robert 2015). Similar high temperatures were also observed earlier in September 2013 in the survey area (Figure 18-2 and Figure 18-3, left panels). Despite the anomalous temperature, our data indicate that nutrient, chl concentrations and phytoplankton community composition during the September 2014 survey were similar to those observed in previous years.

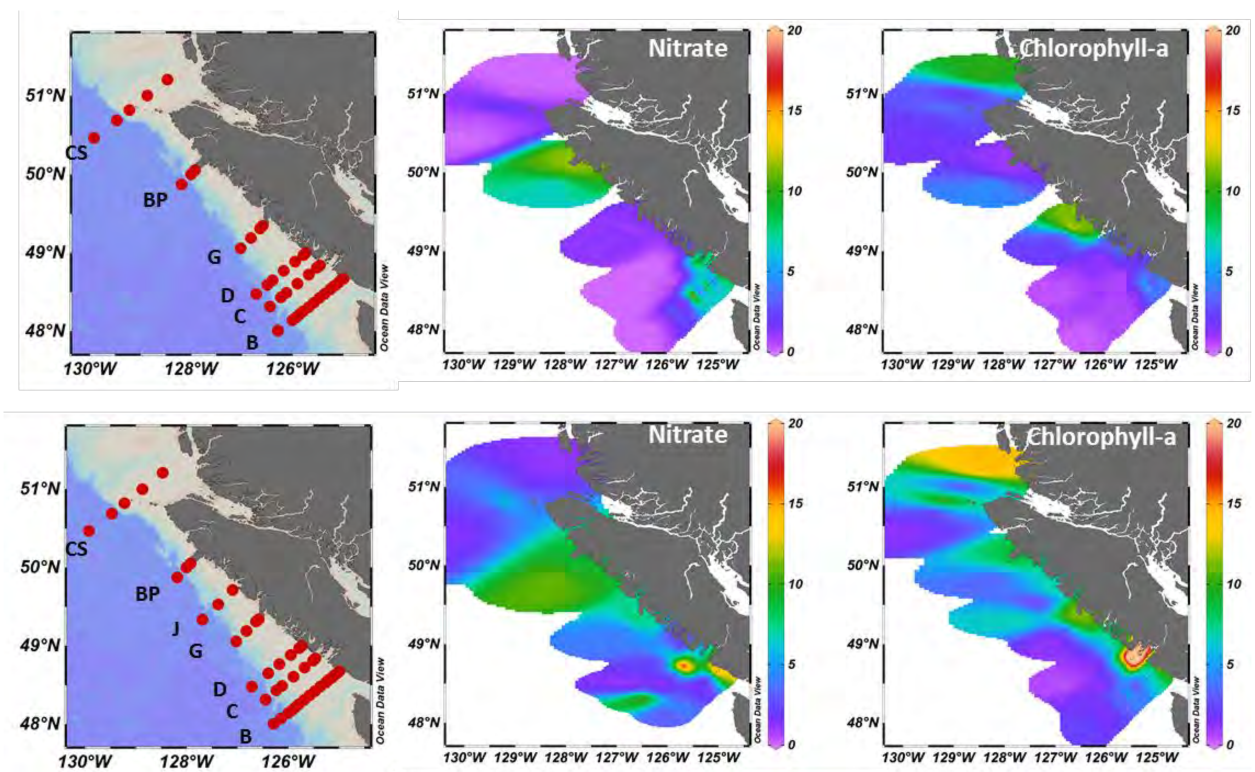

Figure 18-1. Location of sampling stations, nitrate (mmol/m³) and chlorophyll-a (mg/m³) at 5 m depth over the study area in May/June (top row) and September (bottom row) of 2014.

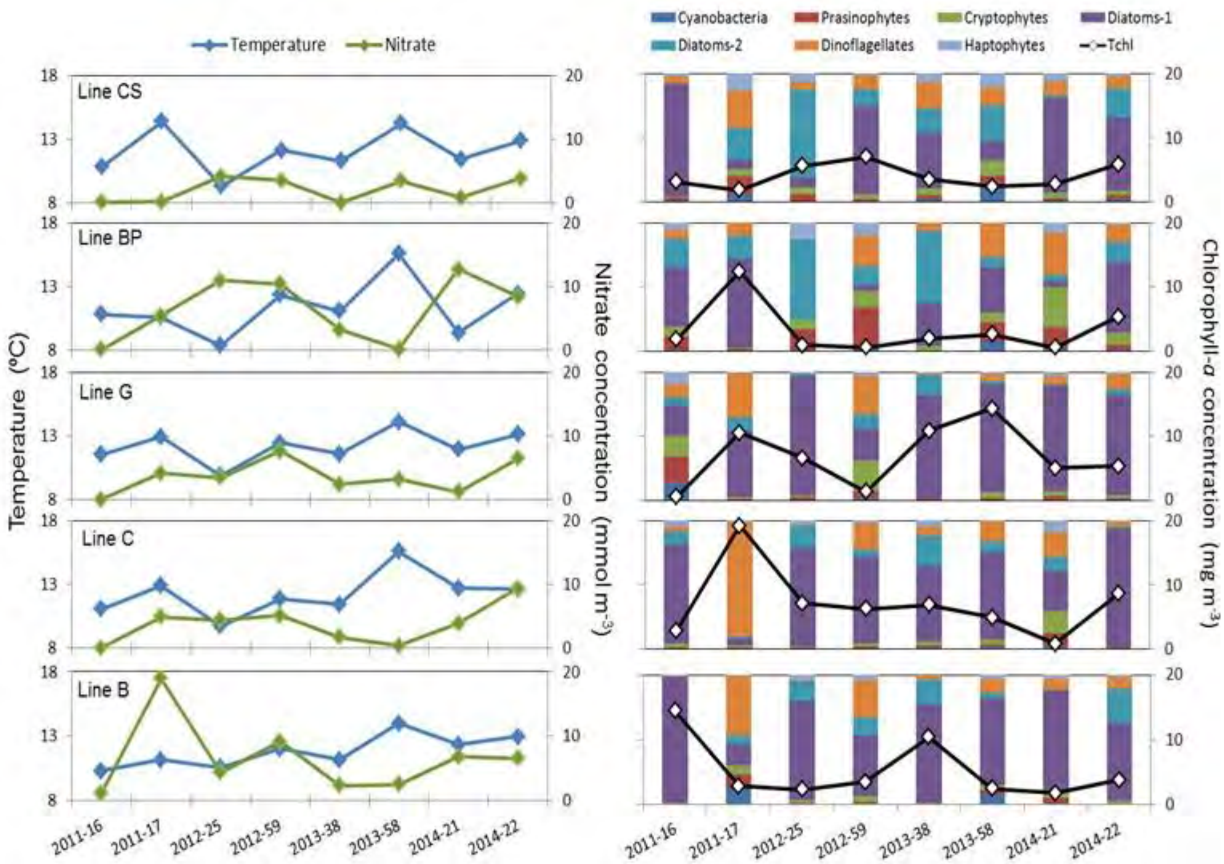

Figure 18-2. Time-series of mean temperature and nitrate (left panel), relative phytoplankton composition and chl concentration (right panel) at stations on the continental shelf for Line B, C, G, BP and CS (see Figure 18-1). X-axis identifies the cruise numbers, with the lower number for each year representing May, and higher numbers representing September, surveys.

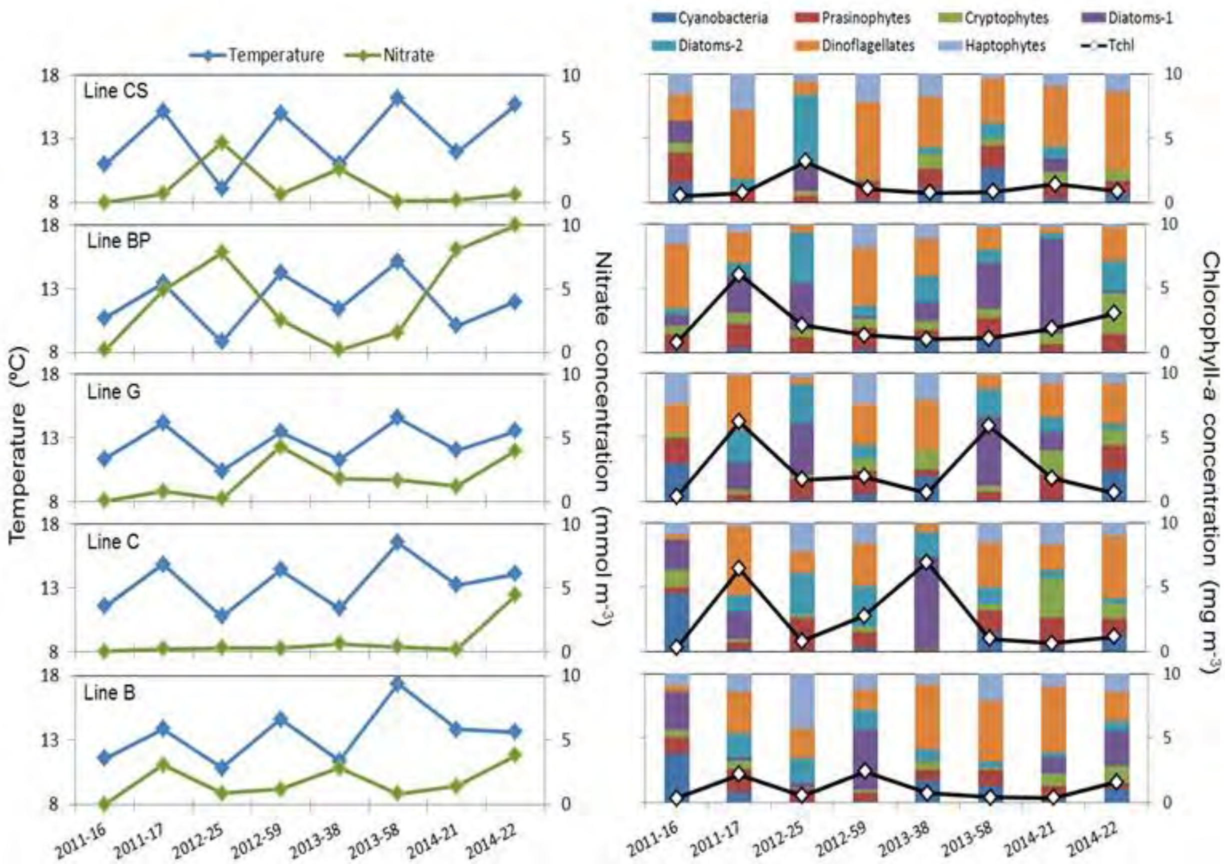

Figure 18-3. Time-series of mean temperature and nitrate (left panel), relative phytoplankton composition and chl concentration (right panel) at stations beyond the continental shelf for Line B, C, G, BP and CS (see Figure 18-1). X-axis identifies the cruise numbers, with the lower number for each year representing May, and higher numbers representing September, surveys.

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19. ZOOPLANKTON ALONG THE B.C. CONTINENTAL MARGIN 2014, AND THE IMPACTS OF WARM OFFSHELF WATERS

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19.1. Highlights

- 2014 started off as a cool year in the continental shelf region, with strongly positive anomalies for both sub-Arctic and boreal zooplankton, but by late summer and fall warm offshore water with higher abundances of southern zooplankton species had moved onto the B.C. continental shelf.
- The source of the warm water appears to be offshore and oceanic rather than from a south to north alongshore movement of coastal water, since many of the warm water species found on the shelf in 2014 are of oceanic origin.
- There was a within-2014 moderation of the annual anomaly signal in all species groups: what was positive at the beginning of the year was negative or near zero by fall (or vice versa), producing a yearly signal closer to the long term average.
- Some species were observed in 2014 that had not been observed in B.C. waters since the mid-2000's or earlier.

19.2. Summary

Zooplankton time-series from the British Columbia continental margin extend from 1979 to present for southern Vancouver Island (SVI), from 1990 to present for northern Vancouver Island (NVI; although with much lower sampling density and taxonomic resolution in 1991 to 1995), and from 1998 to present for southern Hecate Strait (with some scattered earlier sampling between 1983 and 1997). Figures in this year's report cover available data from 1990 to 2014. See previous DFO State of the Ocean reports for SVI figures extending back to 1979 (http://www.pac.dfo-mpo.gc.ca/science/oceans/reports-rapports/state-ocean-etat/index-eng.html).

The 'standard' sampling locations in SVI, NVI and Hecate regions are shown in Figure 19-1. Additional locations are included in averages when they are available. Due to a lack of samples from Hecate Strait for the past several years, there will be no update in this report for that area. Samples are collected during DFO research surveys using vertical net hauls with black bongo nets (0.25 m^2 mouth area, 0.23 mm mesh aperture), from near-bottom to sea surface on the continental shelf and upper slope, and from 250 m to surface at deeper locations. We have also recently compiled historic data from various shorter term sampling programs in the Strait of Georgia (SoG). Most of the SoG sampling did not follow a standard grid or sampling protocols. Because of time-varying taxonomic resolution, the SoG data were merged into broader categories (size classes within major taxa). Our analyses-to-date of the SoG time series are described in Mackas et al. (2013a, b).

We routinely estimate abundance and biomass for more than 50 zooplankton species in the SVI, NVI, shelf and offshore. For these regions, seasonal variability is intense and somewhat repeatable from year-to-year. Because sampling dates vary from year to year, simple annual averages of observations confound seasonal with interannual differences. We deal with this by first estimating a multi-year average seasonal cycle (i.e. “climatology”) for each region, using the data from the start of each time series through 2008, and then using these climatologies as baselines against which we can then compare monthly conditions during any single year. To describe interannual variability, our approach has been to calculate within each year a regional, logarithmic scale biomass anomaly for each species and for each month that was sampled in a given year. We then average the monthly anomalies in each year to give an annual anomaly (see Mackas 1992 & Mackas et al. 2001 for mathematical details; for SoG see Mackas et al. 2013b). It is important to note that the anomalies are log scale and therefore multiplicative on a linear scale: an anomaly of +1 for a given taxon means that taxon had 10X higher biomass than in the climatology; an anomaly of -1 means the biomass was 1/10th the climatology.

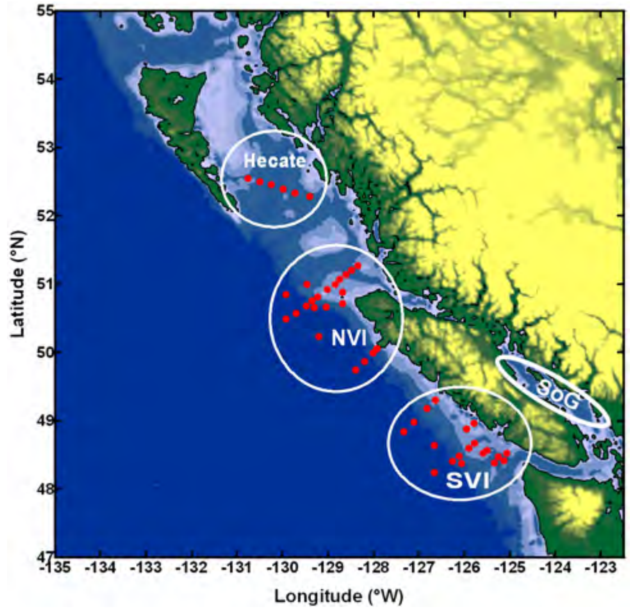

Figure 19-1. Zooplankton time series sampling locations (red dots) in B.C. marine waters. Data are averaged within major statistical areas indicated by ovals; the SVI and NVI regions are further classified into shelf and offshore subregions. The PNCIMA (Pacific North Coast Integrated Management Area) includes both NVI and Hecate Strait areas. Preliminary results from the SoG time series are described in Mackas et al. 2013.

We have learned from our own, and also from other west coast time series (Mackas et al. 2006), that zooplankton species with similar zoogeographic ranges and ecological niches usually have very similar anomaly time series. We therefore often summarize the interannual variability of multiple species by averaging annual anomalies within species groups. For example, the group ‘boreal shelf copepods’ is a composite of the copepods *Calanus marshallae*, *Pseudocalanus mimus*, and *Acartia longiremis,* all of which have distribution ranges that extend from southern Oregon to the Bering Sea. The group ‘subarctic oceanic copepods’ is a composite of *Neocalanus plumchrus*, *N. cristatus*, and *Eucalanus bungii*; all of which inhabit deeper areas of the subarctic Pacific and Bering Sea from North America to Asia. A third group, ‘southern copepods’ is a composite of species from the five genera *Clausocalanus*, *Calocalanus, Ctenocalanus, Mesocalanus* and *Paracalanus* with ranges centered about 1000 kilometers south of our study areas (either in the California Current and/or further offshore in the North Pacific Central Gyre).

Figure 19-2 shows anomaly time series for these copepod species groups, for representative chaetognaths and for euphausiids, in each of the B.C. statistical areas. The range of interannual biomass variability within a species or species group is about one log unit (i.e. factor of 10). This is about 2-3 times greater than the interannual variability of total biomass in our regions. Other features to note are that anomalies often persist for several years and that, in addition to the covariation within species groups mentioned above, there is strong covariation between some species groups. Interannual signals are clearest and have the longest time scale in the three copepod groups and in the chaetognaths. Cool years such as the early 1980s, 1999-2002, and 2007-9 had positive anomalies of boreal shelf and subarctic copepods, and northern chaetognaths. Warm intervals such as 1983, 1993-1998, 2004-2005 and 2010 tended to have negative anomalies of these taxa, but positive anomalies of southern copepods and southern chaetognaths. From previous work, we know that positive anomalies of the cool water zooplankton community off Vancouver Island are also associated with good local survival and growth of juvenile salmon, sablefish, and planktivorous seabirds (Mackas et al. 2007, Borstad et al. 2011, Tucker et al. 2015, M. Trudel, Fisheries and Oceans Canada, Nanaimo, personal communication).

2014 started off as a cool year in the continental shelf region, with strongly positive anomalies for both sub-Arctic and boreal zooplankton. However, in late summer (August and September), warm offshore water with higher abundances of southern zooplankton species moved towards the coast. This trend increased dramatically in late summer and autumn, and is believed to be a result of the resumption of intense down-welling favourable winds (See Dewey et al. 2015). The October NVI samples included the first ever appearance of *Thalia democratica* (a salp species, last recorded at this latitude in the early 1980's at Station Papa). The source of the warm water appears to be offshore and oceanic rather than south to north alongshore movement of coastal water. Many of the warm water species found on the shelf in 2014 are of oceanic origin, and except for the "southern chaetognaths", are not represented in the species groups shown in Figure 19-2.

There is a within-2014 moderation of the annual anomaly signal in all species groups: what was positive at the beginning of the year was negative or near zero by fall (or vice versa), cancelling or tempering each other to give a yearly signal closer to the long term average. A similar situation was seen in 2013 but in 2014 there was no subsequent winter cooling; warm water continued to sit in the offshore area and was pushed onto the shelf by winter storms. The influence of the summer intrusion onto the shelf of warm water was strongest in SVI but by the fall the NVI shelf and offshore regions were also inundated with southern offshore fauna. Boreal shelf copepods fared better in the offshore regions of both NVI and SVI (their normal distribution) than on the shelf. SVI nearshore regions also had a similar but weaker seasonal trend toward southern fauna in both copepods and chaetognaths. As more October samples are analyzed, it is expected this will enhance the warm signal within the anomalies.

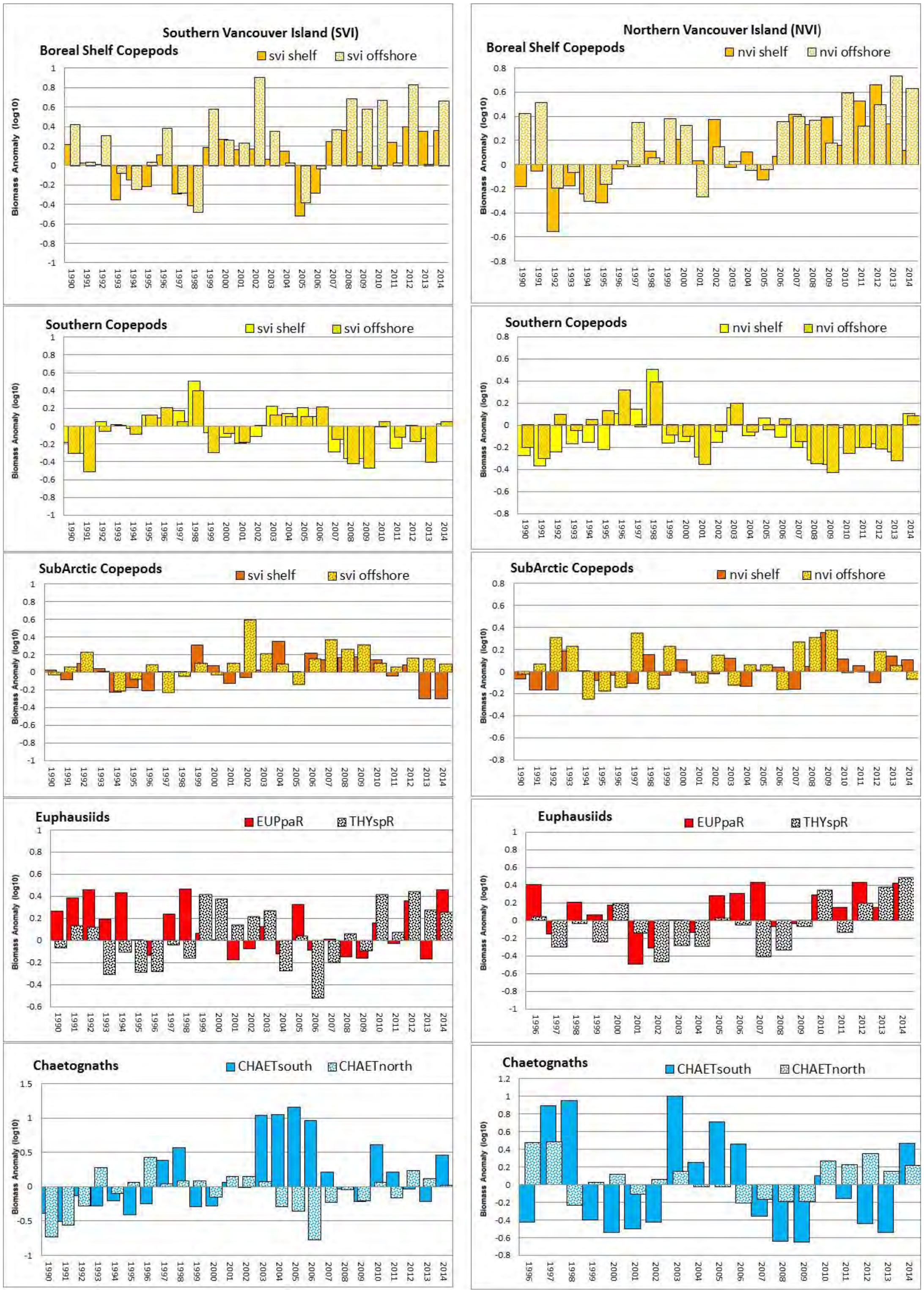

Figure 19-2. Zooplankton species-group anomaly time series (vs climatological baseline) for the SVI (left) and NVI (right) regions shown in Figure 19-1. Bar graphs are annual log scale anomalies. Cool years favor endemic 'northern' taxa, warm years favor colonization by 'southern' taxa. See earlier State of the Ocean reports for pre-1990 anomalies. "R" in Euphausiids indicates data have been corrected for day/night tows. EUPpa: Euphausia pacifica; THYsp: Thysanoessa spinifera; CHAET; Chaetognaths divided into north/south species groups.

Due to this cool to warm transition of sea state, 2014 was overall a near average year (anomalies neither strongly positive nor strongly negative) for many taxa. The intrusion of warm water onto the shelf led to an upward trend for the southern copepod complex and negative anomalies of the subarctic copepods in the coastal areas. Euphausiid anomalies have been mostly positive since 2010. In 2013, boreal copepods fared better on the shelf than in the offshore region for SVI; this is reversed for NVI, but in 2014 it is the offshore areas that are more positive with the shelf showing below average biomass. This may indicate shelf water moving offshore as the warm waters moved onto the shelf. Southern copepods are positive in all regions. February 2015 Line P nearshore samples were dominated by southern species with little or no boreal shelf or subarctic copepods. On the SVI continental shelf and shelf and offshore NVI, annual average anomalies of the subarctic oceanic copepods changed to negative in 2013 and again for 2014. Subarctic oceanic copepods are typically found along the shelf break in the spring so the expectation is that they should do better in the offshore environment than on the shelf.

Several high-order zooplankton taxa (with widely differing ecological niches) are classified as “gelatinous zooplankton”. However, all have high to very high peak reproductive rates compared to the crustaceans and chaetognaths, and all tend to have “boom and bust” population cycles. The most important gelatinous zooplankton groups in the SVI and NVI regions are:

- Salps and doliolids: These are planktonic tunicates, and are primarily herbivorous (broad spectrum filter feeders).
- Thecosomatous pteropods (e.g. Limacina helicina): These are planktonic snails. Unlike the previous two groups, their bodies are not gelatinous, but they use a large external gelatinous feeding web to capture their food.
- Hydromedusae and siphonophores (“jellyfish”) and ctenophores (“comb jellies”): These are predatory on other zooplankton and sometimes on larval fishes, but are mainly competitors with larval fish.

Doliolids and the pteropod *Clio* were absent or rare in nearly all years before 2002, but since then have sometimes been abundant to very abundant in the SVI and NVI regions. Years with positive salp anomalies have occurred throughout the time series (Figure 19-3). Although numerically abundant in 2014, salps were smaller in size (different species) leading to a slightly negative biomass anomaly.

For the past three years ctenophores have seen a positive trend in both NVI and SVI which has been consistent over the shelf and offshore areas. The main ctenophore collected is *Pleurobrachia bachei* but there has been some *Horminophora*, a southern genus, in the offshore areas. Anomalies of siphonophores and hydromedusae were positive for 2014, especially on the shelf and shelf break areas of Vancouver Island. For the last two years, a warm water pteropod, *Corolla spectabilis* was found on the shelf and offshore areas of SVI; its last previous occurrences were in 2005/6 and 1997/98. As with the long term trend in the copepod species groups, the net effect has been to make the zooplankton community off B.C. more like the community found in parts of the California Current System to the south of B.C., less like the historical SVI and NVI

climatology, and less like the present-day zooplankton community off northern British Columbia and Alaska.

Aglantha digitale is one of the most abundant hydromedusae in the North Pacific but comparison of the panels in Figure 19-3 shows that *A. digitale* is not what is driving the positive signal in the hydromedusae off the west coast of Vancouver Island. The majority of the biomass can be attributed to the increase in numbers of Mitrocoma, *Clytia* and *Halitholus*.

With the interest in ocean acidification we have included anomaly trends for *Limacina helicina* and *Clio pyramidata*, pelagic thecosomate (shelled) pteropods (Figure 19-4). These are species with a calcareous shell susceptible to dissolution damage if water in the top 100m is under saturated for aragonite. The overall trend for *L. helicina* is negative; the large positive anomaly in 2013 in NVI was a result of sampling in cool spring conditions along the shelf and shelf break, this was not repeated in 2014. Both the shelf and offshore areas of Northern and Southern Vancouver Island were negative for 2014, for both species.

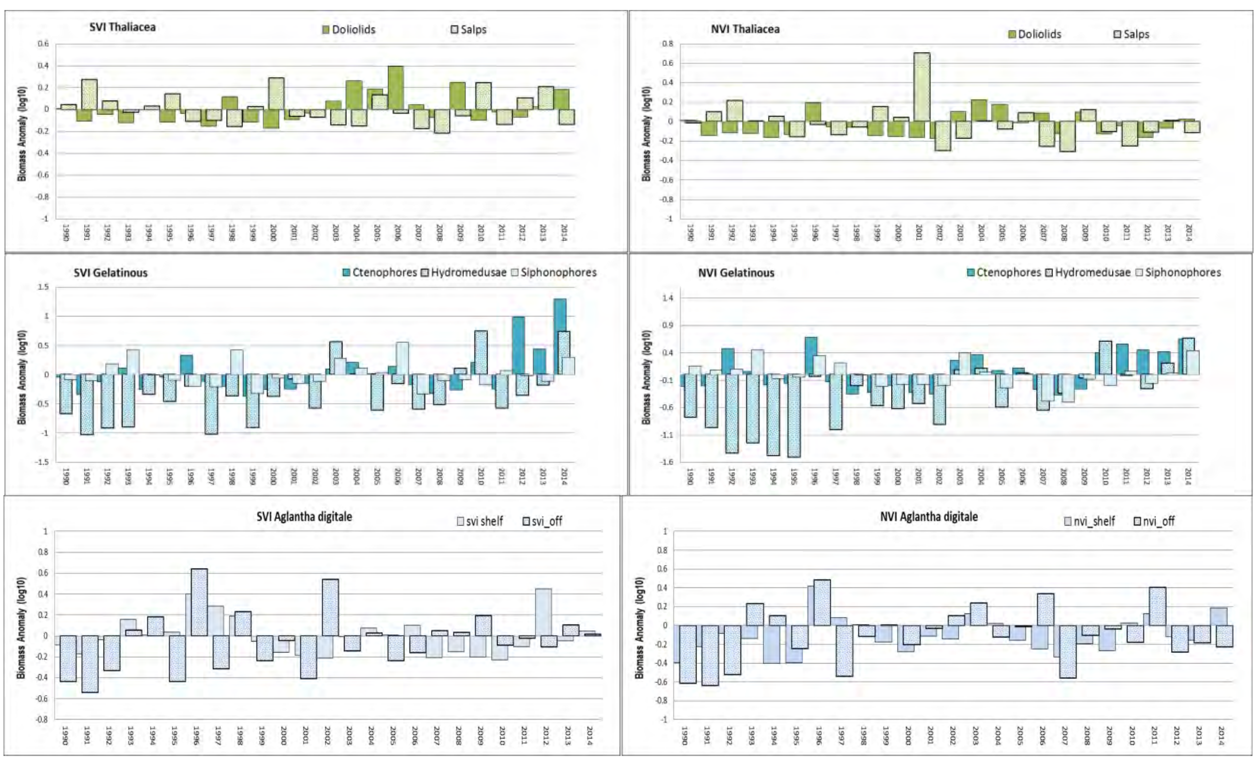

Figure 19-3. Anomaly time series for important gelatinous zooplankton off southern Vancouver Island. Top panel shows doliolids (genus Dolioletta*) and salps (genus* Salpa*). Middle panel hydromedusa, ctenophores and siphonophores, the large positive anomaly in hydromedusae consists primarily of* Mitrocoma*.*

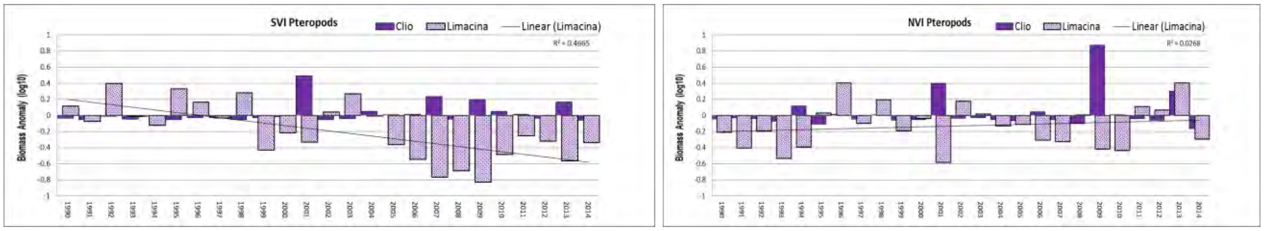

Figure 19-4. Anomaly time series for Limacina helicina *and* Clio pyramidata*; Northern Vancouver Island on the right and Southern Vancouver Island on the left.*

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20. WEST COAST OF VANCOUVER ISLAND PELAGIC ECOSYSTEM NIGHT TRAWL SURVEY

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20.1. Highlights

- No Pacific Sardine were observed in the 2013 and 2014 west coast Vancouver Island night summer trawl surveys.
- Decreases in survey sardine catch per unit effort since 2006 are consistent with a decreasing biomass trend depicted by a population assessment.
- In 2014, Pacific Herring were widely distributed off southwest Vancouver Island.
- In 2014, Eulachon catches were higher than previous survey years.

20.2. Description of indices

Results from a summer DFO trawl survey off the west coast of Vancouver Island (WCVI) are used to explore trends in abundance and distribution of pelagic fish species. Starting in 1997, a trawl survey conducted in the day was originally designed to monitor relative abundance and distribution of Pacific Sardine (*Sardinops sagax*). To improve sampling of the pelagic fish foraging community, starting in 2006 (no survey in 2007), the survey changed to night trawl fishing within a pre-defined survey area (Figure 20-1). For more information on the methods of the night trawl survey, refer to Flostrand et al. (2011). In 2014, the survey was conducted from August 5 to 15. The scheduling of the night survey time series has become biennial and will occur on even years; thus the next survey is planned for 2016.

Trawl survey catch per unit effort (CPUE; kg/m^3 or $tonnes/km^3$) data are used to monitor trends in distribution and relative abundance of pelagic fish species. To monitor species presence/absence, the proportion of trawl catches with a species is calculated. Mean CPUE (with standard error) and the proportion of positive tows are reported for Pacific Sardine, Pacific Herring, Eulachon and Whitebait Smelt. Due to the transboundary nature of the north Pacific Sardine stock, in addition to observations from the WCVI pelagic night trawl survey, we include biomass estimates from the U.S.-led population assessment of the north Pacific Sardine stock (U.S. National Oceanic and Atmospheric Administration; Hill et al. 2015).

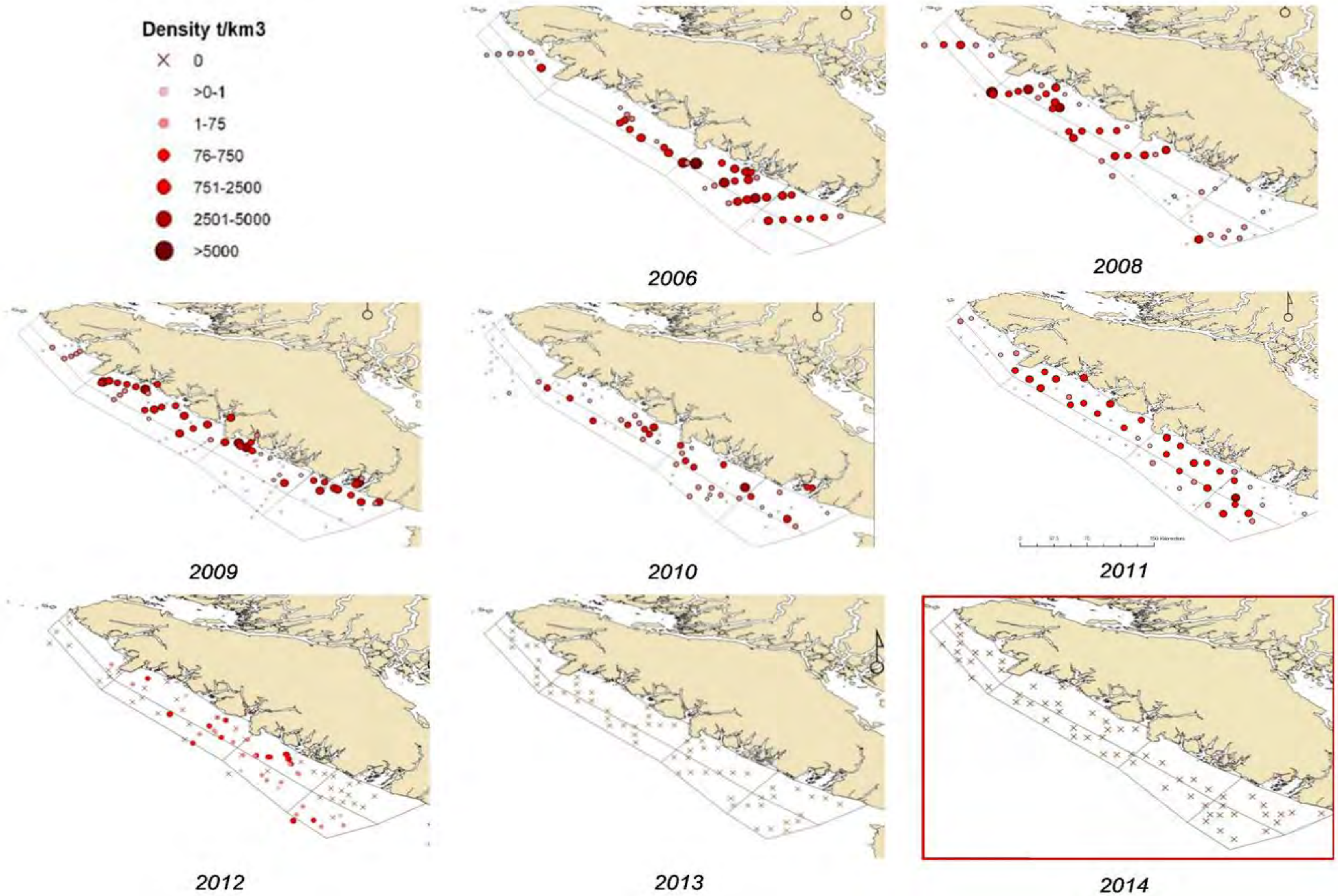

Figure 20-1. West coast of Vancouver Island pelagic night trawl survey sampling locations and relative sardine catch densities (CPUE in tonnes/km³), for 2006 and 2008-2014 (no survey in 2007). Lines delineate core survey region and zones.

20.3. Status and Trends

The composition of species sampled in the pelagic night trawl survey varies interannually, but has been composed mainly of Pacific Sardine, Pacific Herring, Spiny Dogfish, Jack Mackerel, Chub Mackerel, Pink Salmon, Coho Salmon and Chinook Salmon (20-2). Other species commonly observed (but generally in lower amounts) include Sockeye Salmon, Chum Salmon, Pacific Hake, Eulachon, Whitebait Smelt, Northern Anchovy, Lanternfish (myctophids) and invertebrates such as species of squid, jellyfish, salps and shrimp.

The U.S. Pacific Sardine assessment indicates that the population biomass has been decreasing since a peak in 2007, coinciding with several years of low recruitment (Figure 20-3, Hill et al. 2015). Pacific Sardine CPUE estimates from the WCVI pelagic night trawl survey show a decreasing trend since 2006 and no sardine were observed in either the 2013 or 2014 surveys (Figures 20-1, 20-2 and 20-4), nor were any observed and caught by the B.C. sardine fishery in either year.

WCVI pelagic night trawl survey observations for Pacific Herring, Eulachon and Whitebait Smelt have considerably different trends (Figure 20-4). Pacific Herring mean CPUE in 2014 was relatively similar to 2006 and 2010-2013 but the proportion of positive tows was slightly higher than other years. Eulachon mean CPUE and proportion of positive tows was notably higher in 2014 compared to previous years. Whitebait Smelt mean CPUE in 2014 was relatively low compared to a peak in 2012 but the proportion of positive tows in 2014 was similar to what was observed in 2012 and 2013.

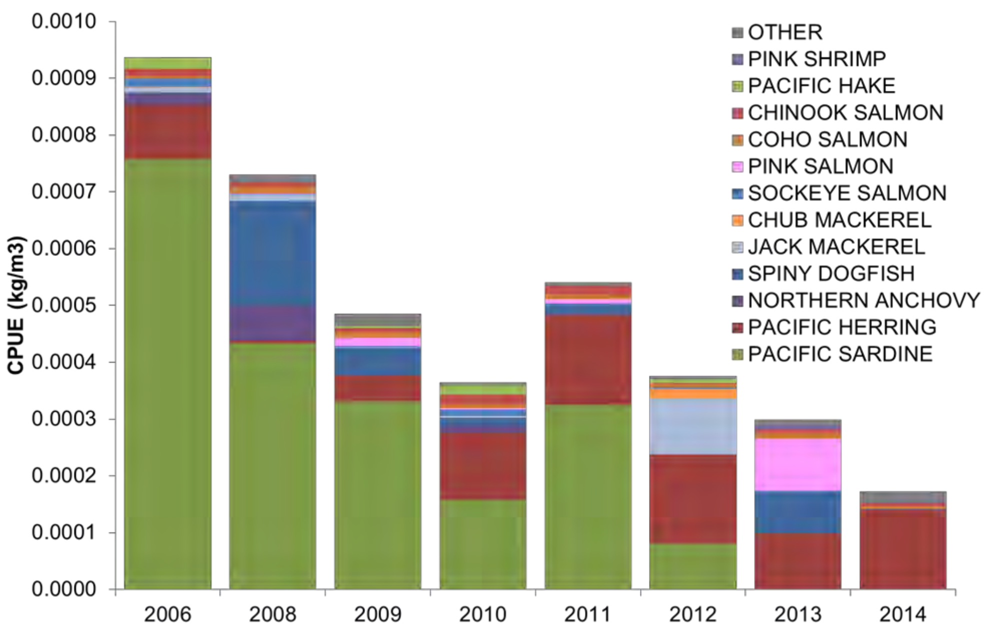

Figure 20-2. Average CPUE (kg/m[3]) of pelagic species sampled in the pelagic ecosystem night time trawl survey. Large average CPUE values in any one year can be the result of one or two large catches (e.g., spiny dogfish in 2013). Note: Average CPUE values were updated from the 2013 State of the Ocean report (e.g. Perry 2014) to include zero catches.

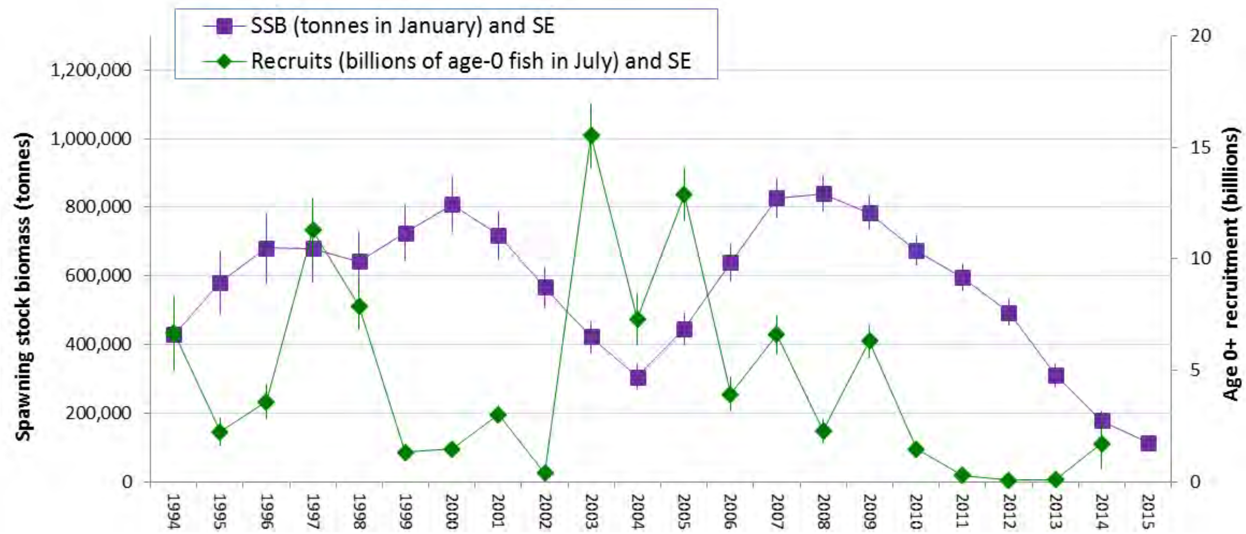

Figure 20-3. Estimates (and standard error, SE) of Pacific Sardine spawning stock biomass (SSB, in tonnes) and year class recruitment (billions of age-0 fish) from a Stock Synthesis assessment of the north Pacific Sardine population (Hill et al. 2015).

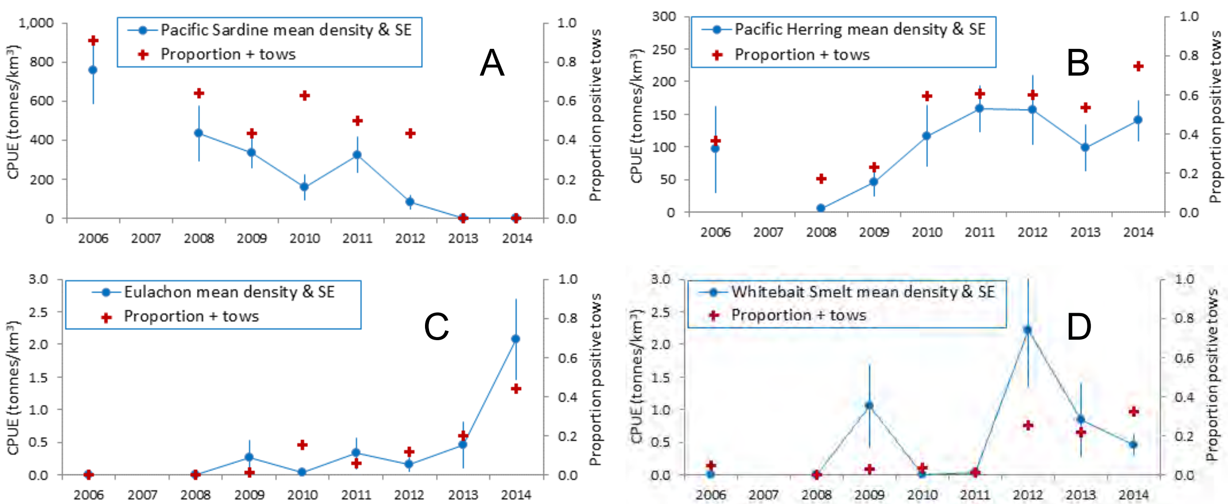

Figure 20-4. Pelagic ecosystem night trawl survey average CPUE (tonnes/km³), CPUE standard error (SE) and proportion of positive tows for: A) Pacific Sardine; B) Pacific Herring; C) Eulachon; and D) Whitebait Smelt.

20.4. Factors causing trends

Changes in species composition in the pelagic ecosystem night survey are likely due to a variety of environmental, biological and behavioural factors. In addition, CPUE estimates can be influenced by one or two particularly large trawl hauls (e.g., Figure 20-2, the 2013 average Spiny Dogfish CPUE was influenced by one large catch).

Further quantitative analysis of these data is in progress to improve the understanding of factors affecting the relative abundance and distribution of pelagic fish species.

Ecological behaviour that may confound the survey's CPUE observations from being reliable indicators of a species relative abundance and distribution include variability in a species' summer migration schedules through the survey region and vertical migration within the water column (e.g. within and between 24 hour periods). Spiny Dogfish, Pacific Hake and most species of salmon display both of these types of behaviours. Eulachon and Whitebait Smelt exhibit both demersal and pelagic behaviour and may not be well sampled by the surface trawl; therefore survey observations for these species may be less indicative of actual population dynamics.

In addition, although Pacific Salmon, Pacific Herring and Eulachon captured in the survey may be from multiple spawning stocks inhabiting the WCVI ecosystem in the summer, CPUE trends provide information on ecosystem structure. Readers are referred to Cleary et al. (2015) for additional information on Pacific Herring and to Boldt et al. (2015) for Eulachon.

The north Pacific Sardine population ranges from waters off Baja, Mexico to B.C., Canada with variations in the proportion of the population seasonally migrating into B.C. waters, predominantly in summer and fall months. In winter and spring months, most of the Pacific Sardine population resides in waters off the California coast. Prior to, and during summer months, large aggregations of Pacific Sardine migrate from key spawning habitat to more northern waters, predominantly to forage on plankton. Typically, most Pacific Sardine that migrate into B.C. waters are the larger and older fish in the population (Flostrand et al. 2011). Sardine are believed to mostly reside in the relatively warm surface waters when they are present off the WCVI.

The abundance of sardine and the timing of their annual northward migration are influenced, in part, by stock size, age and size composition, recruitment relationships that are not well understood, and environmental factors (Lo et al. 2010, Hill et al. 2015, Nieto et al. 2015). Low levels of recruitment to the population in recent years appear to explain decreases in the population's spawning biomass and WCVI pelagic night trawl survey mean CPUE observations. One explanation for recent low juvenile recruitment is related to changes in marine conditions near the California coast spawning grounds associated with an increase in mesoscale ocean eddies (Nieto et al. 2015). Nieto et al. (2015) suggest that these eddies may transport Pacific Sardine eggs and larvae too far from shore for the young progeny to access nearshore foraging and rearing habitat for their continued survival.

Historical sardine abundance has been extremely variable along the U.S. and Canadian west coast, cycling over approximately 60-year periods (Cushing 1971, Hill et al. 2011). The decline in sardine biomass in the late 1940s was attributed to environmental conditions and overfishing (Clark and Marr 1955, Jacobson and MacCall 1995). During a relatively cold period from the 1950s to 1970s, the sardine population's productivity was generally low and the population's distribution contracted to the southern part of the range (Jacobson and MacCall 1995). During the relatively warm period in the 1990s and in 2003-2007, increases in sardine productivity were apparent (Jacobson and

MacCall 1995) and along with a larger stock size was a more northerly seasonal distribution of the stock (McFarlane et al. 2001, Zwolinski et al. 2011, Zwolinski et al. 2012). In addition to recent fishing patterns and intensities being different to those leading up to the biomass declines in the 1940s, the recent environmental conditions may also be quite different. Although cooler spring and summer ocean temperatures along the migration corridors may contract northern migration, low population sizes are believed to be an important contributing factor to the lack of sardine observed in the 2013 and 2014 WCVI surveys.

20.5. Implications of trends

Changes in species composition, relative abundance, and distribution can be indicative of ecosystem-wide changes and can have implications for other trophic levels (both prey and predators). A clearer understanding of the environmental and biological factors affecting pelagic species and their interactions and trophodynamics is needed.

In B.C. waters, Pacific Sardine are consumed by a variety of fish, such as Coho and Chinook Salmon (Chapman 1936), Spiny Dogfish and other sharks, Albacore Tuna and other tuna, Pacific Hake, Jack Mackerel as well as by marine mammals, such as Humpback Whales, California Sea Lions and other pinnipeds. Historically, sardine populations have undergone extreme variations in abundance and it is likely that many predators utilize this resource when it is abundant. However, changes in sardine abundance and distribution would also likely influence the distribution of some of their migratory predators. A time series of diet data from sardine predators would improve our ability to examine temporal trends in predator-prey interactions and the implications of those trends.

The resurgence of a commercial B.C. sardine fishery in 2002 occurred following the recovery of the coast-wide population and the return of sardines to B.C. waters in the 1990s. Between 2002 and 2012, the B.C. sardine fishery realised increased landings and established markets. A lack of sardines and sardine landings in B.C. (such as in 2013 and 2014) place the B.C. sardine fishery at risk of not prospering in the near future.

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21. EULACHON STATUS AND TRENDS IN B.C.

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21.1. Highlights

- COSEWIC (2011) assessed eulachon in B.C. as three populations (or designated units):
  - Central Pacific coast population and Fraser River populations were assessed as endangered, and
  - Nass/Skeena Rivers population was assessed as Special Concern.
- The estimated eulachon spawning stock biomass in the Fraser River decreased during 1994-2010 with slight increases in 2011 and 2012; the 2013 and 2014 biomass estimates were slightly lower than the 2012 estimate.
- The spawning stock biomass has been below the action level since 2004.
- It is unknown what has caused declining trends in eulachon abundance.

21.2. Description of indices

Three indices of eulachon (*Thaleichthys pacificus)* population trends are: 1) eulachon catches occurring in annual offshore shrimp trawl surveys off the West Coast of Vancouver Island (WCVI, 1973-2012) and in Queen Charlotte Sound (QCS, 1998-2012); 2) commercial eulachon catches in the Fraser (1900-2004) and Columbia (1888-2010 and 2014-2015) River systems; and 3) a spawning stock biomass estimate based on annual Fraser River eulachon egg and larval surveys, 1995 to 2014. In the past, information from these indices was used to assess population trends and provide science advice regarding eulachon catch recommendations. Offshore indices of juvenile eulachon abundance, however, do not always reflect the abundance of adult eulachon that return to rivers (Schweigert et al. 2012) and Fraser River and Columbia River commercial fisheries have been closed in recent years (except for a re-start of the Columbia commercial and recreational fishery in 2014); therefore, the only updated index presented here is the spawning stock biomass estimate based on annual Fraser River eulachon egg and larval surveys.

21.3. Status and trends

Eulachon have experienced long-term declines in many rivers throughout their distribution from California to Alaska. COSEWIC assessed eulachon in B.C. as three populations (or designated units): the Central Pacific coast population and Fraser River populations were assessed as endangered, and the Nass/Skeena River population was assessed as Special Concern (COSEWIC 2011). Information in support of a recovery potential assessment (Levesque and Therriault 2011) and a recovery potential

assessment are available online (Schweigert et al. 2012). Catches in the Columbia River system decreased dramatically in the early-1990s. Columbia River eulachon were federally-listed in the U.S.A. as threatened under the Endangered Species Act (ESA) effective May 17, 2010 and all eulachon-directed fisheries were closed in 2011 (NOAA 2010). In 2014 and 2015 commercial and recreational fisheries in the Columbia River were re-opened on an experimental basis. Indices of eulachon abundance in central and southern British Columbia rivers remain at low levels. The estimated eulachon spawning stock biomass in the Fraser River decreased during 1994-2010 with slight increases in 2011 and 2012; the 2013 and 2014 biomass estimates were slightly lower than the 2012 estimate (Figure 21-1). The spawning stock biomass has been below the action level (150 tonnes; Hay et al. 2003) since 2004. The biomass in the Fraser River will be estimated by an egg and larval survey in April-May, 2015.

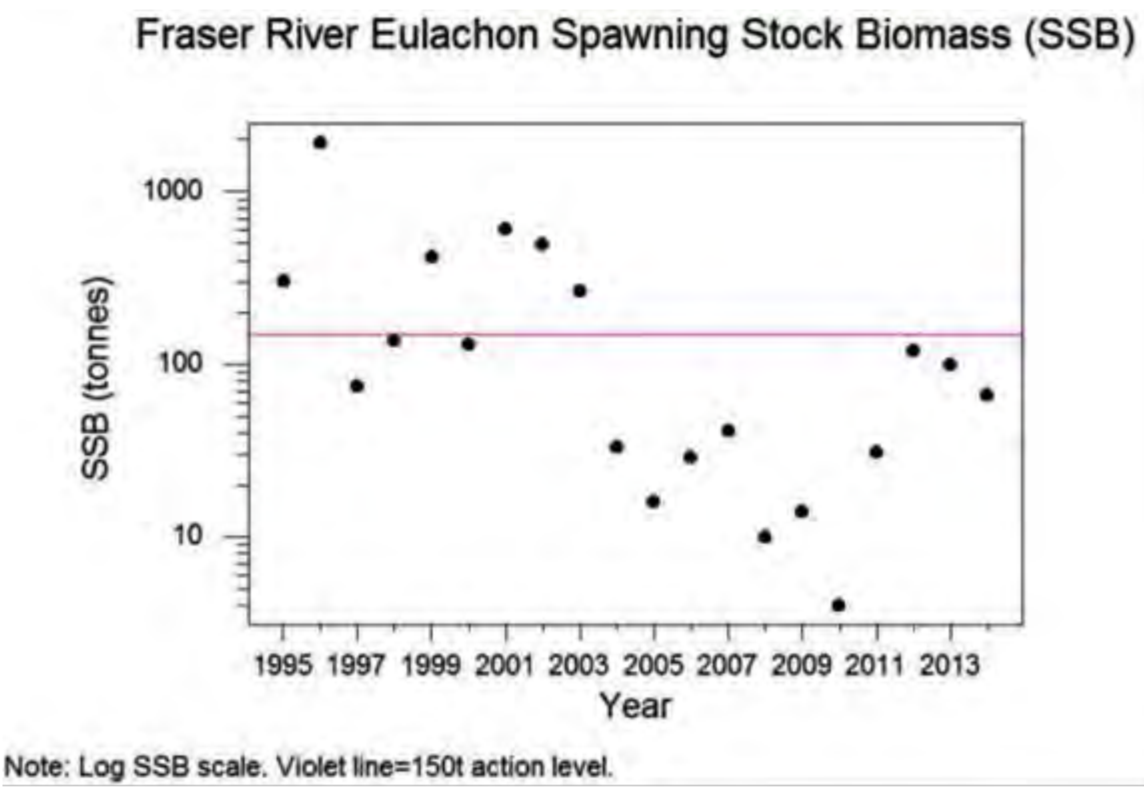

Figure 21-1. Estimated spawning stock biomass (SSB in tonnes) of eulachon in the Fraser River, 1995-2014. Y-axis is on a log-scale. Horizontal pink line shows the 150 tonne action level.

21.4. Factors causing those trends

It is unknown what caused declining trends in eulachon abundance. Schweigert et al. (2012) state that "No single threat could be identified as most probable for the observed decline in abundances among DUs [designated units] or in limiting recovery. However, mortality associated with coastwide changes in climate, fishing (direct and bycatch) and marine predation were considered to be greater threats at the DU level, than changes in

habitat or predation within spawning rivers." Also, DFO (2015) states that "Some existing threats are unlikely to have been responsible for recent declines (e.g., food, social and ceremonial (FSC) fisheries, marine mammal predation, and degradation of freshwater habitat) but may now be preventing recovery from low population abundance."

21.5. Implications of those trends

Reduced biomass of eulachon has negative implications for First Nations and commercial fishers. Eulachon are socially and culturally significant to local First Nations and are fished by First Nations, recreational and commercial fishers.

Reduced eulachon abundance also likely has negative impacts on their predators. Important predators of eulachon include: marine mammals (particularly seals and sea lions in the estuaries, and porpoises), Chinook and Coho Salmon, Spiny Dogfish, Pacific Hake, Sturgeon, Pacific Halibut, Walleye Pollock, Sablefish, rockfish, Arrowtooth Flounder, and others (Levesque and Therriault 2011). Diet data time series of all animals in the ecosystem would improve our ability to examine temporal trends in predator-prey interactions and the implications of those trends.

21.6. References

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22. PACIFIC HERRING IN BRITISH COLUMBIA, 2014

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22.1. Highlights

- There were increased biomass estimates in the last 1 to 5 years in 3 of the 5 main fishing stocks of herring.
- Biomass estimates in 2014 relative to 2013 increased for the west coast Vancouver Island (WCVI), Central Coast (CC), and Strait of Georgia (SOG) stocks, were similar for the Prince Rupert District (PRD) stock, and decreased for the Haida Gwaii (HG) stock
- Factors contributing to changes in biomass and stock status include:
  - consecutive years of below or above average recruitment;
  - increases or decreases in model estimates of natural mortality;
  - increases or decreases in mean weight-at-age.
- There has been a decreasing weight-at-age trend for all stocks with a slight increase in recent years.

22.2. Summary

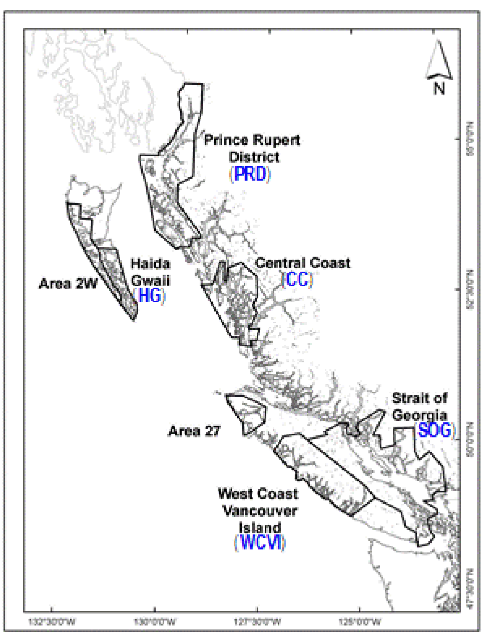

Figure 22-1. *Location of the five major (Strait of Georgia, west coast of Vancouver Island, Prince Rupert, Haida Gwaii, and the Central Coast) and two minor (Area 2W and Area 27) Pacific herring fishing stocks in B.C.*

Model estimates of Pacific Herring biomass, derived from a catch-age model fitted to time series data (commercial and test fishery biological samples (age, length, weight, sex, etc.), herring spawn dive survey data (spawn index), and commercial harvest data), reflect herring population trends for five major fishing stocks: Strait of Georgia (SOG), west coast of Vancouver Island (WCVI), Prince Rupert District (PRD), Haida Gwaii (HG; previously referred to as the Queen Charlotte Islands stock), and the central coast (CC), and two minor stocks (Area 2W and Area 27) (DFO 2015; Figure 22-1). In 2014, a statistical catch-age model was used to provide (in part) estimates of Pacific Herring spawning biomass and age-2 recruit abundances (DFO 2015).

22.3. Status and trends

22.3.1. West Coast Vancouver Island (WCVI)

The median spawning biomass has increased since 2008 (Figure 22-2) from historically low levels, due in part to above average recruitment in 2010 (Figure 22-2; DFO 2015) and apparent decreases in model estimates of natural mortality. The WCVI stock was closed to commercial fisheries from 2006 to 2011 and in 2013 (DFO 2015). A commercial harvest option was available in 2012 but was not pursued. WCVI herring weight-at-age has declined since the mid-1970s or mid-1980s with an increase in recent years (Figure 22-3).

22.3.2. Strait of Georgia (SOG):

The median spawning biomass has increased since 2010 (Figure 22-2) due in part to above average recruitment in 2010 and 2011 (Figure 22-2; DFO 2015) and apparent decreases in model estimates of natural mortality. The combined total validated catch for the seine roe, gillnet roe, food and bait and special use fisheries was 20,307 t for the 2013/14 herring season (DFO 2015). SOG herring weight-at-age has declined since the mid-1970s with an increase in recent years (Figure 22-3).

22.3.3. Prince Rupert (PRD), Haida Gwaii (HG), and Central Coast (CC):

Exploitable herring biomass in the Pacific North Coast Integrated Management Area (PNCIMA) region represents a combination of migratory stocks from the HG, PRD and CC areas (DFO 2012). In HG, there was low apparent recruitment of age-2 herring in 2013 and 2014 and an increase in model estimates of natural mortality in recent years. The model estimated that the 2014 spawning stock biomass declined from 2013 (DFO 2015; Figure 22-2). No commercial herring fishery occurred in this area from 2005 through 2014. In CC, an increase in median estimates of spawning biomass was estimated for 2012 to 2014, due in part to above average recruitment of age-2 herring in 2010, 2012, and 2014, a high spawn index in 2013 (preceded by seven years with low index values), and apparent decreases in natural mortality (DFO 2015; Figure 22-2). In the CC, no commercial herring fishery occurred from 2008 through 2013; in 2014, the commercial gillnet roe fishery caught 687 t (DFO 2015) and there were commercial spawn-on-kelp operations. In PRD, there was below average recruitment of age-2 fish in 2013 and 2014 and apparent decreases in model estimates of natural mortality for recent years. Model estimates of spawning stock biomass for 2014 are similar to the 2013 levels (DFO 2015). PRD, HG, and CC herring weight-at-age has declined since the mid-1970s with an increase or leveling off in recent years (Figure 22-3).

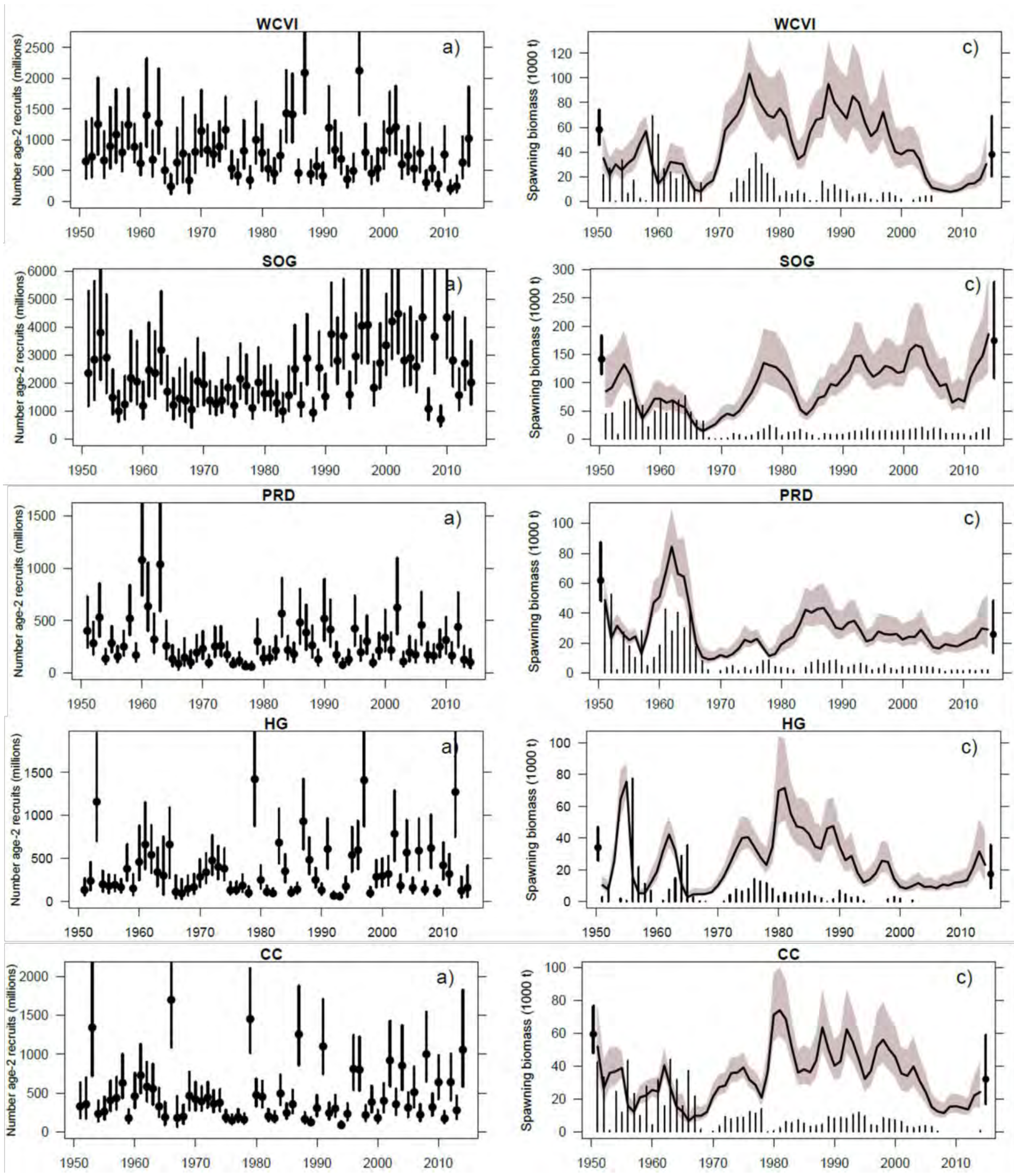

Figure 22-2. Summary of the dynamics of the five herring stocks from 1951 to 2014, where solid circles with vertical lines, and solid lines with surrounding pink envelopes, represent medians and 5-95% credible intervals. Left panels (a) show the reconstruction of number of age-2 recruits (millions); right panels (c) show the reconstruction of spawning biomass (SBt) for each year t, with unfished values shown at far left (solid circle and vertical lines) and the projected spawning biomass given zero catch (SB2015) shown at the far right (solid circle and vertical lines). Time series of thin vertical lines denote commercial catch (excluding commercial spawn-on-kelp). Figure adapted from DFO (2015).

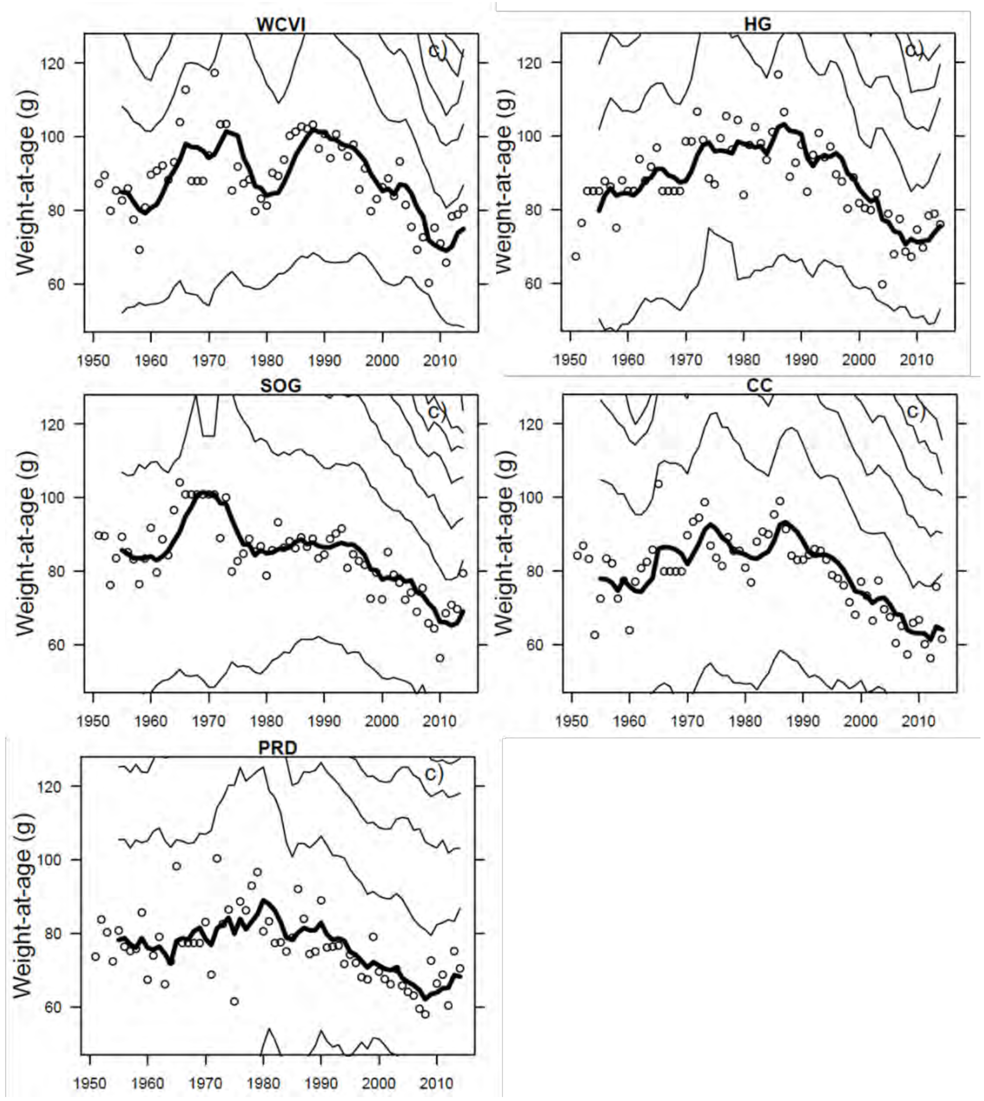

Figure 22-3. Time series of observed weight-at-age 3 (circles) and five-year running mean weight-at-age 3 (dark line) for major herring stocks. Thinner black lines represent five-year running mean weight-at-age 2 (lowest) and ages 4-7 (incrementing higher from age 3).

22.4. Factors influencing trends in herring biomass

The biomass of Pacific Herring in three major fishing stocks (HG, CC and WCVI) have experienced prolonged periods of low biomass in the absence of fishing (DFO 2015). The two areas that are open to fishing maintain stable or high biomass estimates (PRD and SOG). Consideration of these biomass trends in combination with the declining trend in herring weight-at-age observed for all fishing stock areas suggests that factors other than (or in addition to) fishing may be influencing herring population trends. Changes in food supply and quality, predator abundance, and competition are factors that could affect trends in herring biomass and weight-at-age (Schweigert et al. 2010, Hay et al. 2012).

Pacific Herring are zooplanktivorous, consuming primarily euphausiids (krill) and some copepods (Wailes 1936). Changes in ocean conditions, such as temperature or currents, could affect the amount and types of prey available. For example, a northerly current direction could result in the presence of California current waters off the WCVI, bringing California Current zooplankton species that have a lower energetic value, creating poorer feeding conditions for herring (Schweigert et al. 2010, Mackas et al. 2004). In addition, Tanasichuk (2012) related WCVI herring recruitment to the biomass of euphausiids.

There are a wide variety of herring predators, including Pacific Hake, Lingcod, Spiny Dogfish, Pacific Cod, Sablefish, Arrowtooth Flounder, Pacific Halibut, Steller Sea Lions, Northern Fur Seals, Harbour Seals, California Sea Lions, and Humpback Whales (Schweigert et al. 2010). Off the WCVI, fish predator abundance has decreased in recent years, while the abundance of most marine mammal predators has increased (Olesiuk 2008, Olesiuk et al. 1990). This has resulted in a relatively stable or slightly decreasing trend in the amount of WCVI herring consumed by predators since 1973 (Schweigert et al. 2010). Although a significant proportion of the herring population could be cropped annually by predation, trends in model estimates of natural mortality of WCVI herring were not found to be directly attributable to trends in estimates of predation (Schweigert et al. 2010). Herring recruitment, however, has been correlated with piscivorous hake biomass (piscivorous hake are those hake that are large enough to consume herring), suggesting predation may be an important factor influencing WCVI herring recruitment (Tanasichuk 2012).

22.5. Implications of trends

Trends in herring biomass have implications for both fisheries and predators. Pacific Herring comprise an important component of commercial fisheries in British Columbia. Fisheries Management uses forecasts of herring biomass, in conjunction with decision tables, performance metrics, and harvest rates to set total allowable catches (TAC).

Trends in herring biomass have implications for herring predators, such as fish, marine mammals and seabirds. The relative importance of herring in each predator’s diet varies; however, herring may represent up to 88% of Lingcod diet (Pearsall and Fargo 2007), 40% of Pacific Cod and Pacific Halibut diets (Ware and McFarlane 1986), and 35% - 45% of pinniped diets (Olesiuk et al. 1990, Womble and Sigler 2006, Trites et al. 2007, Olesiuk 2008). Depending on the level of diet specialization and ability to switch to alternate prey, herring abundance and condition may affect predators’ growth and abundance. Time series of diets of animals in this ecosystem would improve our ability to examine temporal trends in predator-prey interactions and implications of those trends.

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23. 2014 GROWTH OF JUVENILE COHO SALMON OFF WCVI THE HIGHEST ON RECORD SINCE 1998

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23.1. Highlights

- 2014 had the highest growth of juvenile Coho Salmon off the west coast of Vancouver Island since 1998, foretelling high survival for the cohort.
- For the 2014 ocean entry year, physical indicators predict lower smolt survival, opposite to that being predicted from biological indicators.

23.2. Summary

Integrated pelagic ecosystem surveys for juvenile salmon and ocean conditions (physical/biological) salmon have been used to assess the distribution, growth, condition, and survival of Pacific salmon in different parts of the British Columbia coastal ecosystem since 1998. These surveys are usually conducted in late spring-early summer (June-July) and in the fall (October-November). This work assumes that marine survival will be higher in years when salmon are growing rapidly and are in good condition than in years of poor growth and condition. Hence, marine survival is expected to be positively correlated to indicators of juvenile salmon growth rate (Trudel et al. 2008).

Since 1998, growth rates of juvenile Coho Salmon during the summer season off WCVI have been estimated using samples collected in the fall (Trudel et al. 2008). The lowest growth observed in the time series occurred in 2005 followed by 1998 (Figure 23-1), which were also the two warmest years of the time series (Table 23-1). Interestingly, the highest growth of the time series was observed in 2014, also an unusually warm year. High growth rates were also observed for juvenile Coho Salmon off Oregon and Washington (Brian Beckman, NOAA Fisheries, Seattle, personal communication) and juvenile Pink Salmon in Southeast Alaska in 2014 (Joe Orsi, NOAA Fisheries, Alaska, personal communication).

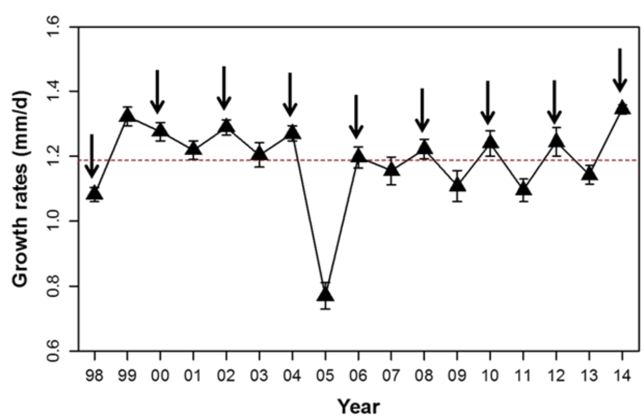

Figure 23-1. Growth rates (May-October) of juvenile Coho Salmon off the west coast of Vancouver Island. The red dotted line represents the 1998-2014 average. The error bars are 2 times the standard error. Even years are indicated by a downward arrow. Details on the procedure used to estimate growth rate are provided in Trudel et al. (2007).

The high growth rates observed for juvenile Coho Salmon off the west coast of Vancouver Island in 2014 suggest that smolt survival will also be high for that year. In contrast, predictions based on physical indices such as the Pacific Decadal Oscillation (PDO), North Pacific Gyre Oscillation (NPGO), and sea surface temperature (SST) indicate the opposite i.e. low smolt survival. Clearly, one of these relationships is bound to break given that their predictions are at the opposite end of the spectrum (very high vs very low).

Table 23-1. Physical and biological indicators of smolt survival for WCVI Coho Salmon. PDO: Pacific Decadal Oscillation (averaged between May and September); NPGO: North Pacific Gyre Oscillation Index (averaged between May and September); ENSO: El Nino Southern Oscillation Index (averaged between May and September); Mean SST: Sea Surface Temperature at Amphitrite point (averaged between March and June); WCVI Coho Summer Growth: Growth of juvenile Coho Salmon from ocean entry to the Fall (October-November). Ocean conditions are ranked from best (rank 1; green) to worst (rank 17; red) for Coho Salmon. Note that ocean conditions off WCVI were generally favourable to Coho Salmon in 1999-2001 and 2008, and not favourable during the 1998 El Nino, and in 2005-2006.

RANK SCORES																	
Environmental Variables	***98***	***99***	***00***	***01***	***02***	***03***	***04***	***05***	***06***	***07***	***08***	***09***	***10***	***11***	***12***	***13***	***14***
PDO (May-Sep)	10	4	6	5	11	15	14	16	12	13	2	9	7	3	1	8	17
NPGO (May-Sep)	14	5	3	1	8	10	13	17	16	9	2	11	6	7	4	12	15
ENSO (May-Sep)	8	2	7	9	16	10	12	11	13	3	6	17	1	5	14	4	15
Mean SST - WCVI (Amphitrite) - Mar	16	1	8	3	4	12	15	17	11	5	6	9	13	10	2	7	14
WCVI Coho Summer Growth	16	2	4	9	3	10	5	17	11	12	8	14	7	15	6	13	1
Mean Rank	12.8	2.8	5.6	5.4	8.4	11.4	11.8	15.6	12.6	8.4	4.8	12.0	6.8	8.0	5.4	8.8	12.4
Rank of Mean Ranks	16	1	5	3	8	11	12	17	15	8	2	13	6	7	3	10	14

Data Sources:
PDO: http://jisao.washington.edu/pdo/PDO.latest
NPGO: http://www.o3d.org/npgo/data/NPGO.txt
ENSO: http://www.esrl.noaa.gov/psd/enso/mei/table.html
Amphitrite SST: http://www.pac.dfo-mpo.gc.ca/science/oceans/data-donnees/lighthouses-phares/data/amphitrt.txt

Interestingly, juvenile Coho Salmon growth has generally been higher in even years than odd years since 2001, and this pattern continued in 2014 (Figure 23-1). An odd-even year pattern is also apparent in the residuals of the smolt survival and PDO, SST, and NPGO relationships, with higher survival observed in even years (Figure 23-2).The underlying mechanism generating this pattern is unclear at this point. In marine waters of southern British Columbia, juvenile Pink Salmon are typically most abundant in even years (Beamish et al. 2008, Irvine et al. 2014). However, they rarely occur off WCVI during summer, and are only present in moderate numbers during fall in even years. One possibility is that juvenile Coho Salmon compete with adult Fraser River and Puget Sound Pink Salmon when they return in coastal waters in the summer of odd years.

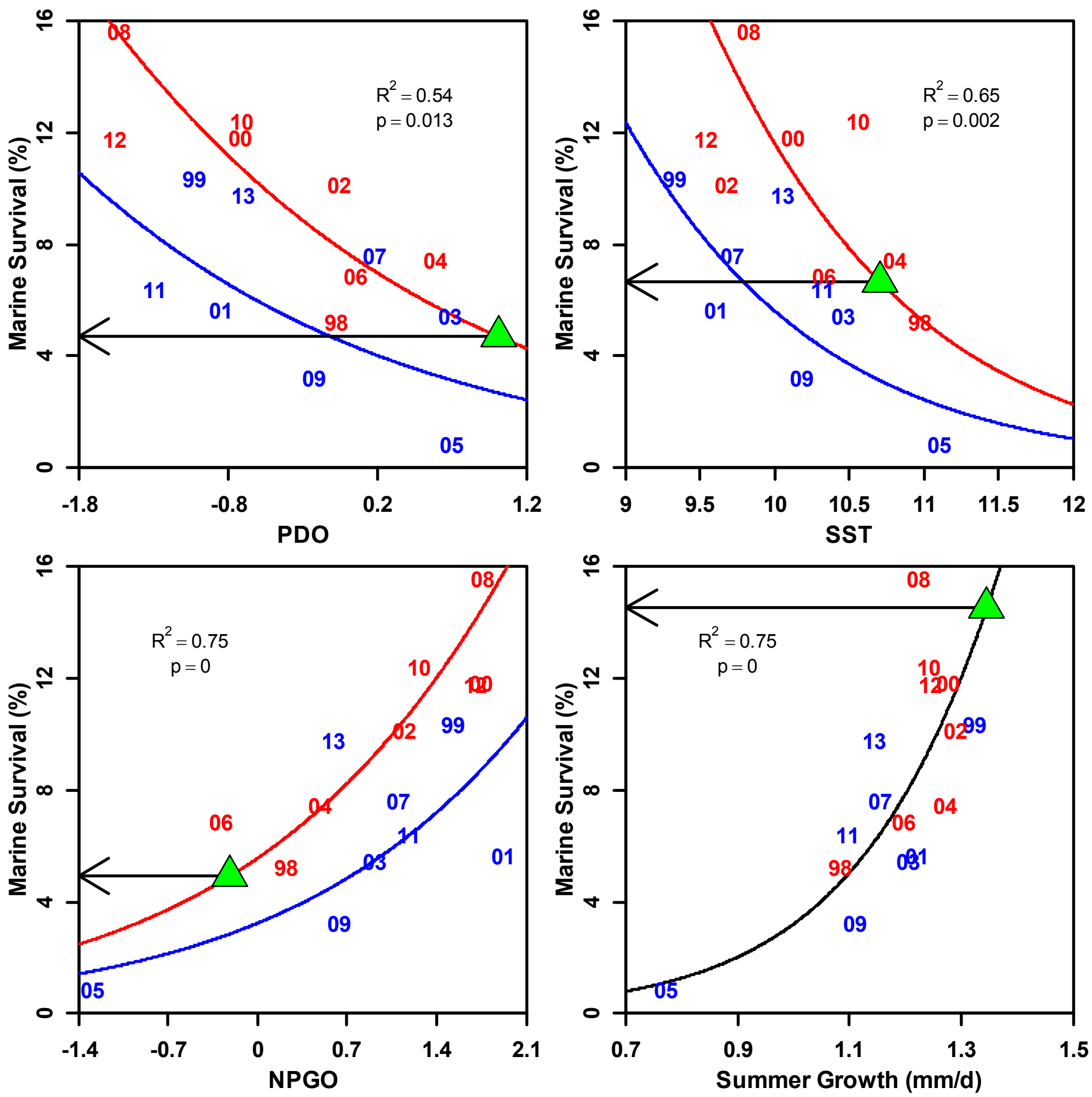

Figure 23-2. Correlations between survival of Robertson Creek Coho Salmon smolts with the Pacific Decadal Oscillation (PDO; May-September average), sea surface temperature off Amphitrite Point on the west coast of Vancouver Island (SST; March-June average), North Pacific Gyre Oscillation (NPGO; May-September average), and juvenile Coho Salmon growth off the west coast of Vancouver Island (May-October). The numerical symbols represent the ocean entry year. Odd years are in blue, even years are in red. The green triangle represents the predicted value for the 2014 ocean entry year.

23.3. References

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24. SMALL-MESH BOTTOM-TRAWL SURVEYS WEST OF VANCOUVER ISLAND: UPDATE FOR 2014

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24.1. Highlights

- Smooth Pink Shrimp biomass in Areas 124 and 125 in 2014 was the highest observed since the surveys began in 1973 (almost twice as high as the previous maximum).
- Among the “well-sampled” fish taxa, Walleye Pollock and Pacific Halibut also had record high biomass in this survey in 2014.
- The composition of the “well-sampled” taxa show changes which correspond to the regime shifts described for the NE Pacific from 1970 to 1990, and further changes in the 2000’s, most recently between 2006-2009 and 2010-2014.

24.2. Summary

Fishery-independent bottom trawl surveys using a small-mesh net (targeting the Smooth Pink Shrimp *Pandalus jordani*) have been conducted during May since 1973 in two regions, and since 1996 in three regions, off the west coast of Vancouver Island (Figure 24-1). The survey masks for these regions, over which the total biomass of each species has been estimated, generally occur between the 100 m and 200 m isobaths for Areas 124 and 125.

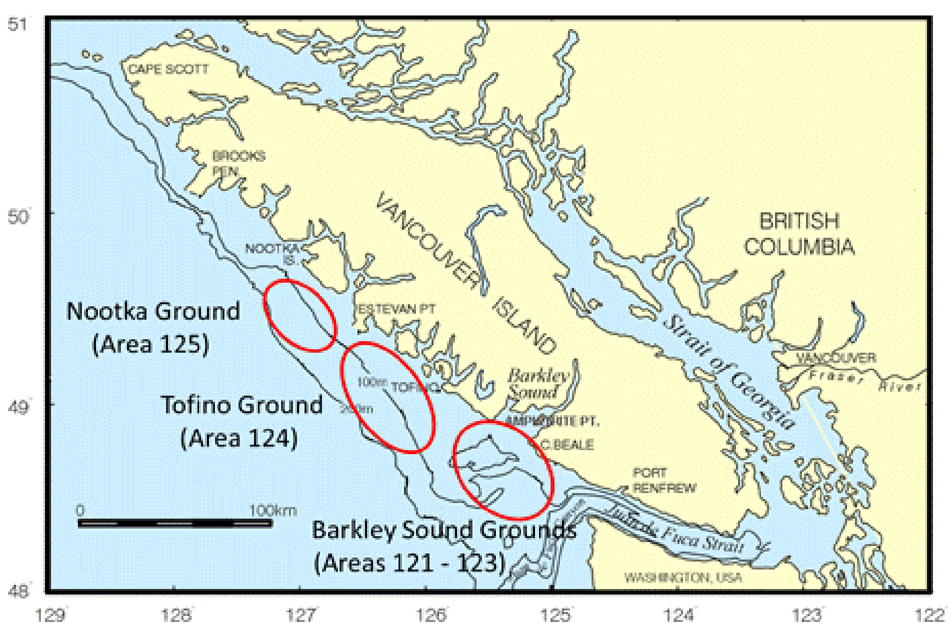

Figure 24-1. Map showing the three main shrimp (Pandalus jordani) fishing grounds and survey areas off Vancouver Island (red ovals). The Nootka (Area 125) and Tofino (Area 124) Grounds are the northern and middle ovals, respectively, and have been surveyed since 1973. The southern oval represents the shrimp fishing grounds off Barkley Sound, surveyed since 1996.

This small-mesh bottom trawl survey was designed to target Smooth Pink Shrimp on the shrimp fishing grounds in a relatively small area off the west coast of Vancouver Island. The interannual variability of biomass estimates of other taxa caught along with Smooth Pink Shrimp depends on whether these other taxa are highly mobile in and out of the survey area or are highly patchy in their distribution. An autocorrelation analysis indicates that of the 36 taxa regularly sampled and identified to species on this survey, 16 of them appear to be well-sampled (i.e. have positive autocorrelations of at least a one year lag; Table 24-1). Of those species shown in Figure 24-2, all are well-sampled by this survey gear except for Spiny Dogfish, Pacific Hake, and English Sole.

Table 24-1. List of 'core' species which have been sampled and identified routinely during these small mesh surveys since 1973 and for which annual biomass estimates are calculated. Taxa in black are those with significant (p<0.05) autocorrelations and which are therefore considered to be "well-sampled" by this survey.

Pelagics	Demersals		Benthics
Pacific hake	Silvergrey rockfish	Pacific cod	Sea mouse
American shad	Darkblotch rockfish	Sablefish	Heart urchin
Pacific herring	Green rockfish	Lingcod	Sea urchins
Eulachon	Yellowtail rockfish	Ratfish	Sea cucumber
Dogfish	Boccacio	Smooth pink shrimp	
Walleye pollock	Canary rockfish	Dover sole	
	Redstripe rockfish	Pacific sanddab	
	Pacific Ocean perch	Petrale sole	
	Arrowtooth flounder	Rex sole	
	English sole	Flathead sole	
	Pacific halibut	Slender sole	
	Yelloweye rockfish	Spot Prawn	

Blue taxa names represent no significant autocorrelations

Surveys in May 2014 found the biomass of *Pandalus jordani* shrimp off central Vancouver Island at a record high level, about twice the previous high observed in 1976 (Figure 24-2). The biomass of Pacific Halibut, English Sole, and Walleye Pollock was also at record high levels, with Walleye Pollock (*Theragra chalcogramma*, a cold water species) almost twice as high as previously observed (Figure 24-2).

Smooth Pink Shrimp biomass in a given year is weakly related to the mean spring (April, May, June) sea surface temperature at Amphitrite Point on the west coast of Vancouver Island two years previously [regression of shrimp biomass (yr = i) versus SST (AMJ yr = i-2): $R^2 = 0.24$, $P<<0.01$]. The regression is improved by including Pacific Hake biomass measured during these surveys in May in the current year (yr = i). The analysis conducted in 2014 (Perry et al. 2014) used Amphitrite SST data from spring 2012 and 2013 and the relationship between SST and Smooth Pink Shrimp biomass to estimate potential trends in shrimp biomass for 2014 and 2015. The

observed shrimp biomass in May 2014 was well-outside the projected range of variability for 2014, but in the right direction (an increase from the biomass in 2013; Figure 24-3). The majority of this increased shrimp biomass was composed of age 1 males, with proportions of 0.34 and 0.62 in 2014 compared with 0.06 and 0.10 for 2008-2013 for Areas 124 and 125, respectively.

Based on the well-sampled taxa, survey years from 1973 to 2014 were clustered to identify years with similar taxonomic compositions, using a chronological clustering method. Results indicate seven clusters, with one outlier year (2002). The largest composition change separated 1996 and prior years from 1997 and subsequent years (Figure 24-4). Note that, whereas 2014 clustered with years 2010-2013, it did so only weakly. The previous year which clustered at a similar weak level was 2001, after which significant composition changes occurred.

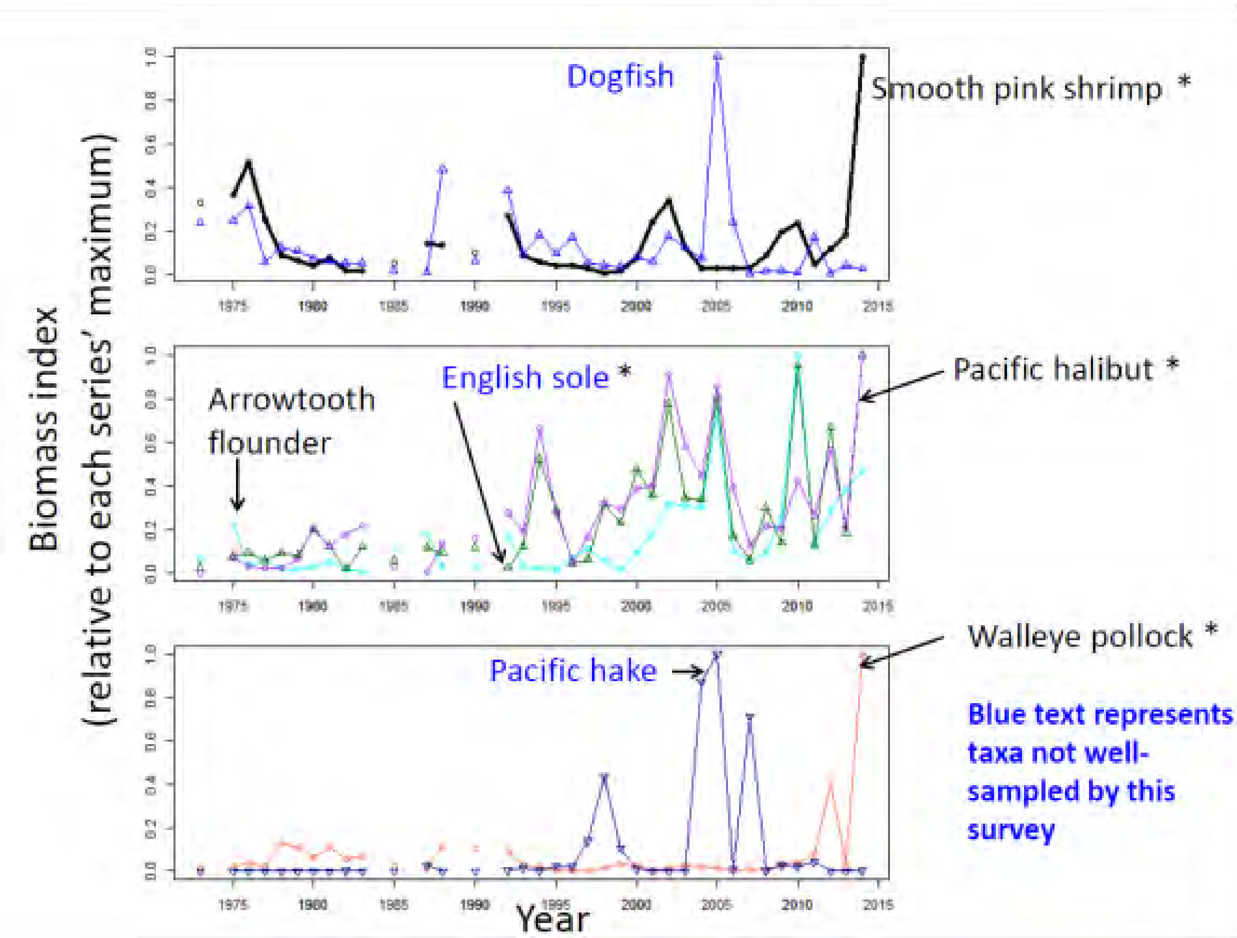

Figure 24-2. Time series of normalised (to maximum biomass) survey catches in Areas 124 and 125 of Smooth Pink Shrimp, Spiny Dogfish, Pacific Halibut, Arrowtooth Flounder, English Sole, Pacific Hake and Walleye Pollock. Sampling was conducted in May of each year. Blue text identifies those taxa believed to be not well-sampled by the survey, based on an autocorrelation analysis. Asterisks represent species for which a new maximum biomass was observed in 2014.

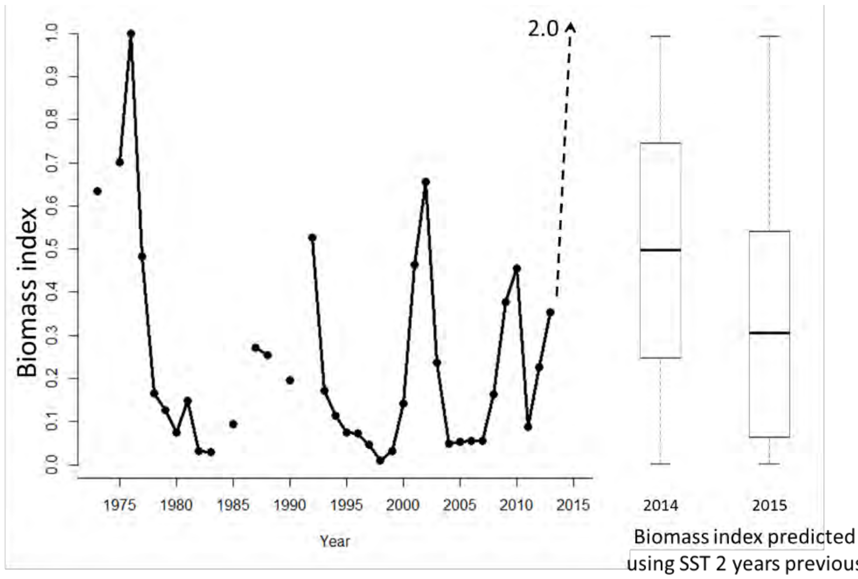

Figure 24-3. Time series of normalised (to maximum biomass in 1976) survey catches in Areas 124 and 125 of Smooth Pink Shrimp (left graph). On the right are projections (as boxplots; horizontal bar represents the median estimate) of the biomass of Smooth Pink Shrimp based on a regression with mean sea surface temperature at Amphitrite Point (west coast Vancouver Island) in April, May and June two years previously (2014 projections based on SST from 2012; 2015 projections based on SST from 2013). Dashed line points to the shrimp biomass index observed in 2014.

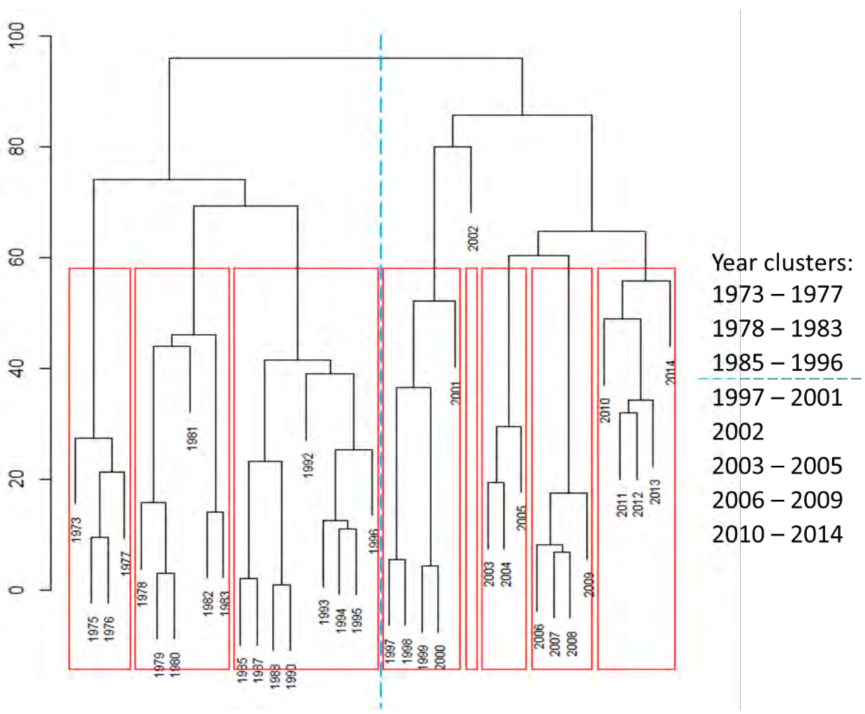

Figure 24-4. Dendrogram of years and clusters based on biomasses of well-sampled taxa (black font taxa in Table 24-1) using a chronological clustering method. The largest break separated clusters in 1996 and prior years from 1997 and subsequent years. Sampling was conducted in May of each year.

24.3. Conclusions from this analysis are the following:

- Smooth Pink Shrimp biomass in Areas 124 and 125 in 2014 was the highest observed since the surveys began in 1973 (almost twice as high as the previous maximum). This is likely a result of cooler waters in 2012 and 2013 (Pink Shrimp have a 2-yr lag from hatch to recruitment at age-2). Most of this high biomass was of one year old shrimp, with a higher proportion in Area 125 (Nootka Ground) than in Area 124 (Tofino Ground);
- among the well-sampled fish taxa, Walleye Pollock and Pacific Halibut also had record high biomass in this survey in 2014 (note Walleye Pollock is considered a cool water species). English Sole, considered to be not-well sampled by this survey, was also at a new maximum biomass;
- species composition of the “well-sampled” taxa in 2014 clustered weakly with the composition during 2010-2013, suggesting that biomass composition may be changing;
- the composition of the “well-sampled” taxa show changes which correspond to the canonical regime shifts described for the NE Pacific from 1970 to 1990, and further changes in the 2000’s, most recently between 2006-2009 and 2010-2014;
- the largest composition change occurred between 1996 and 1997.

24.4. References

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25. SOCKEYE SALMON INDICATOR STOCKS – REGIONAL OVERVIEW OF TRENDS, 2014 RETURNS, AND 2015-2016 OUTLOOK

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25.1. Highlights

- SST and ENSO indices in the Pacific remained negative to neutral in 2011-2013 so Columbia River (principally Okanagan) and west coast Vancouver Island Sockeye (principally Barkley Sound) Salmon marine survivals are likely to remain near their all-year average for the 2011-2013 sea-entry years (i.e. 2013-2015 adult return years). Returns of Barkley and Okanagan sockeye are anticipated to remain well above their all-year averages in 2015 due to increases in fry and smolt production associated with lake residence in 2011-2012 (i.e. 2012 and 2013 sea-entry).
- Conditions on the continental shelf at the time of sea entry by juvenile salmon in 2014 remained survival-favourable for adult returns expected in 2016 but are likely to be highly unfavourable in 2015 (i.e. adult returns beginning in 2017) for sockeye making ocean entry from the south to central coast of B.C.
- Impacts of elevated sea temperatures on sub-adult salmon in offshore waters through all of 2014 may be expressed through impacts on maturation rate (i.e. age at maturity), size-at-age (i.e. reductions possible) or return timing to terminal marine areas and fisheries in 2015.

25.2. Summary

Studies by Mueter et al. (2002a, 2002b) and Pyper et al. (2005) suggest associations between Pacific salmon survival and coastal environmental variables (upwelling index, sea surface temperature [SST], and sea surface salinity [SSS]) are strongest at local spatial scales (<500 km intervals) for adjacent stocks and exhibit little to no co-variation at scales larger than 1000 km. Correlation scales for SST in summer most closely matched the correlation scales for salmon survival. Regional averages of SST appeared to be better predictors of survival than large-scale measures of SST variability (e.g. the Pacific Decadal Oscillation, Mueter et al. 2002b). Regional-scale variations in coastal SST's may reflect processes causing co-variation in survival rates of neighbouring stocks. Thus, neighbouring stocks may exhibit stronger similarities in survival and production variations than widely separated stocks. In addition, geographical overlap of salmon species during freshwater and early marine life stages appear more important in determining shared environmental effects on survival rates than life history differences between species (Pyper et al. 2005).

Comparisons of forecasts and observed returns of Sockeye Salmon for major rivers and fisheries in B.C. have been completed annually by DFO for decades (Figure 25-1). Given the observations above, production trends for major sockeye populations or stock aggregates (i.e. "indicator stocks") may reflect environmental changes and production

trends for other salmon species originating from coastal-areas constituting separate production domains. Trend comparisons (1970-2013) among sockeye indicator stocks permit the following generalizations:

- Return variations are large with maximum annual returns at 10-90 times minimum returns.
- Maximum returns for all Sockeye indicator stocks from the North Coast to the Fraser occurred in the early 1990s in association with a powerful 1989 La Niña event 2-3 years earlier. Similarly, a major La Niña in 2008 was followed in 2010/11 by record to near-record returns of Sockeye to Vancouver Is. (Barkley), Fraser R. (Chilko), and Columbia R. (Okanagan), reversing a trend for several years of sub-average returns (Figure 25-1).
- As anticipated earlier (Hyatt et al. 2011, 2012), southern Sockeye stocks, with sea-entry into the northern California Current upwelling domain (Okanagan, Barkley sockeye) exhibited rapid rebuilding (2009-2013) to record (Okanagan) or near record (Barkley) returns in 2014, i.e. the decadal-scale, geographically-widespread, production-decline of Sockeye from southeast Alaska to southern B.C., reported by Peterman and Dorner (2012), is over.
- By contrast, Transboundary (Tahltan, Tatsamenie) and North Coast (Nass, Skeena) stocks continued a decadal-scale, average (Transboundary) to sub-average return trend (Nass Skeena) through 2014.
- Although there are several examples in each Sockeye indicator series for which observed returns diverged greatly from pre-season forecasts (Figure 25-1), the latter commonly anticipate decadal-scale trends within each of their six coastal production domains of origin. Returns for all stocks in 2014 were generally close to pre-season expectations.
- SST and ENSO indices in the Pacific remained negative to neutral in 2011-2013 so Columbia River (principally Okanagan) and west coast Vancouver Island Sockeye (principally Barkley Sound) Salmon marine survivals are likely to remain near their all-year average for the 2011-2013 sea-entry years (i.e. 2013-2015 adult return years). Returns of Barkley and Okanagan sockeye are anticipated to remain well above their all-year averages in 2015 (panels 5 and 6 in Figure 25-1) due to increases in fry and smolt production associated with lake residence in 2011-2012 (i.e. 2012 and 2013 sea-entry).The 2014-2015 North Pacific warming documented elsewhere in this report, represents a rare event that lies outside of the range of our direct observations of how salmon might respond but the weight of evidence is that such conditions will reduce B.C. salmon production rather than increase it.
- The issue of precisely when salmon abundance will be affected is less certain. Observations of exceptionally warm offshore waters in the North Pacific throughout 2014 and of warming of inshore waters by late June were associated with biological signals that reflected an ambiguous mixture of “cold ocean” spring conditions and “warm” ocean summer conditions along British Columbia’s continental shelf (various contributions elsewhere in the current report). However, by spring 2015, sea entry conditions for salmon in the south were associated with uniformly “warm” (El Nino-like) conditions.

- The weight of evidence indicates that salmon survival is determined primarily during the first several weeks after sea entry. Thus, for Sockeye and Chinook salmon from B.C.'s south coast, conditions for sea entry were ambiguous in 2014 affecting adult returns expected in 2016 and then highly unfavourable in spring 2015 for adult returns beginning in 2017.
- Persistent, sub-average marine survivals exhibited by sockeye indicator stocks originating from production domains on the Central Coast (Rivers & Smith Inlets), North Coast, and Transboundary (Tatsamenie, Tahltan) areas (Hyatt et al. unpublished observations) suggest total returns there will remain sub-average in 2013 through 2015.
- Setting aside effects on salmon survival, immediate effects of exceptionally warm offshore waters and associated reduced productivity through the summer, fall and winter of 2014-15 could drive a variety of changes to returns of all salmon species in 2015 including: reduced growth (which would show up as reduced size-at-age), changes in age-at-maturity (which given multiple ages-at-return could affect numbers for a given salmon species returning in 2015, 2016 or 2017), return routes (Lapointe et al. 2015) and/or return timing.
- Stock assessment biologists and fisheries managers use in-season observations of abundance-at-age (inferred survival) and abundance-by-week (inferred timing) to develop an informed opinion of whether a given return will follow a pre-season forecast or deviate greatly from it.
- Potential influence of these very warm conditions on traits of salmon noted above will make interpretation of the correct meaning of in-season observations for harvest management of 2015 and 2016 salmon returns very challenging.

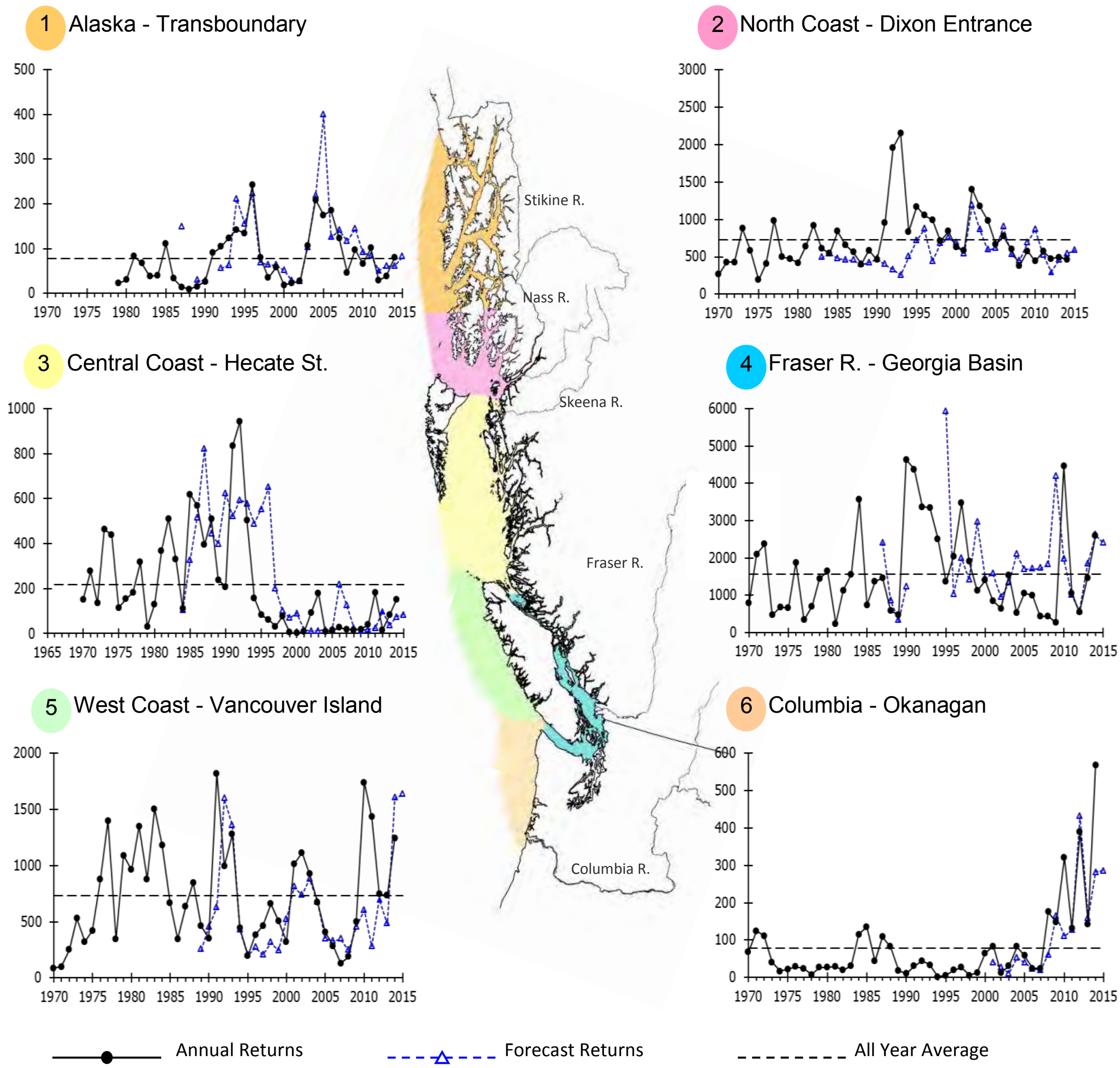

Figure 25-1. Trends in the total returns and forecasts for British Columbia sockeye index stocks including: 1. Tahltan, 2. Nass, 3. Smith's Inlet, 4. Chilko, 5. Barkley Sound, and 6.Okanagan sockeye salmon. Y-axis represents returns in thousands of fish.

25.3. References

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26. GEOGRAPHIC AND SEASONAL DISTRIBUTION OF HUMPBACK, FIN AND BLUE WHALES OFF SOUTHWESTERN VANCOUVER ISLAND

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26.1. Highlights

- Multi-year systematic aerial surveys off southwestern Vancouver Island were conducted from September 2012 to March 2015. The data collected suggest mostly discrete distribution differences, particularly between Humpback Whales, which were observed most often on the continental shelf, and Fin Whales and Blue Whales, which were sighted in deeper water westward of the shelf
- Survey effort was concentrated in fall and winter. Fin Whale sightings were recorded in most months with surveys carried out from the slope of the continental shelf westward over the abyssal plain. In contrast, Humpback Whales, considered a highly migratory species, were sighted in greatest numbers in the fall on the continental shelf off southwestern Vancouver Island.

26.2. Introduction

Large whale species occupy shelf-break regions that frequently coincide with shipping lanes. Southwestern Vancouver Island includes a large shelf-break region that coincides with the shipping traffic approaches to Juan de Fuca Strait. This shipping corridor connects to Port Metro Vancouver, one of the largest ports on the west coast of North America, as well as to the ports of Seattle and Tacoma, WA. Vessel collisions with whales are a significant anthropogenic source of mortality for several species including Blue, Fin, and Humpback Whales (Laist et al. 2001, Jensen and Silber 2004). Ship strikes resulting in mortalities to these species have been reported from British Columbia, Washington and California (Gregr et al. 2006, Douglas et al. 2008, Ford et al. 2009).

Assessing the extent of ship strike risk requires an understanding of whale distributions in the vicinity of shipping corridors. To assess the distribution of whale species off southwestern Vancouver Island, replicate systematic line transect surveys were conducted from 2012 to 2015 over a 40,000 km^2 region that included the entrance to Juan de Fuca Strait, the continental shelf, the shelf edge and slope, and the abyssal plain. The resulting data reveal spatial and seasonal distribution patterns among Blue, Fin and Humpback Whales off southwestern Vancouver Island.

26.3. Methods

To systematically survey such a large area that extends so far offshore, surveys were made from a twin-engine DeHavilland Canada DHC-8-102 *Dash 8* aircraft operated by Transport Canada's National Aerial Surveillance Program. This aircraft is custom fitted with a large window on either side of the aircraft from which dedicated observers recorded sightings. The study area was divided into survey blocks and transects within each (Figure 26-1). Surveys followed these transects as the plane flew at 1000 ft and a speed of 150 knots. Each survey lasted two to three hours which was sufficient time to complete one survey block, although visibility at times resulted in two or more partial blocks comprising a three hour survey.

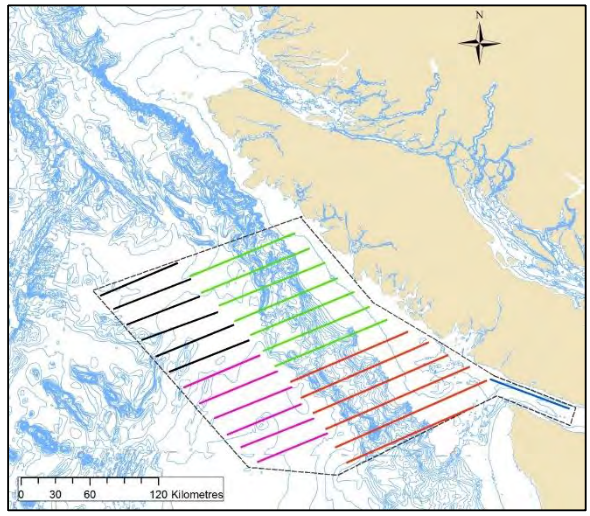

Figure 26-1. The study area (dashed line) was divided into five survey blocks, each displayed by one of five colours. Each block had 6 to 7 transect lines, except western Juan de Fuca Strait which had only one transect due to the size of the area. Transect lines indicate the shoreward extent and seaward extent of survey effort.

26.4. Results and Discussion

Thirty-four surveys were flown from September 2012 to March 2015 with survey effort concentrated in the fall and winter (82% of surveys) (Figure 26-2). Prior to these surveys, there were few whale distribution data for the region offshore of southwestern Vancouver Island, except historical whaling catch data that ended in the late 1960s.

Thirteen species of cetaceans were recorded on these surveys including Blue, Fin and Humpback Whales (Table 26-1). These new survey data reveal distinct differences among these three species in both their seasonal and spatial distributions off southwestern Vancouver Island (Figure 26-3). Sightings of Humpback Whales, which are considered a highly migratory species, peaked in the fall off southwestern Vancouver Island after which they were much less frequently encountered. Presumably this was because most animals had migrated to winter breeding grounds in Hawaii and Mexico (Ford et al. 2009).

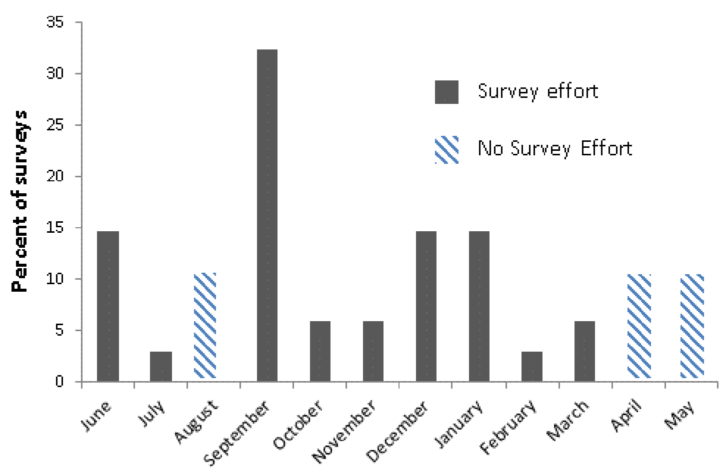

Figure 26-2. Seasonal distribution of survey effort, all effort from 2012 to 2015 combined (n = 34 surveys). Months with blue diagonal stripes indicate that no survey was conducted.

The aerial survey data indicate Fin Whales, were present fairly evenly through the survey period, a pattern that is consistent with recent acoustic monitoring in the study area (Ford et al. 2010) and with re-analysis of historical survey and tagging data. This evidence suggests that Fin Whales may be only weakly migratory in the North Pacific (Mizroch et al. 2009). Sightings of Blue Whales were the least common of these three species, but the sightings in summer and winter were consistent with acoustic presence based on passive acoustic monitoring data, off southwestern Vancouver Island (Burtenshaw et al. 2004). Acoustic monitoring data from La Perouse Bank, which is on the shelf of southwestern Vancouver Island and from Union Seamount, located over the abyssal plain, are consistent with the pattern of occurrence of these three species suggested by the aerial survey data (Figure 26-3 and Figure 26-5).

Table 26-1. Cetacean species observed during surveys September 2012 to March 2015.

Species	**Number of Individuals**
Blue whale	5
Fin whale	190
Humpback whale	551
Minke whale	1
Grey whale	12
Sperm whale	18
Killer whale	50
Baird’s beaked whale	12
Pacific white-sided dolphin	1073
Northern right whale dolphin	804
Risso’s dolphin	692
Harbour porpoise	23
Dall’s porpoise	73
Cuvier’s beaked whale	12

The survey data also suggest relatively discrete spatial distribution patterns. Humpback Whales were observed mostly on the continental shelf whereas Fin Whales and Blue Whales were predominantly sighted on the continental slope and over the abyssal plain. All three species, however, overlapped spatially particularly in the continental slope region in the vicinity of Nitinat and Barkley Canyons (Figure 26-5). The strength of these apparent seasonal and spatial distribution patterns will be further examined using spatial habitat modelling techniques.

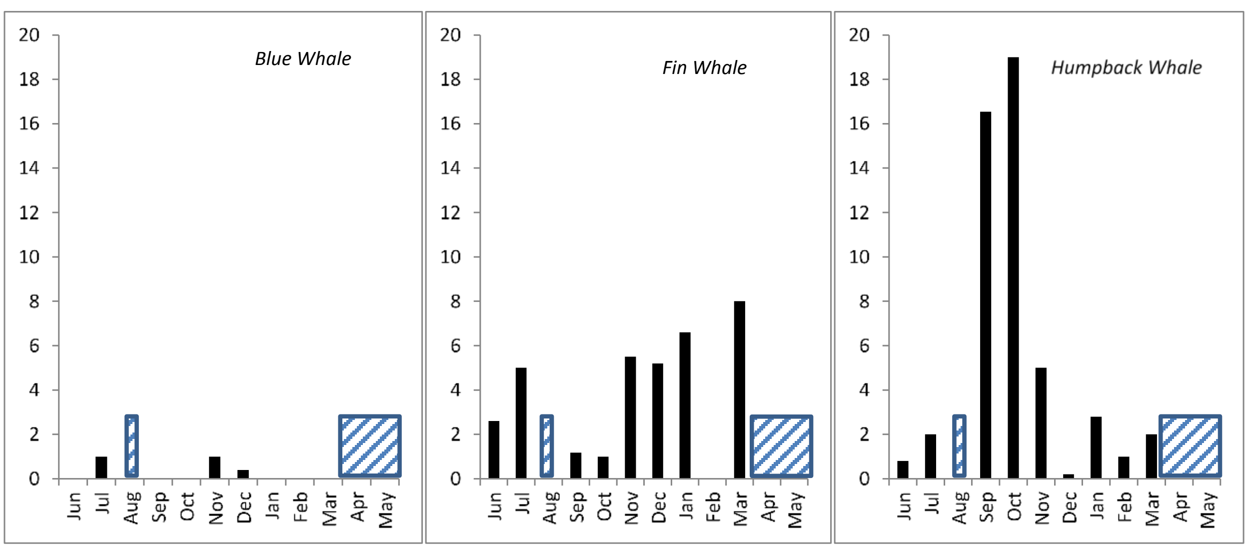

Figure 26-3. Number of sightings per survey grouped by months, all years combined, black bars = sightings, striped bars = no survey effort.

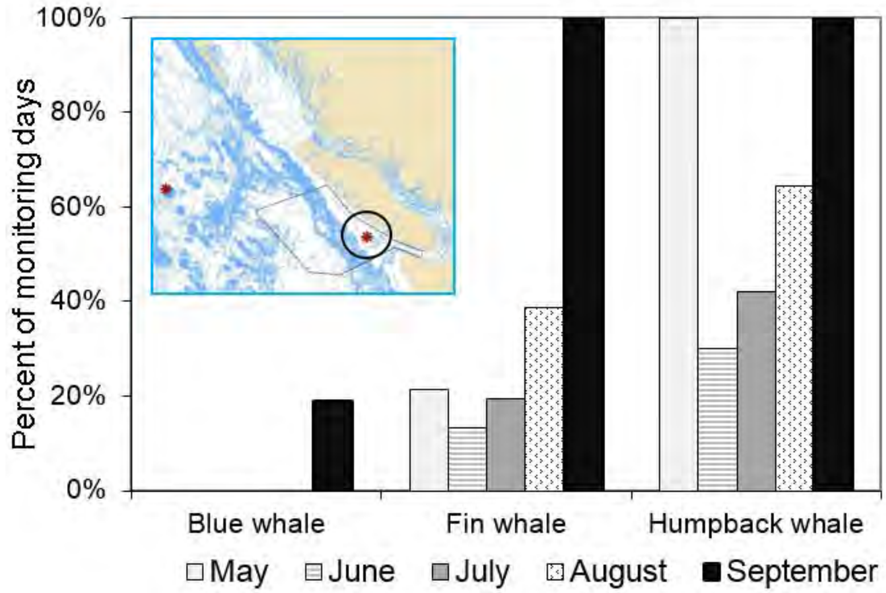

Figure 26-4. Seasonal presence of Blue, Fin and Humpback Whales at La Perouse Bank acoustic monitoring station from May through September 2007, based on the percent of monitoring days each species was heard each month. (adapted from Ford et al. 2010). Inset map shows location of the acoustic monitoring station (circled red symbol) and the study area (dashed polygon).

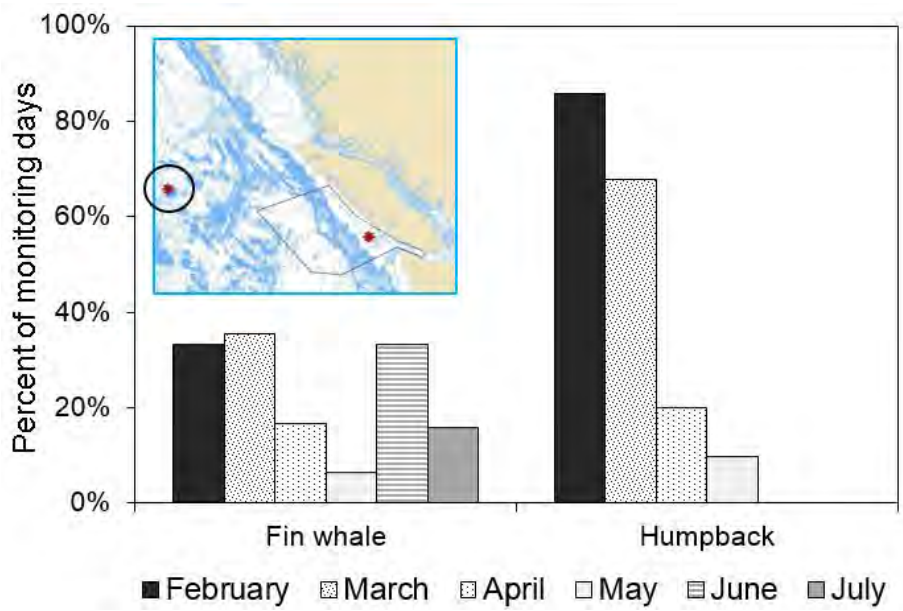

Figure 26-5. Seasonal presence of Fin and Humpback Whales at Union Seamount acoustic monitoring station from February to July 2006, based on the percent of monitoring days each species was heard each month. (adapted from Ford et al. 2010). Inset map shows location of the acoustic monitoring station (circled red symbol) and the study area (dashed polygon).

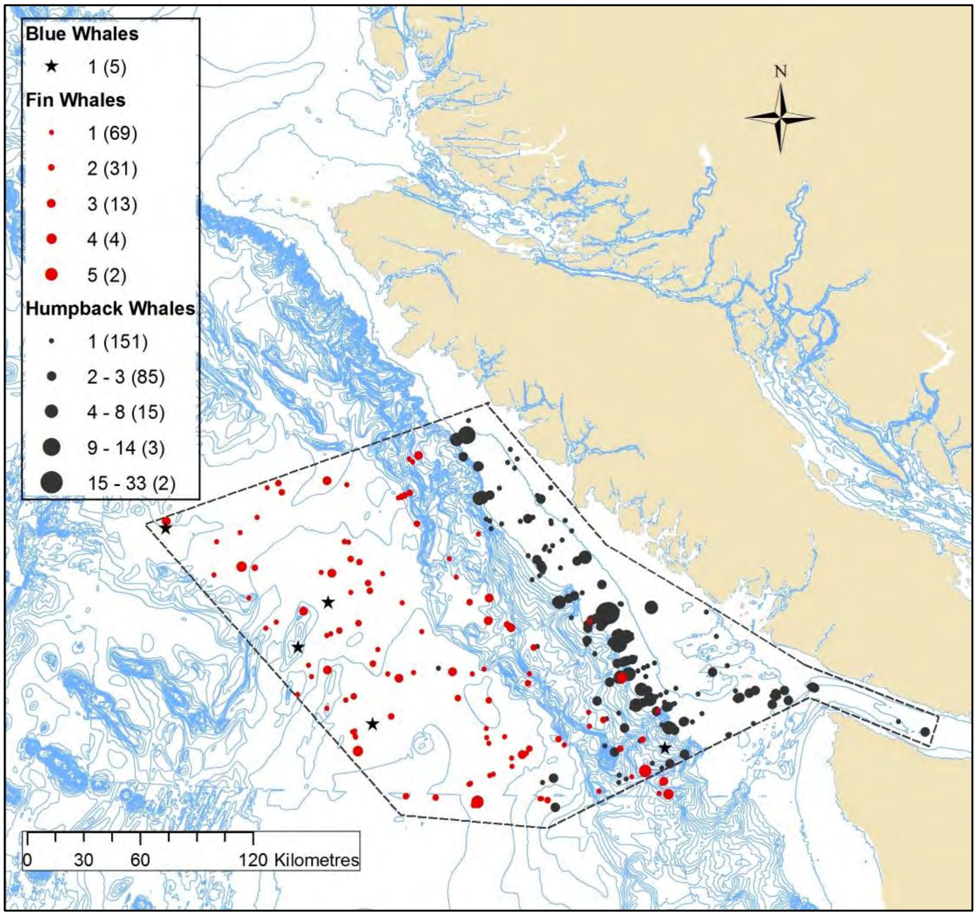

Figure 26-6. Distribution of all sightings of Blue, Fin and Humpback Whales in the study recorded on aerial surveys in the study area (dashed line) from September 2012 to March 2015. Circle sizes represent the number of animals sighted, numbers in brackets are the number of sightings.

26.5. Acknowledgements

We thank the following for their assistance on surveys or with analysis, R. Abernethy, G. Ellis, L. Flostrand, B. Gisborne, S. Majewski, C. McMillan, P. O'Hara, J. Pilkington, L. Spaven, H. Sohn, E. Stredulinsky, J. Towers, B. Wright, Transport Canada's National Aerial Surveillance Program (NASP) and Environment Canada's Marine Aerial Reconnaissance Team (MART). These surveys were made possible with funding and support from: the InterDepartmental Recovery Fund (IRF), the Strategic Program for Ecosystem-Based Research and Advice (SPERA), DFO's Species at Risk Program, Transport Canada's National Aerial Surveillance Program (NASP), and Port Metro Vancouver (PMV).

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27. OBSERVATIONS ON SEABIRDS ALONG THE OUTER COAST

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27.1. Highlights

- Cassin's Auklets had a banner breeding season in 2014 on the world's largest colony at Triangle Island, off the northwest tip of Vancouver Island.
- Strong production on B.C. colonies in recent years was undoubtedly a key demographic factor underlying the extreme mortality event that befell Cassin's Auklets in fall and winter 2014/15.
- In general, conditions for breeding by marine birds on Triangle Island have been very good since 2007-2008, with the notable exception of 2010.
- Juvenile salmon continues to be an increasingly important prey item for Rhinoceros Auklets breeding on Pine Island, in Queen Charlotte Strait.

27.2. Growth rates of Cassin's Auklet nestlings

Like other breeding parameters, growth rates of Cassin's Auklet (*Ptychoramphus aleuticus*) nestlings are very strongly affected by oceanographic conditions, which have a profound influence on seasonal patterns of prey availability. In general, nestling auklets grow more quickly on Triangle Island, the world's largest breeding colony, in cold-water years when the copepod *Neocalanus cristatus* persists in their diets through the bulk of the provisioning period from May to July (Hipfner 2008). In general, growth rates (gauged by 25 day masses) have been above average on Triangle Island in every year since 2007, with the notable exception of 2010; the 2014 season was particularly productive (Figure 27-1).

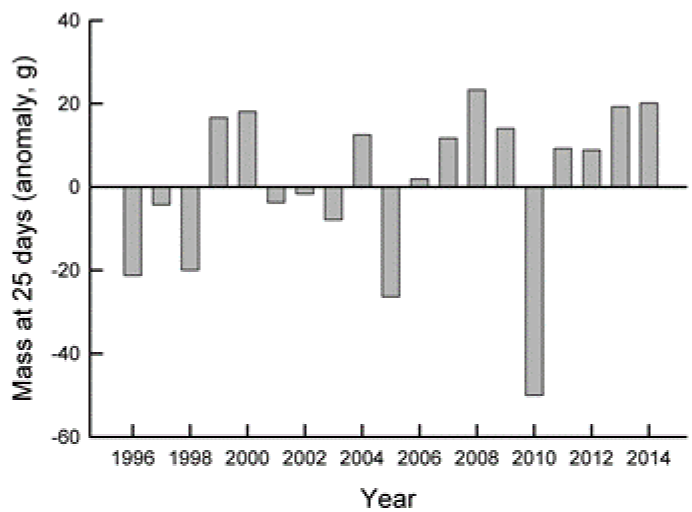

Figure 27-1. Yearly anomalies of mean 25 day mass (a proxy for growth rate) of nestling Cassin's Auklets on Triangle Island, B.C., in 1996-2014.

This recent period of strong production on the very large B.C. colonies, combined with the tendency for auklets from these colonies to disperse widely along the Pacific coast outside of the breeding season, was undoubtedly a key demographic factor underlying the massive, coast-wide (California to B.C.) mortality event that befell the auklets in fall and winter 2014/15. Similar mortality events, although of smaller magnitude, have occurred in previous years, notably in 1997-1998, and in 2005. Unlike the 2014/15

event, however, neither of these earlier events was preceded by a period of strong production.

27.3. Salmon in Rhinoceros Auklet diets

Pacific salmon (*Oncorhynchus* spp.) have an anadromous life-cycle, spending a few months to 2 years in freshwater, followed by 1-4 years at sea where they fall prey to a variety of fish, mammals and birds. Mortality rates during the marine phase of the life cycle of Pacific salmon generally exceed 90%, and it is widely believed that most mortality is due to predation in the first few weeks to months following ocean entry (Beamish & Mankhen 2001). On their northerly seaward migration, the vast majority of Pink Salmon (*O. gorbuscha*), Chum Salmon (*O. keta*) and Sockeye Salmon (*O. nerka*) smolts from stocks in southern and central British Columbia funnel past aggregations of hundreds of thousands of Rhinoceros Auklets (*Cerorhinca monocerata*) breeding on colonies scattered along the province's Central and North coasts. The auklets are wing-propelled, pursuit-diving seabirds that forage mainly in the top 5-10 m of the water column and within ~90 km of their breeding colonies. The smolts' migration occurs in June and July, coinciding with the period when the auklets are delivering whole and intact fish, including salmon smolts, to their nestlings.

Scientists with Environment Canada and the Fisheries and Oceans Canada have been quantifying predation by Rhinoceros Auklets on salmon smolts since 2006, and some clear patterns have emerged. First, there is marked temporal and spatial variation in the importance, and species and stock composition, of salmon in nestling diets. In general, salmon is most important, and in fact has been increasingly so, at Pine Island, in Queen Charlotte Strait; in 2014, salmon was present in nearly 50% of meals delivered during the sampling period at this location (Figure 27-2). Salmon has been less important, and less variable at Lucy Island, in Chatham Sound in northern

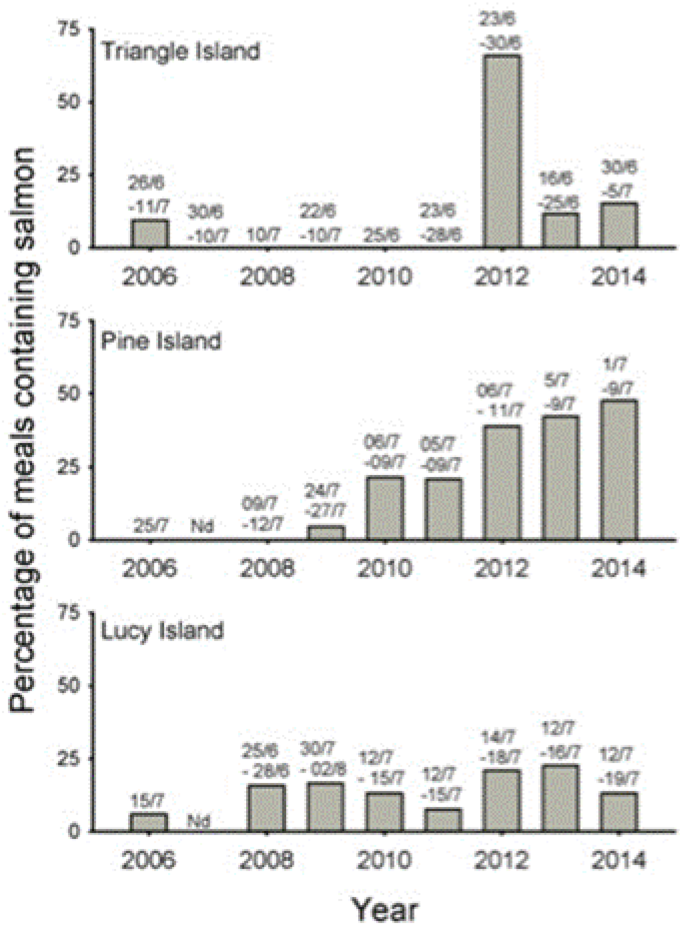

Figure 27-2. Percentage of meals delivered to nestling Rhinoceros Auklets that included one or more salmon (pink, chum, or sockeye) on 3 colonies in B.C., Triangle, Pine and Lucy Islands, in 2006-2014. Dates of sampling (day/month) are indicated above the bars.

B.C., and was only important at Triangle Island in 2012; notably, the salmon component consisted almost entirely of Fraser River sockeye.

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Individual reports on inside waters (including the Strait of Georgia)

28. CENTRAL COAST OCEAN CONDITIONS: HAKAI INSTITUTE

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28.1. Highlights

- Warm conditions occurred in spring 2015, with sea temperatures greater than 1.5 ^{o}C warmer than in spring 2014.
- The spring bloom occurred one month later in 2014 (approximately 15 April) than 2013 (approximately 15 March).
- The buildup of summer zooplankton biomass was similarly delayed by approximately 5 weeks in 2014 compared to 2013.

28.2. Summary

As the inaugural contribution of the Hakai Institute to annual State of the Pacific Oceans report, we briefly outline the institute's ocean monitoring program.

The Hakai Institute launched its first oceanographic monitoring program from its Central Coast research station on Calvert Island in July 2012. After an initial focus on Kwakshua Channel, separating Hecate and Calvert islands, oceanographic monitoring was expanded in 2013 to include the outer coast (Queen Charlotte Sound), the inside passage (Fitz Hugh Sound) and the mainland fjord Rivers Inlet (Figure 28-1). In 2014 and 2015, Hakai Institute monitoring was expanded to include the northern Strait of Georgia and Discovery Islands (as of late 2014), and Johnstone Strait (as of April 2015).

The mandate of Hakai Institute's oceanographic monitoring program is to provide year round long-term monitoring of ocean conditions, while also providing data for a suite of focused research programs. Core oceanographic data collected are conductivity, temperature, nutrients, phytoplankton biomass and size structure, zooplankton biomass and size structure, and the isotope chemistry of these lower trophic level groups. Sampling is conducted year round at all locations. The frequency and spatial coverage of sampling are seasonally modulated, and are most intense (daily to weekly) between spring and fall.

In this report we present data from Pruth station in Kwakshua Channel, Calvert Island, from 2013, 2014, and spring 2015. After the cold spring conditions in 2014 (< 7 ^{o}C through the entire water column in February / March) dramatically warmer conditions are being experienced in spring 2015 (> 8.5 ^{o}C through the entire water column in February / March) (Figure 28-2). The 2015 spring conditions are attributed to the onshore movement of a warm pool ("the blob") that developed in the northeast Pacific in 2013 and moved onto the B.C. shelf in late summer of 2014 (Whitney 2015).

Phytoplankton biomass measurements showed a one month shift in spring bloom timing, from approximately 15 March in 2013 to approximately 15 April in 2014 (Figure 28-3). The delayed bloom in 2014 was associated with cooler ocean conditions and stronger spring winds. The buildup of summer zooplankton biomass was delayed by approximately 5 weeks in 2014, peaking first in the second week of May, compared to the first week of April in 2013 (Figure 28-4). Despite the delayed zooplankton bloom in 2014, summer biomass accumulation exceeded that in 2013.

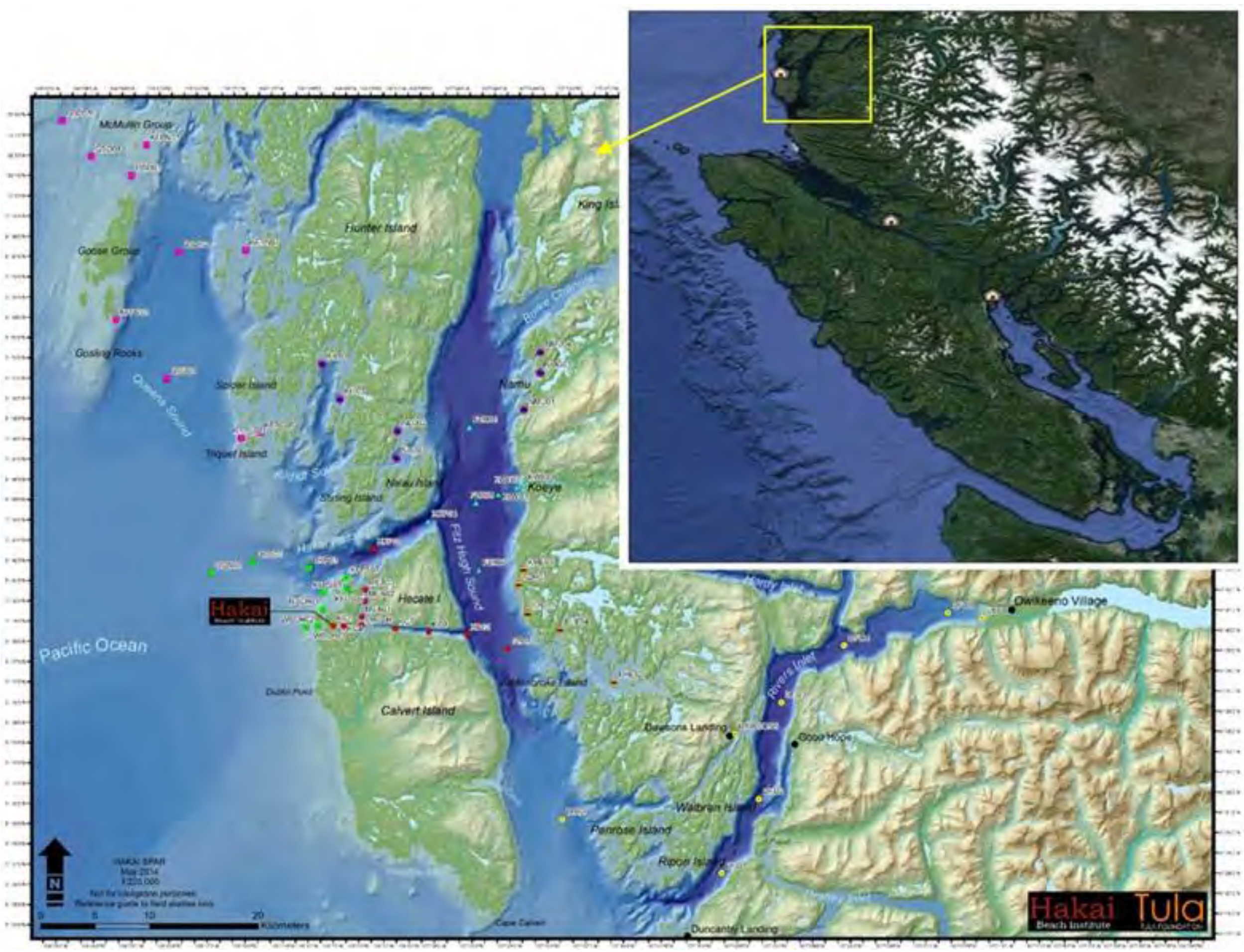

Figure 28-1. (Map Insert) Location of Hakai Institute oceanographic monitoring nodes at Calvert Island, Quadra Island and Johnstone Strait. (Main Map) Hakai Institute Central Coast oceanographic monitoring stations.

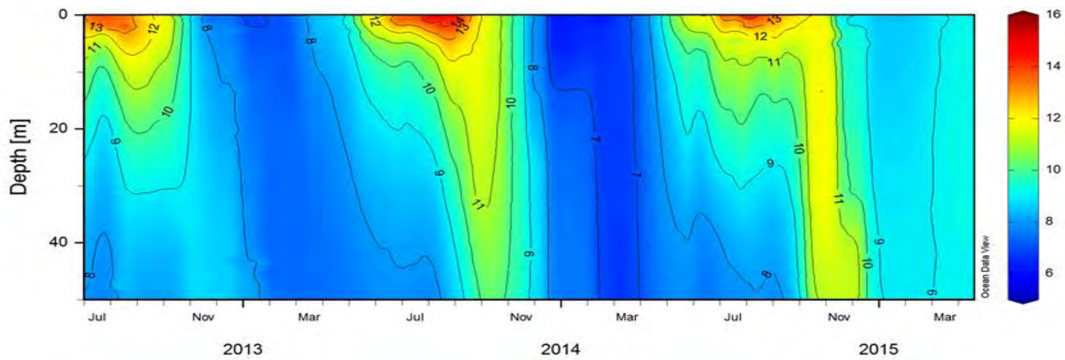

Figure 28-2. Temperature (°C) profiles collected in the upper 50m of the water column at Pruth station, from 14 July 2012 to 2 April 2015. Between 15 March and 15 October of each year profiles are daily.

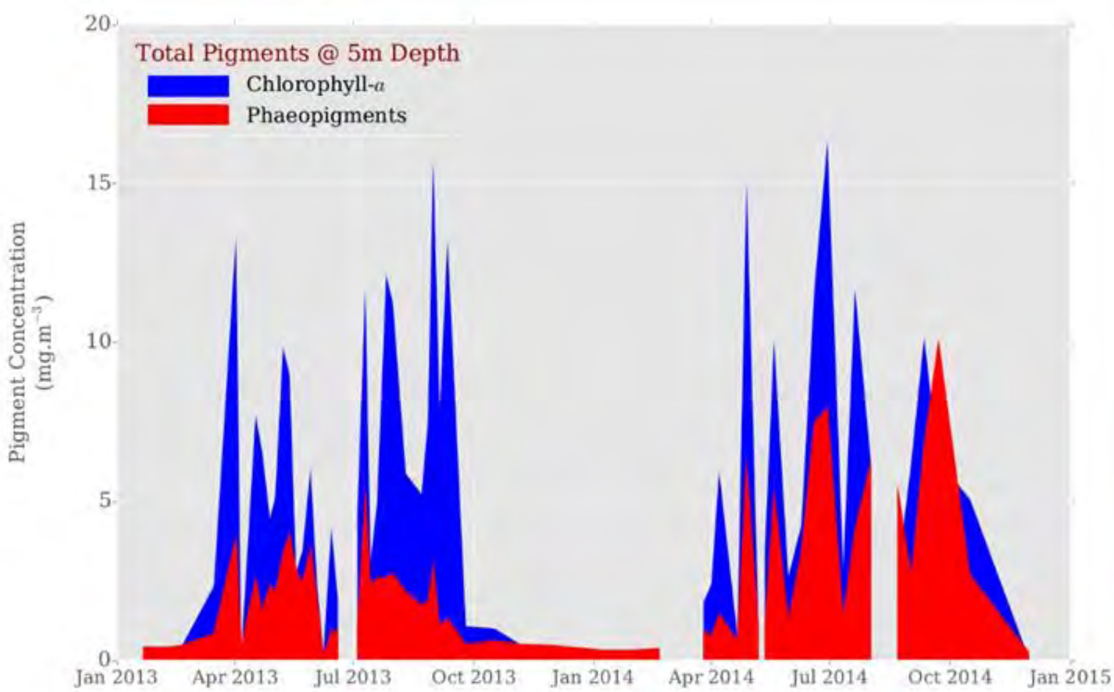

Figure 28-3. Chlorophyll a and phaeopigments (mg.m^{-3}) measured fortnightly at 5m depth at Pruth station in 2013 and 2014.

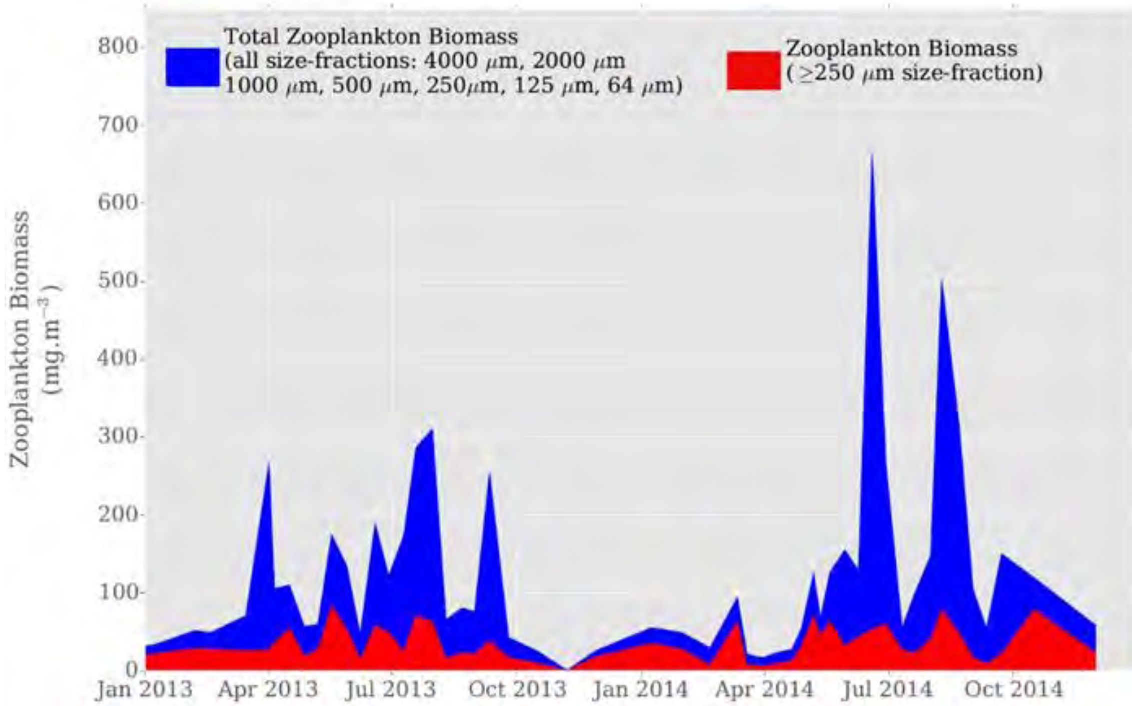

Figure 28-4. Zooplankton dry weight biomass (red, from 250 µm mesh net) and total seston dry weight biomass (blue, from 64 µm mesh net) from fortnightly bongo nets, hauled vertically through the entire water column (70 m deep) at Pruth station in 2013 and 2014.

28.3. Acknowledgements

Oceanographic sampling and data management are made possible by Hakai Institute staff, with special thanks to the Ray Brunsting, Bryn Fedje, Matt Foster, Wayne Jacob, Skye McEwan, Lawren McNab, Nelson Roberts and Adam Turner.

28.4. References

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29. OXYGEN IN DOUGLAS CHANNEL, JULY 2013 – JULY 2014

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29.1. Highlights

- Dissolved oxygen in Douglas Channel is controlled by physical circulation, primary production and remineralization of organic matter
- Deep-water oxygen was low (≥ 2.5 mL/L) in spring 2013, but not hypoxic (<1.4 mL/L)
- Deep-water renewal in June 2013 increased the concentration of oxygen by ~ 1 mL/L, while in June 1978 the renewal decreased the concentration of oxygen in deep water. Was one of those years anomalous, or have oxygen dynamics in this area changed since 1978?

29.2. Study area and initiation of time series

In June 2013, we initiated physical and geochemical time series in southeastern Hecate Strait and Douglas Channel, including rosette sampling of water properties along a transect of Douglas Channel and deployment of moorings at one site in Hecate Strait and two sites in Douglas Channel (Figure 29-1). We reoccupied the water sampling stations in April, July and October of 2014. The moorings were recovered and redeployed in July 2014. Both the HEC1 and FOC 1 moorings included moored oxygen sensors 10 m above the bottom, but the HEC1 oxygen sensor failed in the first year. The data have been compiled by Wright et al. (2015) and interpreted in a geochemical context by Johannessen et al. (2015).

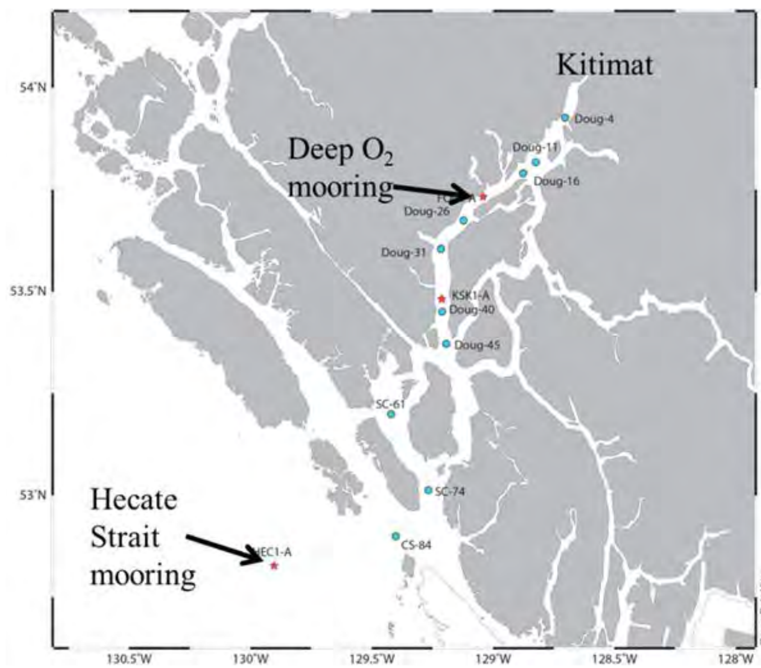

Figure 29-1. Study area and sampling locations (modified from Wright et al. 2015). Blue dots represent Hecate Strait and Douglas Channel sampling sites, June-July 2013, April 2014, July 2014, October 2014. Red Stars represent mooring sites. The oxygen sensor on the FOC 1 mooring (indicated as "Deep O2 mooring") was moored at 336 m.

29.3. Dissolved oxygen by depth and season

In Douglas Channel, the largest seasonal range in dissolved oxygen occurred within the top 50 m. Oxygen was high in all seasons in surface water (uppermost 20-100 m, depending on location and season), ranging from 6 mL/L in July to 10 mL/L in April, due largely to high primary productivity. In July and October, the elevated oxygen was restricted to the uppermost ~ 20 m, associated with the brackish, outflowing surface water. Macdonald et al. (1983) observed a subsurface oxygen maximum just below the outflowing surface layer in 1978 associated with a subsurface chlorophyll maximum, but we did not observe that during 2013-2014 (Figure 29-2).

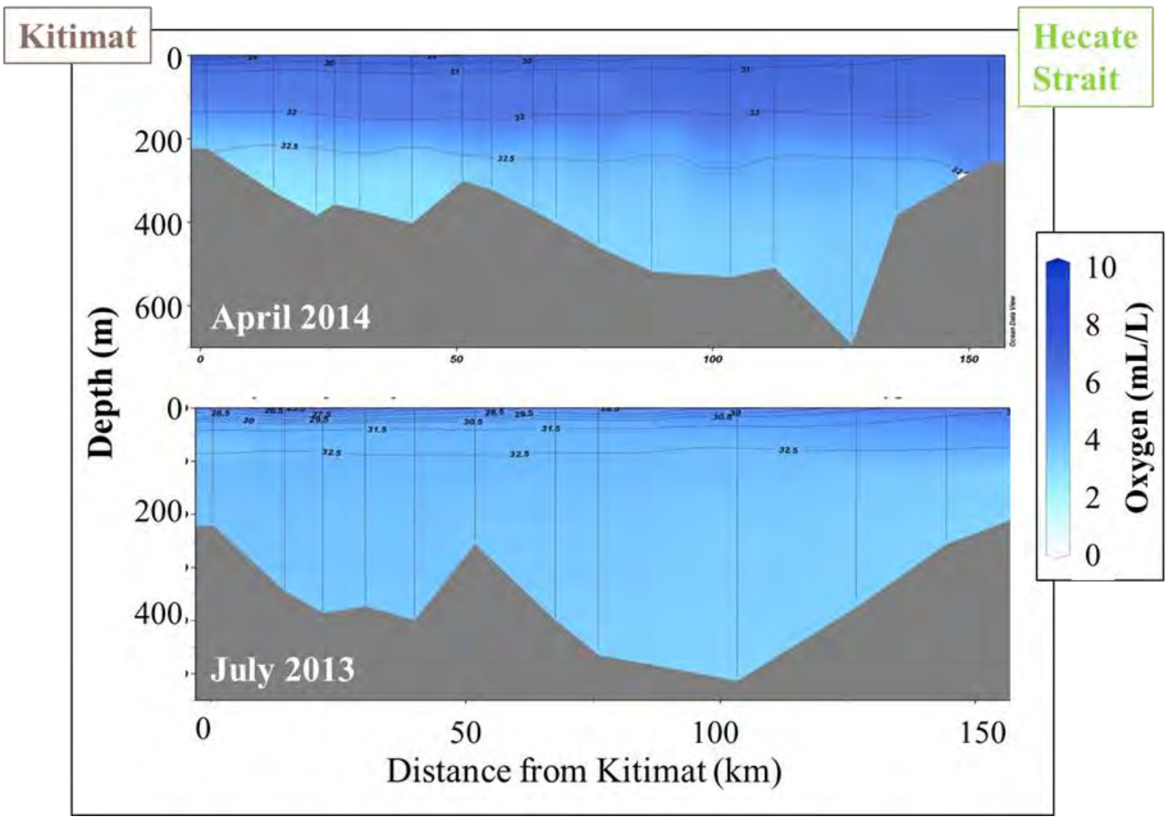

Figure 29-2. Concentration of dissolved oxygen in April 2014 and July 2013, along a transect of Douglas Channel from Kitimat to the entrance to Hecate Strait, overlain with salinity line contours.

The concentration of dissolved oxygen in the intermediate layer (50-200 m) was highest in April (4-7 mL/L), lowest in July (2.5-4 mL/L), and intermediate in October (3.5-4 mL/L). We lack a continuous record of oxygen concentration at mid-depths, but the temperature and salinity records indicate a tight coupling with water properties in Hecate Strait at mid-depth (Johannessen et al. 2015)

In the deep water (336 m sensor at station FOC1, "Deep O_2 mooring" site) the concentration of dissolved oxygen varied seasonally by about 1 mL/L (44.6 μmol/L), from a low of 2.5 mL/L in February - May to a high of 3.5 mL/L in mid-June (Figure 29-3). After the mid-June peak, there was a rapid decline of 0.7 mL/L by mid-August,

followed by a slower decline of 0.3 mL/L over the subsequent six months. The slow, six-month decline likely represented remineralization of organic matter in the bottom water, while the initial, rapid decline might have resulted either from rapid remineralization of a summertime pulse of organic matter, or else from diffusive mixing of more oxygen-depleted water from above. The total annual flux of organic carbon that reached the 50-m sediment traps at the same site was 37 gC/m^2 (Johannessen et al. 2015). Depending on how much of that carbon was remineralized before it reached the deep water, this flux could have been sufficient to support the observed consumption of oxygen. Research is continuing on this question.

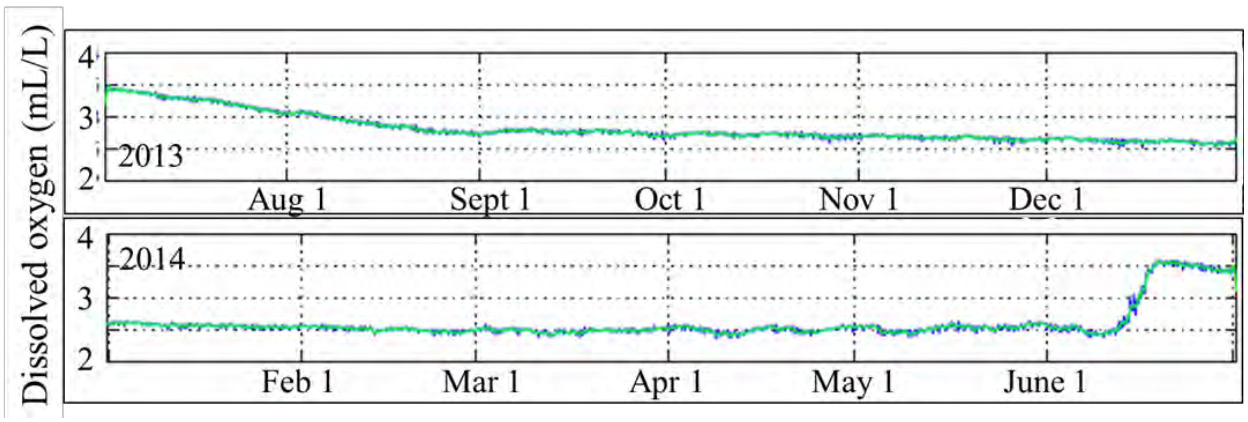

Figure 29-3. Concentration of dissolved oxygen measured hourly at 336 m at site FOC1 (Deep O2 mooring site), July 2013 – July 2014.

1.3. Deep-water renewal of oxygen

Deep-water renewal is not instantaneous throughout the fjord system but progresses along Douglas Channel over a period of several weeks (Macdonald et al., 1983), resulting in temporary pockets of low-oxygen water, such as that observed at the Kitimat end of the inlet in early July 2014 (Figure 29-2). In June 2014, about one week after relaxation of downwelling was observed at the Hecate Strait mooring, we observed a deep-water renewal in salinity, and temperature in the deep water of Douglas Channel at the KSK1 site. (There was no oxygen sensor at KSK1.) About a week after that, the renewal in temperature and salinity reached the FOC1 site, the deep oxygen mooring site, where it was also clearly apparent in the dissolved oxygen (Figure 29-4). The concentration of dissolved oxygen at FOC1 increased from 2.5 mL/L to 3.5 mL/L over 7 days.

In contrast, in June, 1978 Macdonald et al. (1983) observed that the June renewal reduced the concentration of oxygen in the deep water of the Strait by bringing in oxygen-depleted, upwelled water from the shelf. Between 1978 and 2014 subsurface oxygen has declined in coastal waters around the world, so if the upwelled water that replaced the Douglas Channel deep water in 2014 had come from the same depth as that observed in 1978, then we might have expected the 2014 renewal to decrease deep-water oxygen to an even lower concentration than it did in 1978. Since that was not the case, one possibility is that the replacement water in 2014 came from a

shallower depth, and was consequently less depleted in oxygen. The temperature and salinity data give some support to that interpretation: the salinity after replacement appears to have been about the same in the two years, while the temperature was higher in the 2014 water, making it less dense. The discrepancy remains to be resolved and is the subject of ongoing research. Unfortunately, in 2013-2014, the oxygen sensor in Hecate Strait failed, so we do not have a direct comparison of oxygen concentrations inside and outside the channel. In 2014, we deployed additional oxygen sensors at the entrance to Douglas Channel, and will add further sensors in the summer of 2015.

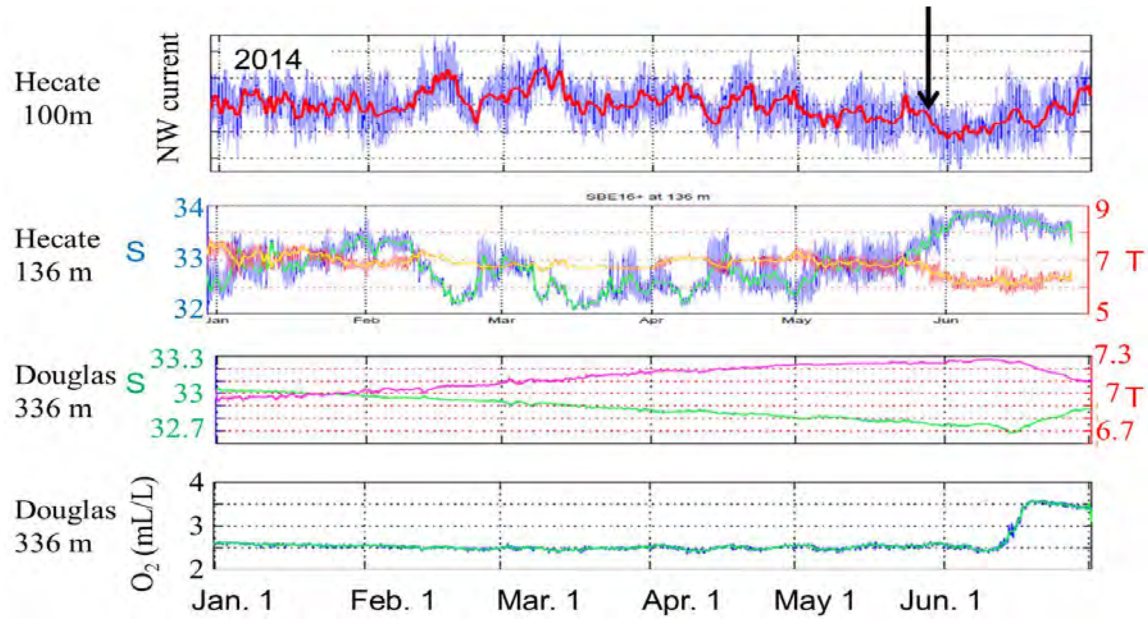

Figure 29-4. Deep-water renewal of oxygen in Douglas Channel and its initiation in Hecate Strait. Northwestward current at 100 m and temperature and salinity at 136 m (10 m above bottom) in Hecate Strait; temperature, salinity and oxygen at 336 m (10 m above bottom) at station FOC1 (Deep O2 mooring) in Douglas Channel. The arrow indicates the beginning of the relaxation of downwelling in Hecate Strait.

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30. FRESH WATER AND FRASER RIVER FLOW

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30.1. Highlights

- Fraser River discharge rates at Hope in 2014 were about average until May when a two month period of high flow volumes were observed. Discharge rates in early 2015 are well above normal and April flows are the highest in 104 years.
- The trend of increased flows earlier in the year and lower flows during the summer were reflected in the 2014 data.
- For the period January to May, the water temperature at Hope was about 1^{o}C warmer in 2015 than 2014. Temperatures in 2014 during the summer months were warmer than normal.
- Snowpack levels in southwestern B.C. were 50% of normal in early 2014, but became closer to normal as the season progressed. Early 2015 snowpack levels are as low as 25% of normal in April 2015.
- There was about a 7% increase in annual (2014) precipitation at Vancouver compared to the 30 year average.

30.2. Summary

The Fraser River drains a watershed of approximately 220,000 km^2, about one quarter of British Columbia, and accounts for about 65 percent of the fresh water in the Strait of Georgia. The timing and volume of the fresh water entering the Strait influences the mixing, stratification, and circulation in the central Strait as well as the estuarine exchange with oceanic shelf water. Other impacts include the growth and survival of out-migrating juvenile salmon and the behaviour of salmon when they return to the river to spawn.

The Water Survey of Canada (WSC) measures river elevations at Hope which are converted to flow using a calibrated stage-discharge relationship. The flow is highly seasonal; typically low in winter when precipitation is stored as snow, with peak flows in mid-June as fresh water is released from snowmelt. Several factors have been identified as contributing to the interannual variability of river runoff including warmer and wetter climactic weather associated with El Niño Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) patterns, as well as deforestation and glacier retreat.

Figure 30-1 shows that early in 2014 conditions were about average until a period of high flow in May and June. Late in 2014, November and December experienced high and variable discharge rates consistent with intense winter rain storms. The early months of 2015 show extremely high discharge volumes, setting new records in March and mid-April. Flow volumes in late-April 2015 were closer to average.

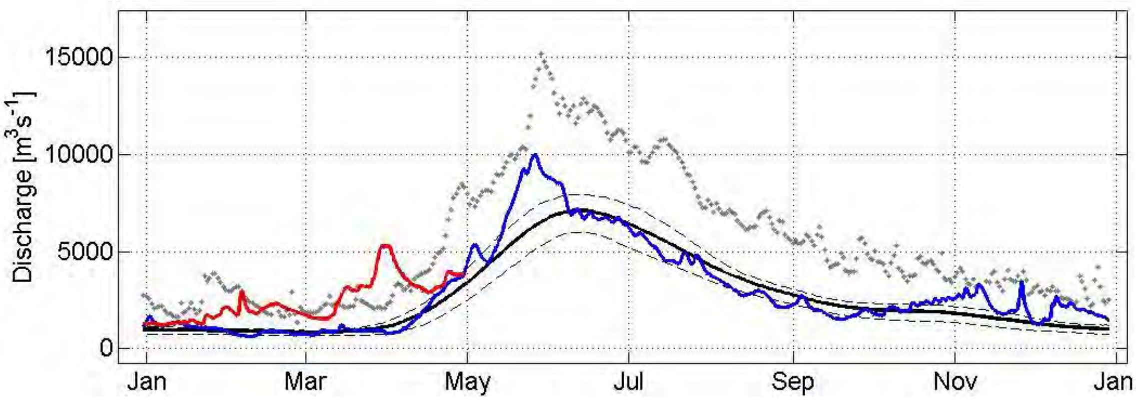

Figure 30-1. Fraser River discharge at Hope B.C.; 2014 (blue), 2015 (red). The solid black line represents the mean daily flow (1912-2015), with the 25% and 75% quartile shown as dashed lines. The maximum flow observed for each day of the year in the 104 year data set are shown as black dots. Data source: Water Survey of Canada.

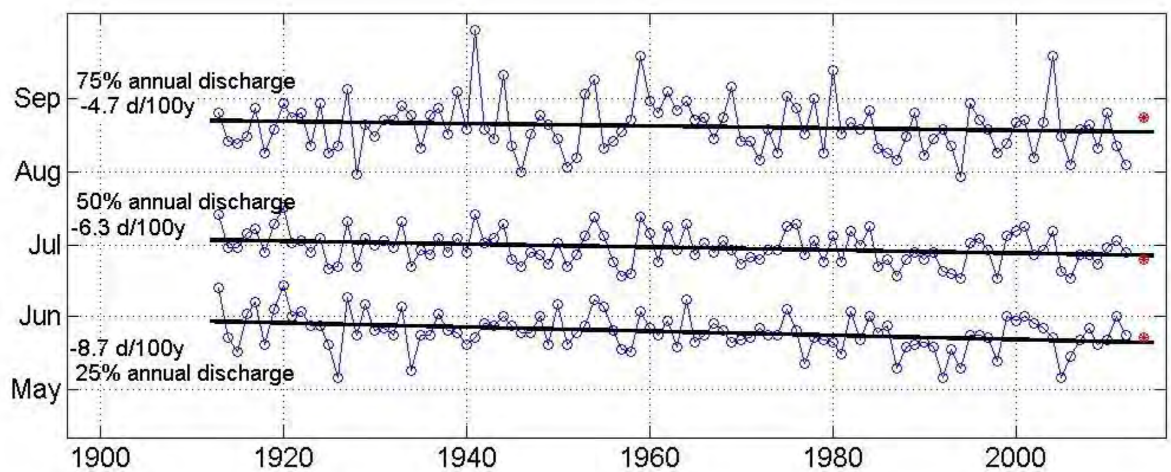

Figure 30-2. The day of year when the Fraser River discharge at Hope reaches 25%, 50% and 75% of its total annual discharge. The 2014 values are shown in red. A linear trend line is fitted to the 104 years of data. Data source: Water Survey of Canada.

The long-term Fraser River discharge data show a trend of more water being discharged earlier in the season; Figure 30-2 shows that 25% of the annual discharge passes Hope about 8 days earlier than it did 100 years ago. Similarly the 50% and 75% thresholds are occurring earlier than previously, but at a slower rate indicating a trend of lower discharge during the summer months. The 2014 conditions reflect these trends.

Since 2013, the Water Survey of Canada has measured the temperature of the Fraser River water at Hope. The 2014 and 2015 data are shown in Figure 30-3. Historical river water temperatures measured in the lower Fraser River are available only for the months when conditions are critical for spawning salmon, July to mid-September. Water temperatures in 2014 were above the long-term average for most of the spawning

season, but did not set any new records. Starting in February water temperatures observed in early 2015 have exceeded those observed in 2014.

Snowpack, expressed as snow water equivalent, is measured by B.C. River Forecast Centre throughout the province. Figure 30-4 shows the results of this monitoring combined for two regions; the lower Fraser River (1D) and the South Coast (3A). The blue shaded area illustrates the snowpack from 2010-2013 as being within the normal range; the blue line shows 2014 conditions which started the year as low but became closer to normal levels later in the season. The 2015 snowpack, shown in red, started the year about 50% of normal, and has steadily decreased. Generally warm and dry weather in the southern portions of the province, with precipitation falling as rain rather than snow, contributes to these low snowpack conditions.

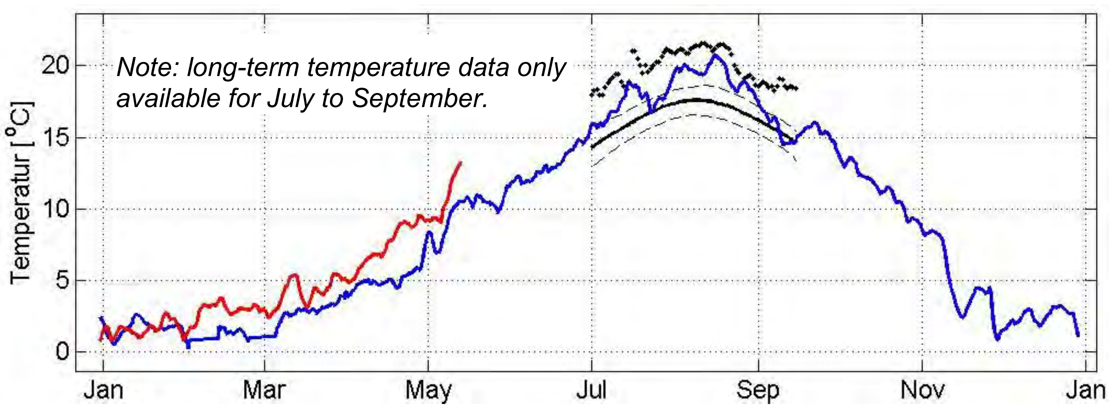

Figure 30-3. Fraser River water temperature at Hope B.C.; 2014 (blue), 2015 (red). The solid black line represents the mean daily temperature (1941-2013), with the 25% and 75% quartile shown as dashed lines. The maximum temperatures observed for each day of the year in the 73 year data set are shown as black dots. Data sources: 2014 and 2015 data from Water Survey of Canada; historical data measured at Hell's Gate and Qualark courtesy of John Morrison.

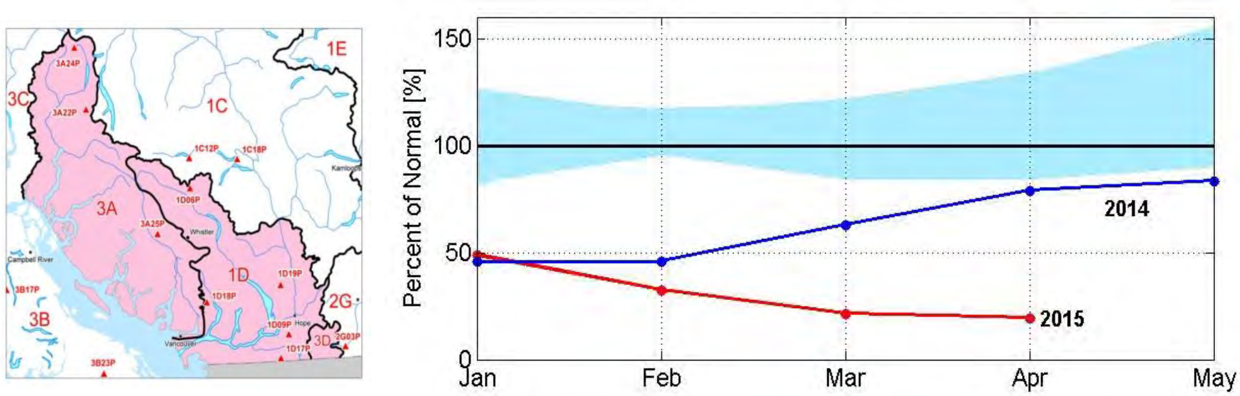

Figure 30-4. The snow basin (pink area shown in left panel) survey showing snow water equivalent as a percent of the normal (31 year average) conditions. The light blue shaded area shows the range of snowpack observed in 2010 – 2013. Data source: the B.C. Government River Forecast Centre.

The other source of fresh water to the coastal ocean is local precipitation. Data collected at Vancouver international Airport by Environment Canada are assumed to represent the precipitation regime in the southern Strait of Georgia. Figure 30-5 compares monthly precipitation in 2014 and 2015 to the climatology derived from 30 years of data (1981-2010). In 2014, above normal precipitation occurred in the spring (February and March) and October, and the summer months (June, July, and August) were drier than normal. Overall there was about a 7% increase in 2014 precipitation compared to the 30 year average.

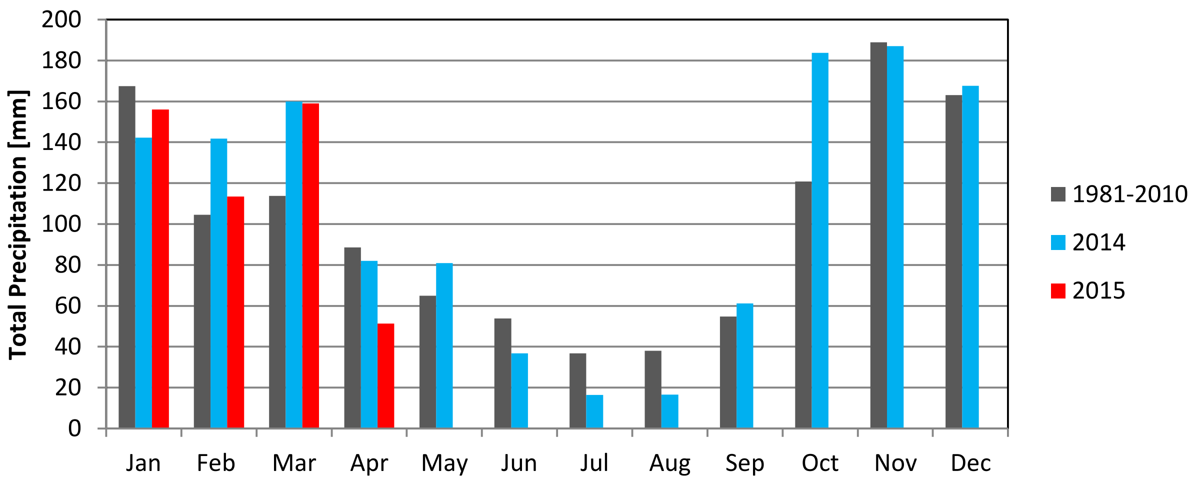

Figure 30-5. Monthly precipitation measured at Vancouver International Airport. Data source: Environment Canada.

30.3. References

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31. TEMPERATURE AND SALINITY OBSERVATIONS IN THE STRAIT OF GEORGIA AND JUAN DE FUCA STRAIT

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31.1. Highlights

- Salinity and temperatures patterns in the Juan de Fuca Strait and Strait of Georgia waters during early 2014 showed little variation from those observed in data collected since 2000.
- Warmer surface water, and greater stratification of water in the upper 100 m, was observed in the Juan de Fuca Strait starting in September.
- Observations in the central Strait of Georgia show temperature and salinity conditions similar to 2013 but warmer than normal surface waters later in the year.

31.2. Summary

Two sources of data are used to describe changes in the temperature and salinity conditions in the Strait of Georgia (east of Vancouver Island) and Juan de Fuca Strait (south of Vancouver Island) in 2014. The first is profile data collected with a SeaBird 911 CTD during the Strait of Georgia water properties surveys (Figure 31-1). In 2014 surveys were carried out in early April, mid-July, early September and a partial survey in late October. The second dataset is provided by the Department of National Defence from the 76 temperature and salinity profiles it collected in 2014 with a SeaBird 19 CTD at its Maritime Experimental and Test Range (CFMETR) near Nanoose. Both sources have information available since 2000 that are compared to the 2014 conditions to identify anomalies from these 14 year average conditions.

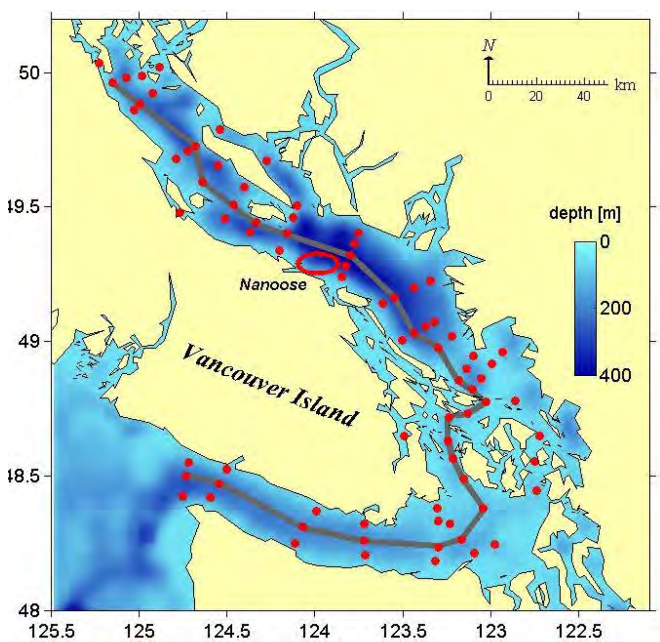

Figure 31-1. Red circles show the locations of 79 stations sampled during the water properties survey in April, June and September/October. The thalweg is shown as the grey line joining the deepest stations along the centerline of the survey. The red ellipse marks the area where depth profiles of temperature and salinity are collected at the Canadian Forces Maritime Experimental and Test Range (CFMETR).

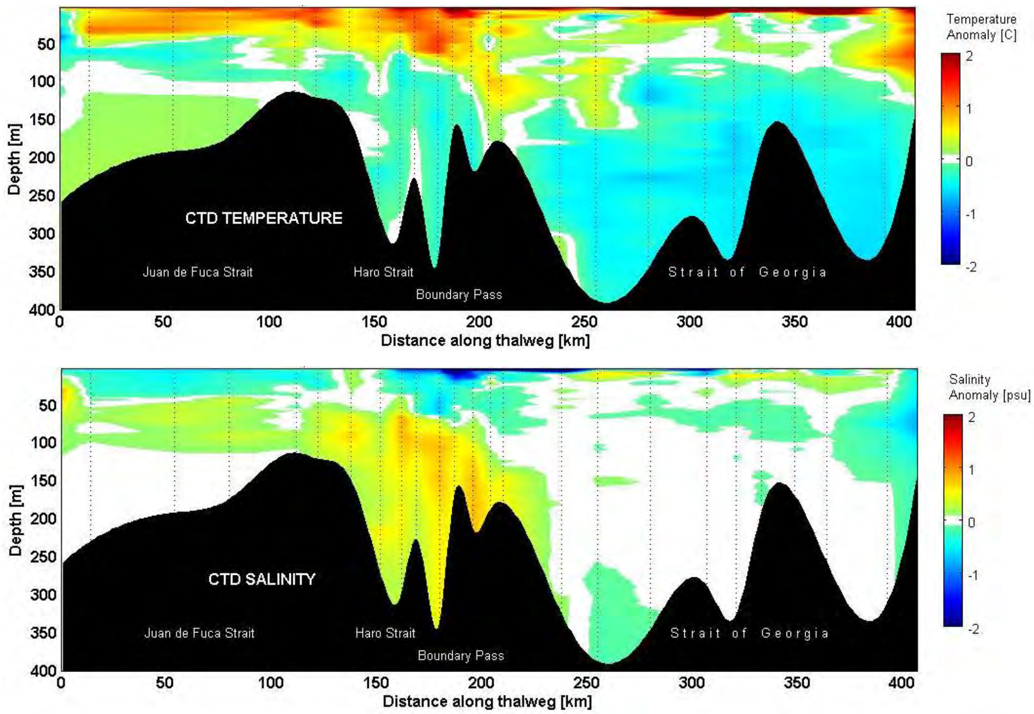

Figure 31-2. The vertical distribution of temperature (upper)and salinity (lower) anomalies along the thalweg observed in the September 2014 water properties survey.

The analysis of the water properties data for the April and June surveys showed near normal conditions. In the September survey (Figure 31-2), a layer of water warmer than normal was observed along the surface of the Juan de Fuca Strait, and a saltier than normal pool of water at depth was observed in the Haro Strait/Boundary Pass region.

The temperature and salinity depth profiles collected off Nanoose are presented in Figure 31-3 to show the annual variation in the central Strait of Georgia. Early in 2014, cold water at the surface overlaid warmer water at depth but as the year progressed this water sank and formed an intermediate depth layer with warmer water above and below it. The heating of the surface layer began in April.

The 2014 temperature and salinity anomalies from the 14 year dataset are shown in Figure 31-4. Early in 2014, positive surface salinity anomalies revealed a saltier surface layer than normal; late in the year the surface layer was fresher than normal; salinities at depth, and during the summer months showed near-normal salinity conditions. The temperature anomalies in the summer of 2014 show typical warm water events in the surface layer due to weather events. A deeper, and more persistent, warming was seen in the upper 100 m from October through the end of the year.

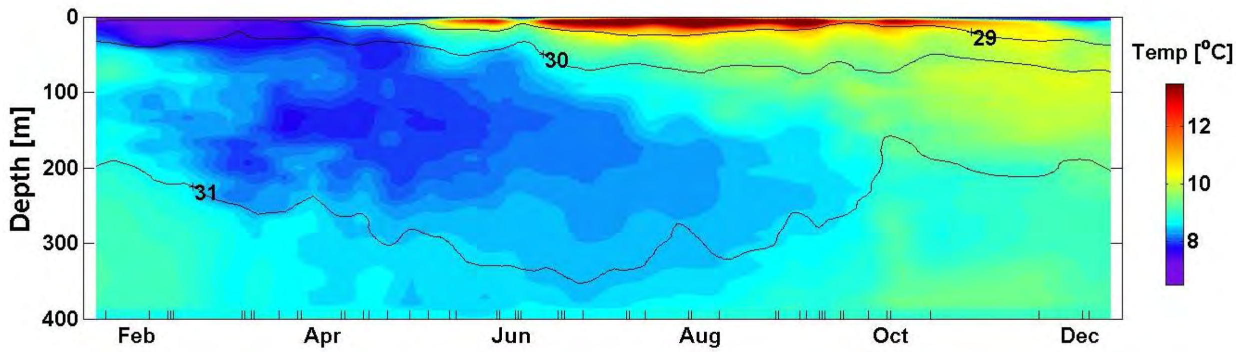

Figure 31-3. The vertical distribution of temperature during 2014 from data collected in the central Strait of Georgia near Nanoose. The ticks along the time axis indicate when the profiles were made. Black contours are lines of constant salinity in psu. Data source: The Canadian Forces Maritime Experimental and Test Range (CFMETR).

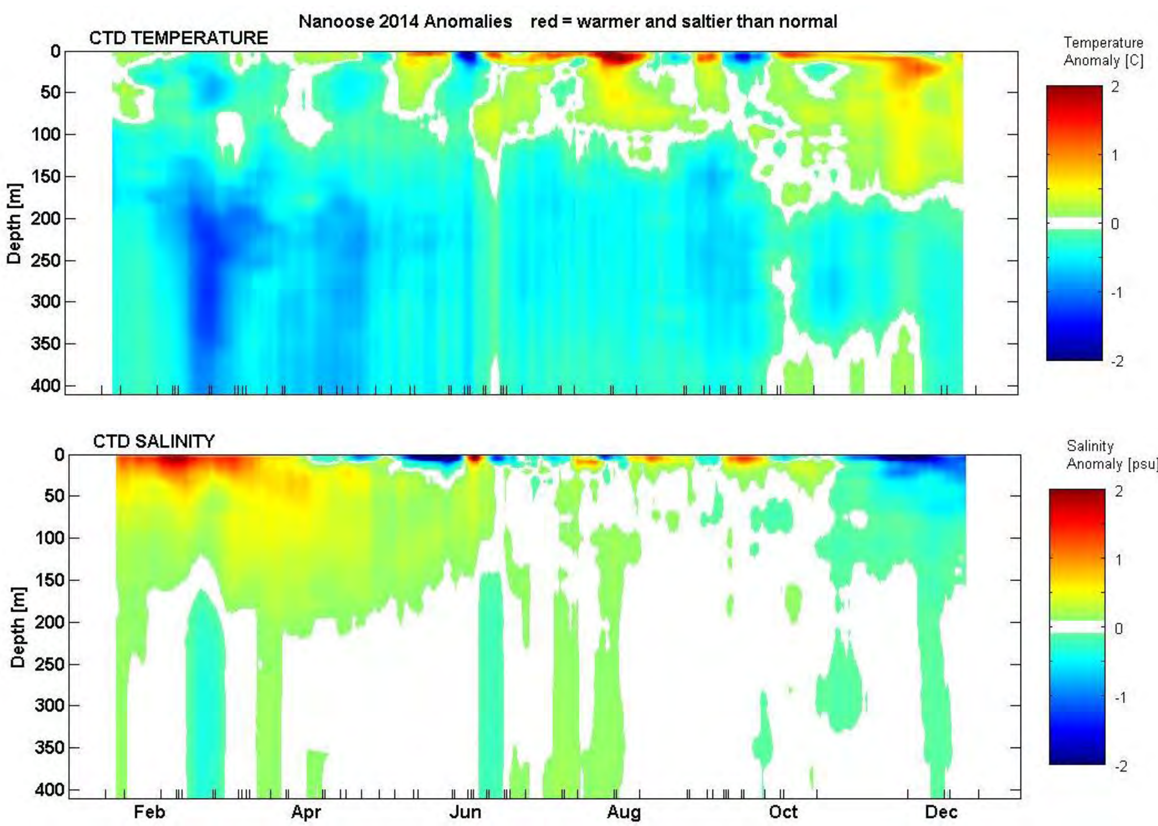

Figure 31-4. The time series of the vertical distribution of anomalies (temperature (upper) and salinity (lower)) collected in 2014 in the central Strait of Georgia near Nanoose. Data source: The Canadian Forces Maritime Experimental and Test Range (CFMETR).

The interannual variations in temperature are shown in Figure 31-5 and it can be seen that the annual cycle in 2014 was not particularly different from previous years. The depth averaged temperature early in 2014 was among the lowest observed since 2000, but considerably warmer than in 2009; the depth averaged temperatures in the summer of 2014 were similar those observed in 2013. The consistency of the annual temperature cycle over two years in 2013-2014 is similar to that seen in 2000-2001.

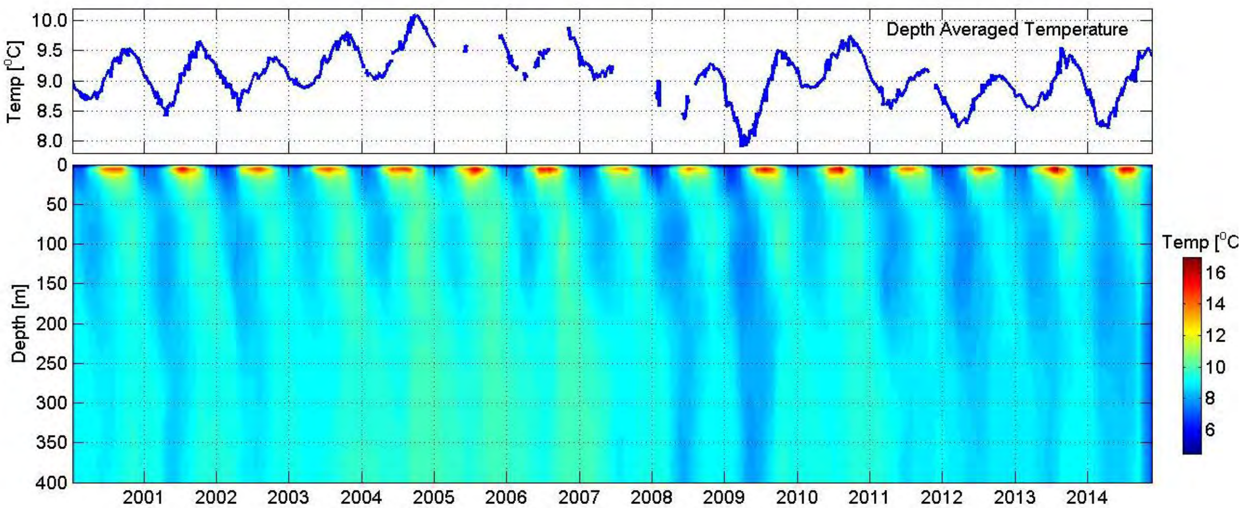

Figure 31-5. The time series of depth averaged temperature collected in the central Strait of Georgia near Nanoose (upper); the vertical distribution of these data (lower). Data source: The Canadian Forces Maritime Experimental and Test Range (CFMETR).

32. SPRING PHYTOPLANKTON BLOOM IN THE STRAIT OF GEORGIA, 2014 AND 2015

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32.1. Highlights

- Timing of the spring phytoplankton bloom in the Strait of Georgia is estimated for 2014 and 2015 from a computer simulation model.
- Model results for 2014 predicted the bloom would occur in late March; observations indicate the bloom was delayed to the end of March by a storm.
- Model results for 2015 predicted the bloom would occur in mid-March, which was as observed. This was the earliest spring bloom in this region since 2005.

32.2. Summary

The timing of the spring phytoplankton bloom in the Strait of Georgia is highly variable, ranging from late February to mid-April. Changes in the timing have been related to the success of herring larval recruitment (Schweigert et al. 2013) and studies in a nearby fjord suggest it may affect the zooplankton species composition (Tommasi et al. 2013). In this well stratified, mid-latitude system, the timing is controlled by the light availability to the phytoplankton which is in turn controlled by the incoming light (cloud fraction decreases this) and by the depth over which the phytoplankton are mixed (wind increases this). The role of freshwater is more nuanced; more river outflow both a) stabilizes the water column which decreases the depth over which the phytoplankton are mixed, increasing their growth rate and b) increases the advection loss of phytoplankton.

Elsewhere in this volume (Gower 2015) observations of the 2014 spring bloom are presented. Here we use results from a computer model coupling the physics and lower trophic levels in the Strait of Georgia. The model has been developed and can successfully model the timing of the spring bloom (Collins et al. 2009) which has allowed a hindcast of the timing since 1969 (Allen and Wolfe 2013, Figure 32-1).

32.3. The 2014 Spring Bloom According to the Model

Winds were reasonably strong through the winter, but good weather in early March seemed to suggest a bloom would occur in third week of March around the median bloom date. However, a severe wind storm on March 17 mixed the water column down to 26 m and delayed the bloom (Figure 32-3). The spring bloom then restarted on March 21 and bloomed on March 27. Observations from the ferry-box on the Queen of Alberni showed the bloom actually starting four days later and reaching a peak on April 3 (Wang 2015).

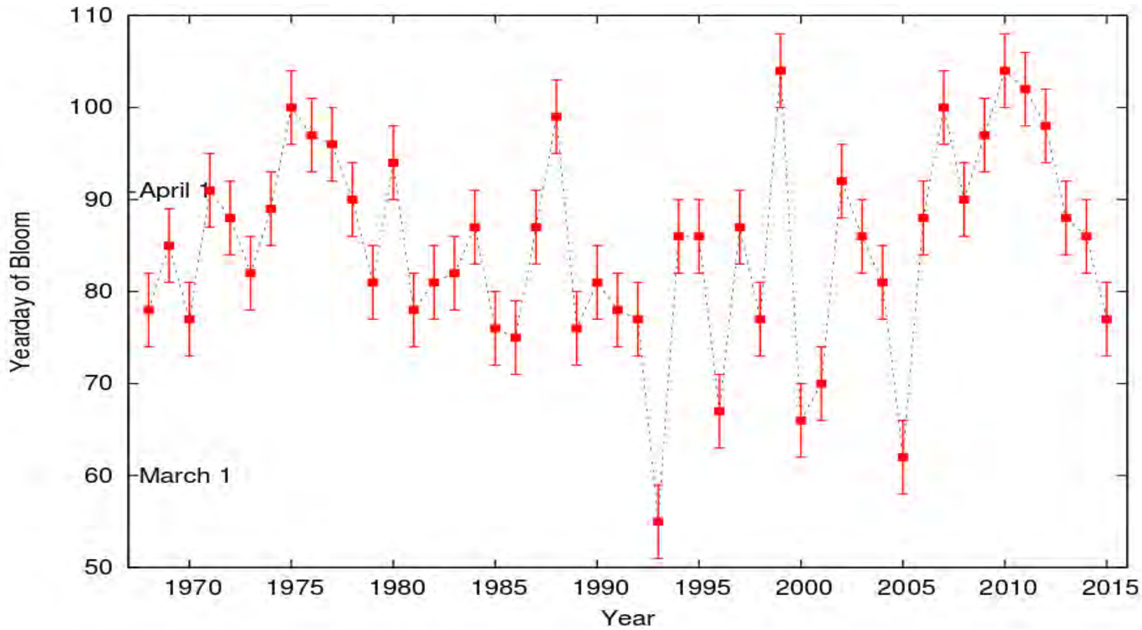
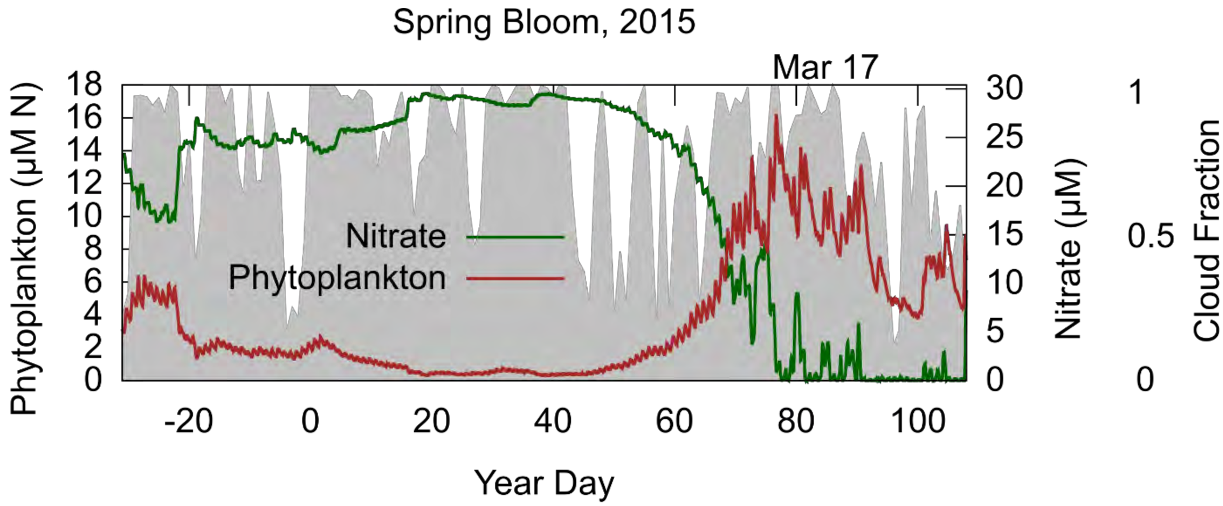


Figure 32-1. A time-series showing 2014 and 2015 spring blooms in the context of previous years. The spring bloom in 2015 was the earliest bloom since 2005.

32.4. 2015 Spring Bloom According to the Model

January and February 2015 were very warm and the Fraser River flow was very high for this time of year (Environment Canada 2015a, b; Gower and Chandler 2015). A period of low clouds in late February led to rapid growth. The peak of the spring bloom (March 13-15 observed by the ferry-box, March 17 hindcast (Figure 32-2)) was the earliest spring phytoplankton bloom since 2005 (Figure 32-1). Variability, however, has been less pronounced since 2006 without the large interannual swings seen in the 1990's and early 2000's (Figure 32-1).



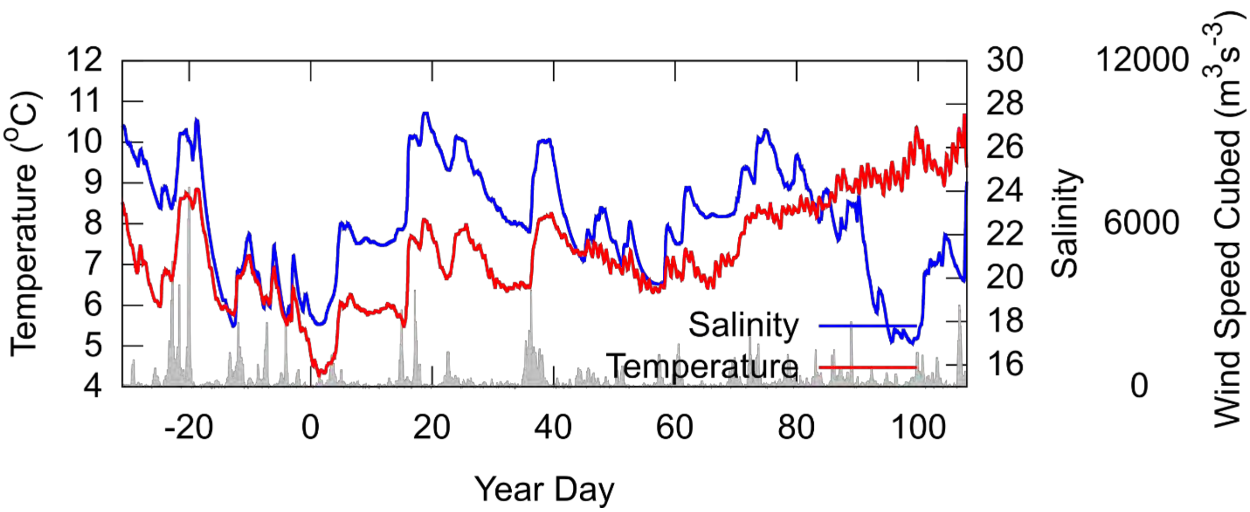


Figure 32-2. Hindcast of the 2015 spring bloom and related conditions in the Strait of Georgia. See Figure 32-3 caption for parameters plotted. Note the very low salinity in January due to record high Fraser River flow for this time of year. The 2015 spring bloom (March 13 observed, March 17 hindcast) was earlier than the mean (March 21) because of low winds throughout January to March and low cloud cover, particularly in February. Plots span the period December 1, 2014 to April 18, 2015.

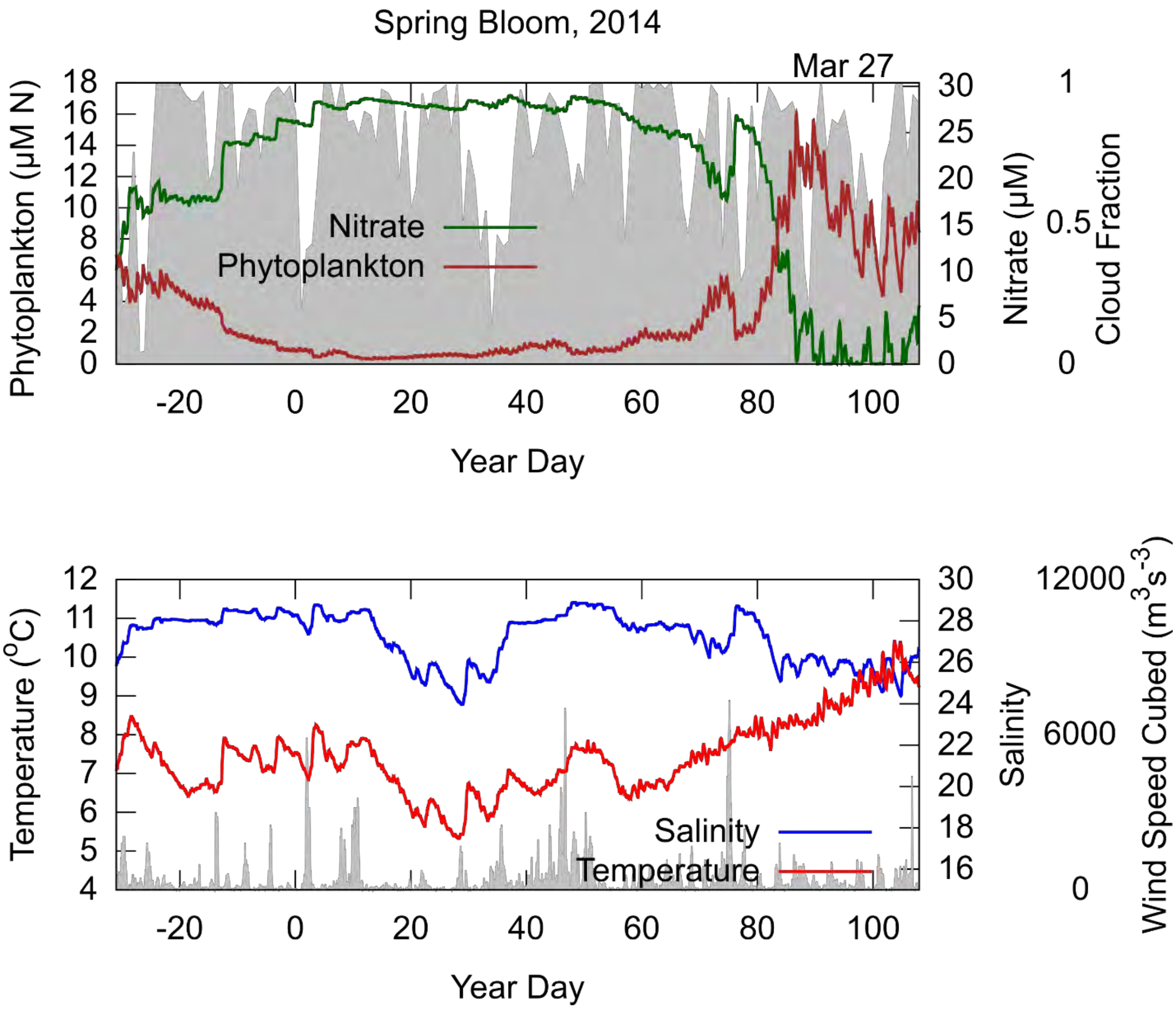


Figure 32-3. Hindcast of the 2014 spring bloom and related conditions in the Strait of Georgia. The lower panel shows temperature (in red) and salinity (in blue) averaged over the upper 3 m of the water column; in grey is the wind-speed cubed which is directly related to the strength of the mixing. One can clearly see the mixing associated with the storm about day 76; salinities increase as deeper high salinity water is mixed into the surface waters. The top panel shows phytoplankton biomass (in dark red) and nitrate (in green); in grey is the cloud fraction averaged over the day. One can see the influence of low wind, low cloud periods such as that after day 76. Here phytoplankton biomass steadily increases and nitrate decreases. The 2014 spring bloom (March 27 hindcast, April 3 observed) was later than the mean (March 21) because of the windiness of February and March. Plots span the period December 1, 2013 to April 18, 2014.

32.5. Details of the coupled-biophysical Model

The model is a vertical-mixing layer model forced by observed winds at Sand Heads, observed air temperature and humidity at Vancouver International Airport (YVR), Fraser River flow at Hope and Englishman River flow at Parksville (Environment Canada 2015a,b). The latter is multiplied by 55 to represent all river flows into the Strait other than the Fraser River. Cloud fraction is interpreted based on the weather description

and the historical average cloud fraction to weather, done by month for the most common weather descriptions. The physical model is based on the Large et al. (1994) KPP-model with an estuarine circulation model added (Collins et al. 2009). To model a spring bloom, only a simple nitrate-diatom biological model is used. The diatom growth parameters are taken from the literature based on the first phytoplankton to bloom in the Strait (*Thalassiosira* spp.). The model zooplankton concentration was taken from observations (Sastri and Dower 2009) and the model was tuned by adjusting the phytoplankton growth rate (Allen and Wolfe 2013) within the range measured in the laboratory. The model was tuned, within 4 days, for the spring blooms of 2002-2005 for which detailed observations were made as part of the STRATOGEM project (Allen and Wolfe 2013). A carbon module that models dissolved inorganic carbon and total alkalinity has been added to the model and allows estimation of aragonite saturation state (Moore-Maley 2014).

Predictions for the 2016 bloom will be available, starting in early 2016, at http://salishsea.eos.ubc.ca/bloomcast/spring_diatoms.html.

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33. TIMING OF THE SPRING PHYTOPLANKTON BLOOM IN THE STRAIT OF GEORGIA BASED ON ANALYSIS OF MODIS-AQUA IMAGES

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33.1. Highlights

- An improved satellite chlorophyll product for the Strait of Georgia demonstrates the inter-annual and geographic variation in bloom initiation:
    - In the central Strait, bloom initiation is generally mid-late March to early-mid April. The earliest blooms were in 2004, 2005 and 2009, and the latest bloom occurred during 2010. In 2014, bloom initiation occurred from March 31 to April 6.
    - In the northern Strait, the early time series shows bloom initiation occurring earlier than the central Strait. In recent years, including 2014, the timing has been similar to that in the central Strait.

33.2. Summary

Satellite remote sensing offers a synoptic, cost effective, and repeatable method of deriving ocean surface chlorophyll *(Chl)* concentrations as a proxy for phytoplankton biomass, in place of traditional ship-based methods. This report includes the analysis of a 13-year time series of MODIS-derived bloom initiation data for central and northern sub-regions of the Strait of Georgia (SoG).

Image data (Level 1a) were accessed from NASA's OceanColor web portal, and processed in the SeaDAS (Seawifs Data Analysis System) environment. All available good quality MODIS-Aqua images from June 2002 through July 2014 at ~1 km^2 nadir spatial resolution were processed. The source of most error for satellite remote sensing in coastal waters is poor atmospheric correction. As a first step three atmospheric correction methods were tested to determine the most suitable: The NASA-standard near infrared (NIR), the shortwave infrared (SWIR), and the Management Unit of North Seas Mathematical Model using SWIR bands (MUMM+SWIR). The Aerosol Optical Thickness (AOT) at 443nm, derived from the Aerosol Robotic Network (AERONET) for atmospheric measurements, acquired within +/- 15 minutes of imagery acquisition were compared (more than 660 images) to evaluate the effectiveness of the atmospheric correction methods. Figure 33-1 shows the comparison of AOTs of three evaluated atmospheric correction schemes to AERONET at 443 nm. The MUMM+SWIR method shows similar R^2, slope closer to 1, and lower RMSE compared to the NIR method, thus indicating its effectiveness.

The OC3M chlorophyll algorithm was applied to the atmospheric corrected reflectances result from each atmospheric method to produce chlorophyll maps. To minimize influence of poor-quality data on the comparison procedure, exclusion criteria (masks) were used. The processing masks included high solar zenith angle, high sun zenith angle, straylight, and pixels with negative reflectance values in the blue, due to obvious atmospheric correction failure. The derived satellite chlorophyll concentrations were validated with *in situ* data from the DFO Institute of Ocean Sciences database and our own HPLC measurements showing the increased performance of the MUMM+SWIR method (r=0.83, n=16 for +/- 1 hour match-up; r=0.77, n=46 for +/-4 hours match-up) for the SoG (Figure 33-2).

After validation, all *Chl* images were spatially binned and then temporally binned to derive mean 8-day *Chl* concentrations. Weekly 8-day *Chl* concentrations were derived for the central and northern sub-regions of the SoG. For each sub-region, median *Chl* was extracted as a robust measure of the central tendency of the population. From that, as a further step to remove potential outliers, the Median Absolute Deviation from the Median (MAD) was used to identify a threshold of extreme values for removal. Timing of bloom initiation was defined as the yearday (+/- 4 days) where *Chl* concentrations were greater than two consecutive measurements over the annual median plus 5% (not considering January and February) or the yearday of the first *Chl* estimate greater than 5.0 mg m^{-3} (similar to Schweigert et al. 2013 and Siegel et al. 2003). Yearday bloom initiation for each sub-region is presented in Figure 33-3 (central) and Figure 33-4 (northern).

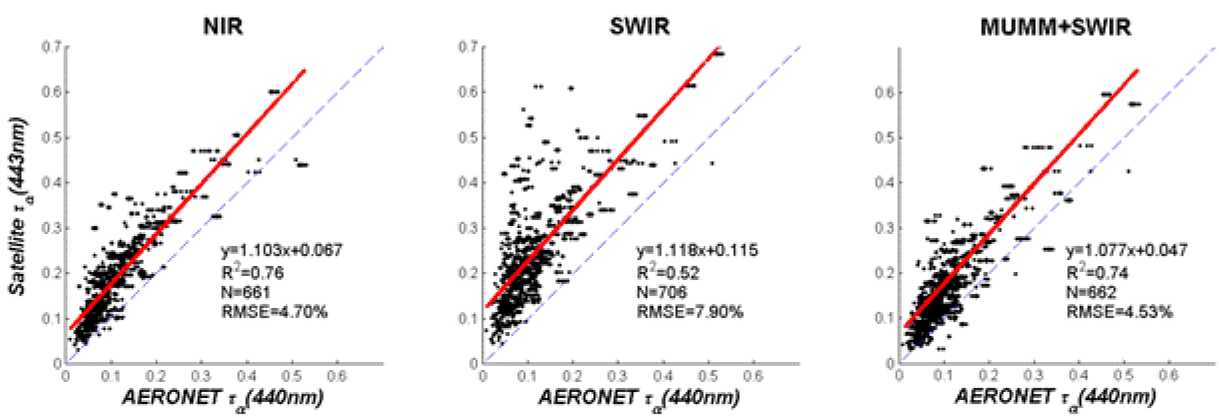

Figure 33-1. Matchup of MODIS to AERONET aerosol optical thickness for three atmospheric correction methods at 440 nm. Red line is the regression line of the equation, and dashed line indicates a hypothetical 1 to 1 relationship.

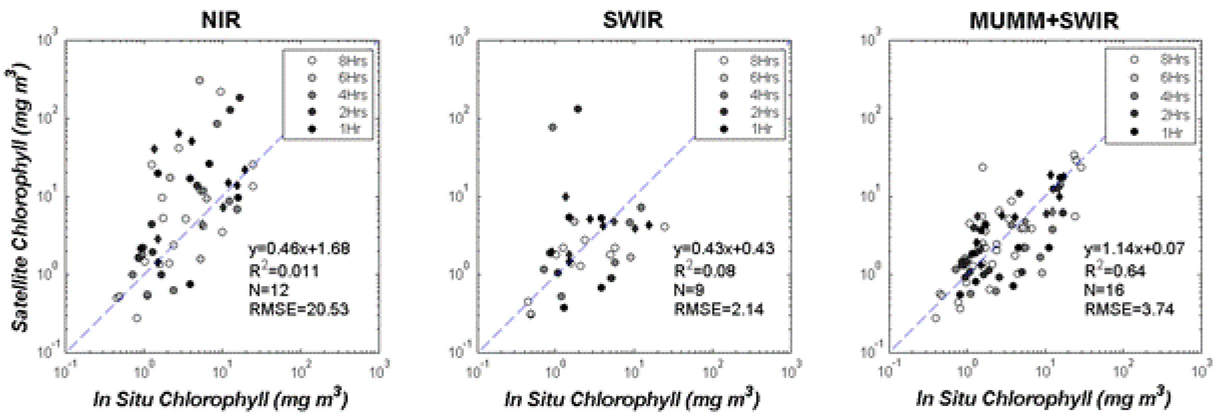

Figure 33-2. Relationship between MODIS derived chlorophyll concentration and in situ samples for different temporal resolutions. Circles represent DFO Institute of Ocean Sciences data, while diamonds represent HPLC results. Statistics are given for the one hour temporal resolution match-up.

For the central sub-region (Figure 33-3), the time series analysis of the MODIS Aqua imagery shows that spring bloom initiation generally happened from mid-late March to early-mid April. The latest spring bloom initiation happened in 2010 in mid-April, and the earliest in 2004 and 2009 in the beginning of March; a much earlier bloom may have happened in mid-February 2005. Bloom initiation in 2014 followed the trend of the majority of the previous years: late March to early April; specifically, from March 31 to April 6, similar to 2013. The MODIS-derived bloom initiation period generally agrees with the model bloom estimates by Allen et al. (2013), but diverge when the bloom happens earlier, such as in 2004 and 2009 when it approximates estimates by Gower et al. (2013).

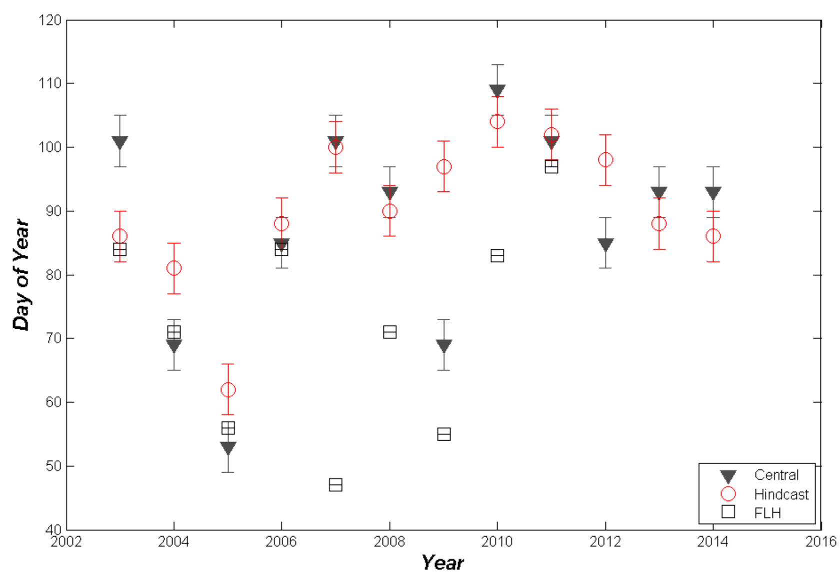

Figure 33-3. Comparison of spring bloom start dates for this study in the central Strait of Georgia sub-region (black triangles), Allen & Wolfe's (2013) Hindcast model (red circles), and Fluorescence Line Height (FLH) (Gower et al. 2013) (white squares).

For the northern sub-region (Figure 33-4), the imagery time series shows that spring bloom initiation happened earlier from 2004 to 2008 and 2012 than in the central sub-region. However, in recent years, including 2014, the time of bloom initiation in the northern region has been similar to the central region; i.e. late-March-early-April. Determining inter-annual relationships between the timing/magnitude/duration of the spring bloom and the residence/condition of juvenile salmon entering the SoG from nursery lakes may be paramount for ecologically based fisheries management. Our approach applied to a 13-year time series of data will help to understand these relationships.

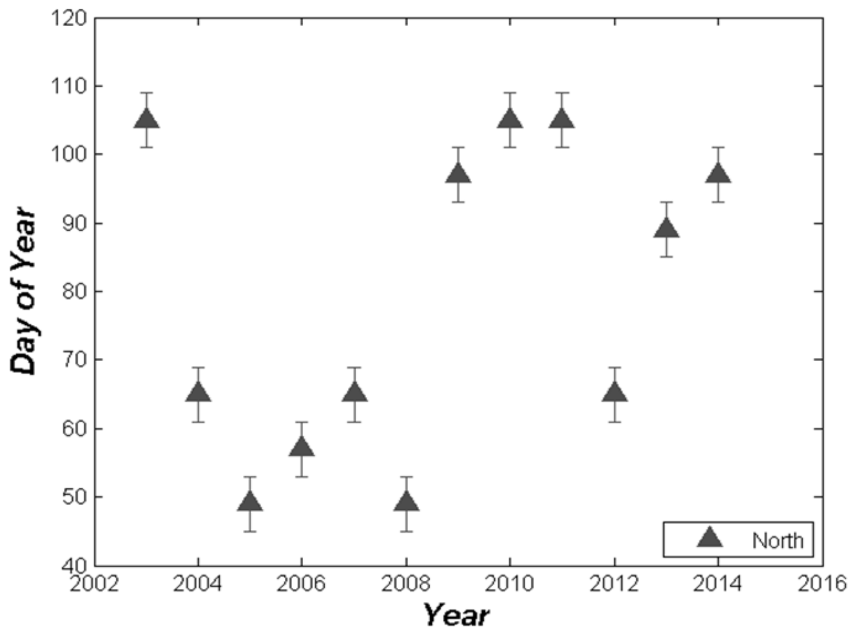

Figure 33-4. Comparison of spring bloom start dates for the northern sub-region of the SOG.

33.3. References

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34. SPRING BLOOM TIMING IN THE STRAIT OF GEORGIA

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34.1. Highlights

- In 2014, increased surface chlorophyll from fluorescence in the central Strait, indicating the start of the spring bloom, first appeared on April 2, day 92.
- In 2014, surface chlorophyll from fluorescence time series were recorded on the buoy on Halibut Bank and on the *Queen of Alberni* ferry in the central Strait, on the *Spirit of Vancouver Island* ferry in the Southern Strait and Gulf Islands, and at Egmont in Jervis and Sechelt Inlets.
- In 2015, these series are again being collected, with an additional series from the buoy on Sentry Shoal in the northern Strait.

34.2. Summary

The time series from the Halibut Bank buoy in the Strait of Georgia (Figure 34-1) shows a clear start to the bloom on about April 2, in agreement with data from the *Queen of Alberni* ferry (Figure 34-2). The series from Egmont (Figure 34-3) shows that bloom activity started earlier in the northern inlets, about March 3 (day 62) but did not seed an early spring bloom in the Strait of Georgia this year.

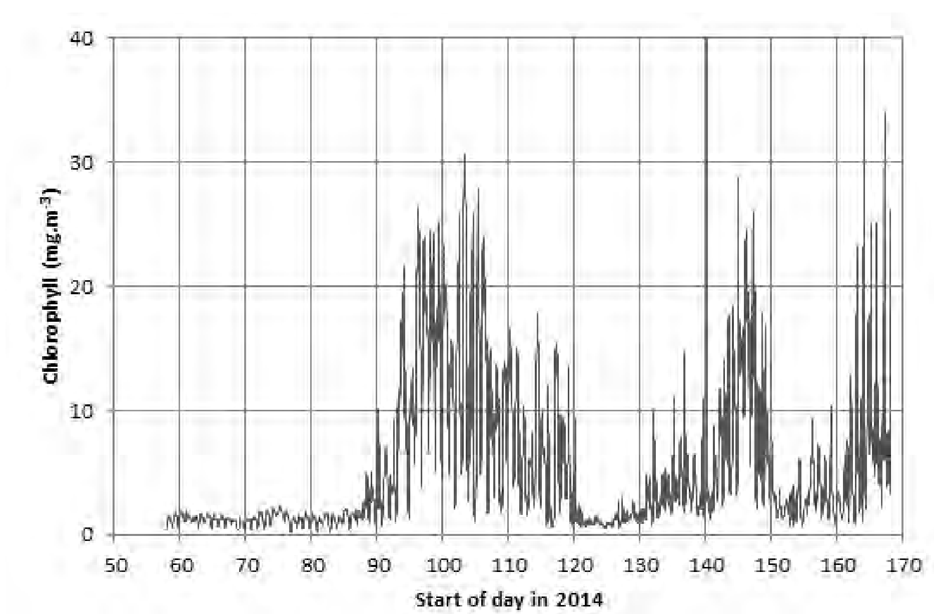

Figure 34-1. Halibut Bank chlorophyll from fluorescence time series for spring 2014 (data provided by Stephanie King, Sea This Consulting). Day 92 is 2 April.

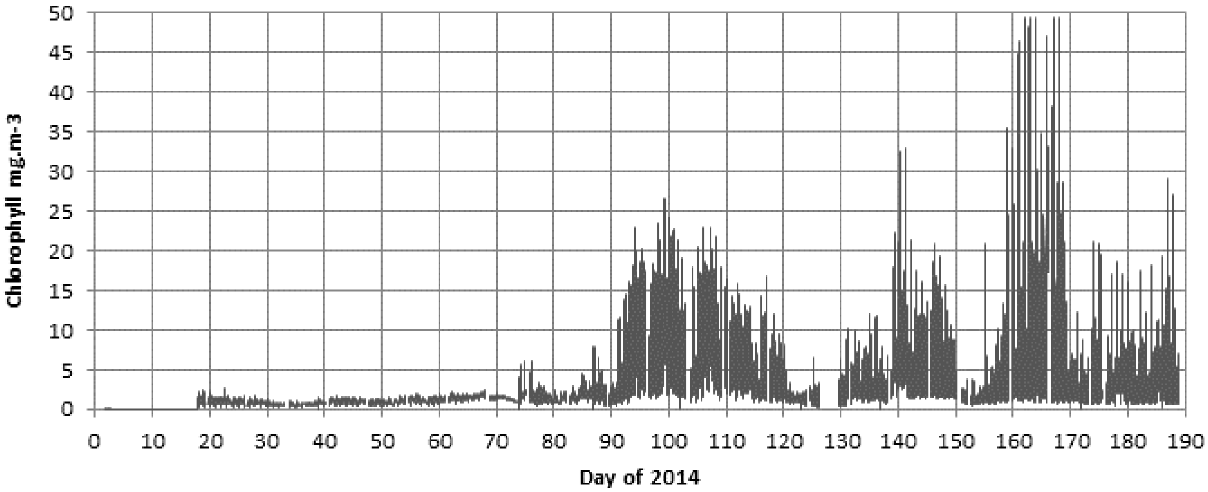

Figure 34-2. ONC (Ocean Networks Canada) instruments on the BC ferry Queen of Alberni on the Tsawwassen-Duke Point run, showing chlorophyll from fluorescence, with start of the spring bloom on day 92 (April 2).

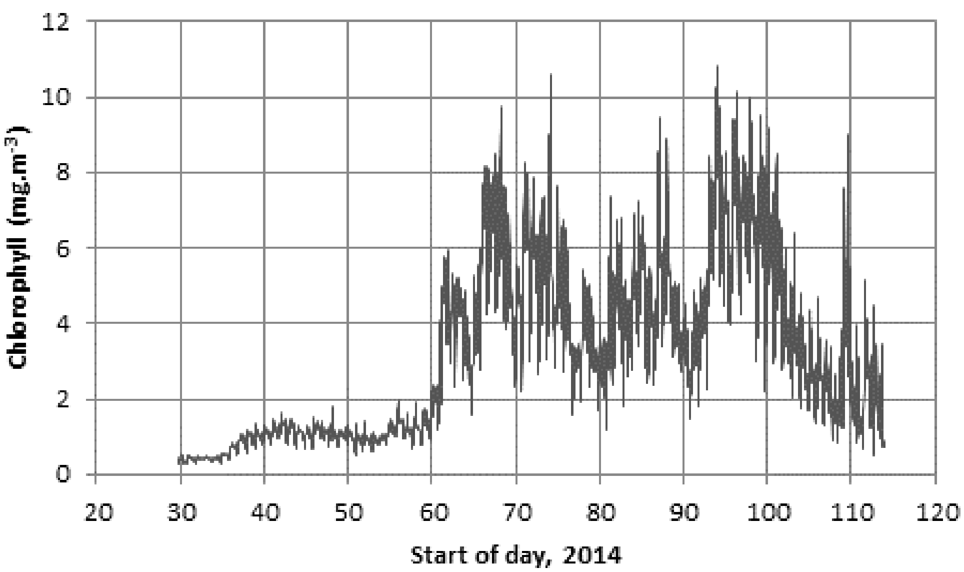

Figure 34-3. Chlorophyll from fluorescence time series from a fluorometer at 1m depth in Egmont at the junction of Jervis and Sechelt Inlets, shows bloom activity starting earlier, at about day 61 (March 2). This bloom appears to have had no seeding effect in the Strait of Georgia.

35. STRAIT OF GEORGIA JUVENILE HERRING SURVEY

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35.1. Highlights

- Preliminary estimates of the relative biomass and abundance of age-0 herring during autumn in the Strait of Georgia (SOG):
    - are presented but subject to change after the publication of a report that is currently in preparation,
    - vary interannually with no overall trend,
    - were relatively low in 2013 and 2014, and
    - may be a leading indicator of the number of recruits joining the population 2.5 years later and the amount available to predators in the SOG.

35.2. Description of indices

The SOG juvenile herring and nearshore pelagic ecosystem survey is a long-term monitoring program that provides samples of the nearshore pelagic fish community, the zooplankton community, as well measurements of physical water column properties (e.g., temperature, salinity, oxygen). One goal of the survey is to provide an index of age-0 herring biomass (abundance) and relate it to abundance of age-3 herring in the stock assessment model. This index may also represent trends in potential prey availability to salmon and other predators. Currently, a report is being assembled to identify the best method of calculating an index of age-0 herring from the survey data collected to date. Some preliminary results from that report are presented here, but are subject to change, as the report is finalized.

There are ten core transects, each with 3 to 5 core stations, distributed at approximately equal intervals around the perimeter of the SOG that have been consistently sampled during the autumn since 1992 (except 1995; Thompson et al. 2013; see Thompson et al. 2003 for detailed survey design and methods; Figure 35-1). Sampling was conducted after dusk when herring were near the surface and, generally, one transect was sampled per night over the course of a 4-7 hour period. The stations were sampled with “blind” (undirected) purse seine sets (sets were made at predetermined stations). Catch weights were estimated and all fish (or a subsample of fish) were retained for sampling in the laboratory, with the exception of large predator species (e.g. adult salmon and flatfish), which were individually measured in the field. In the laboratory,

fish from each station were sorted to species and up to 100 individual age-0 herring were identified, weighed and measured. Herring were measured to standard length (nearest millimeter) and were between 54 and 125 mm long in all years sampled. The number of herring (and other species) caught at each station was determined by dividing the total catch weight (kg) by the average individual weight of herring (or species-specific weights) weighed in the lab. Two-stage sampling formulae from Szarzi et al. (1995) were used to calculate the mean and variance of bootstrapped juvenile herring catch weight, CPUE, and abundance.

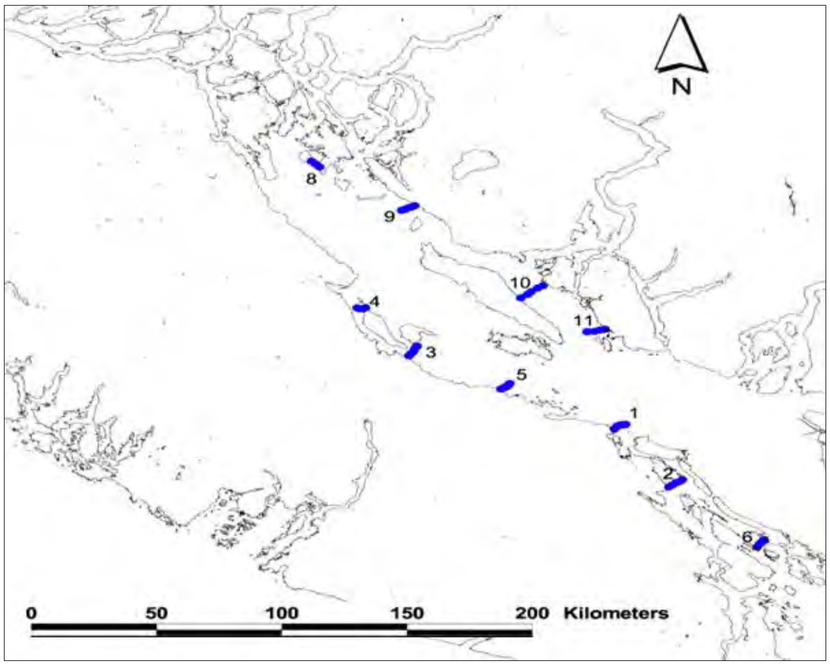

Figure 35-1. Purse seine set locations along the 10 core transects of the Strait of Georgia juvenile herring survey.

35.3. Status and trends

Preliminary estimates of age-0 catch weight, CPUE, and abundance varied annually, with no overall trend during the time series (Figure 35-2). Age-0 herring indices tended to peak every two or three years, with the peaks occurring in even years during 2004-2012. Indices were relatively low in 2013 and 2014, relative to the peaks within the time series.

35.4. Factors causing trends

Factors that can potentially affect herring abundance and distribution include zooplankton prey availability (including timing), predator and competitor species abundance, environmental factors, and disease. For example, herring recruitment and survival has been linked to water temperatures (Tester 1948, Ware 1991) and bottom-up control of production (Ware and Thompson 2005, Perry and Schweigert 2008, Schweigert et al. 2013).

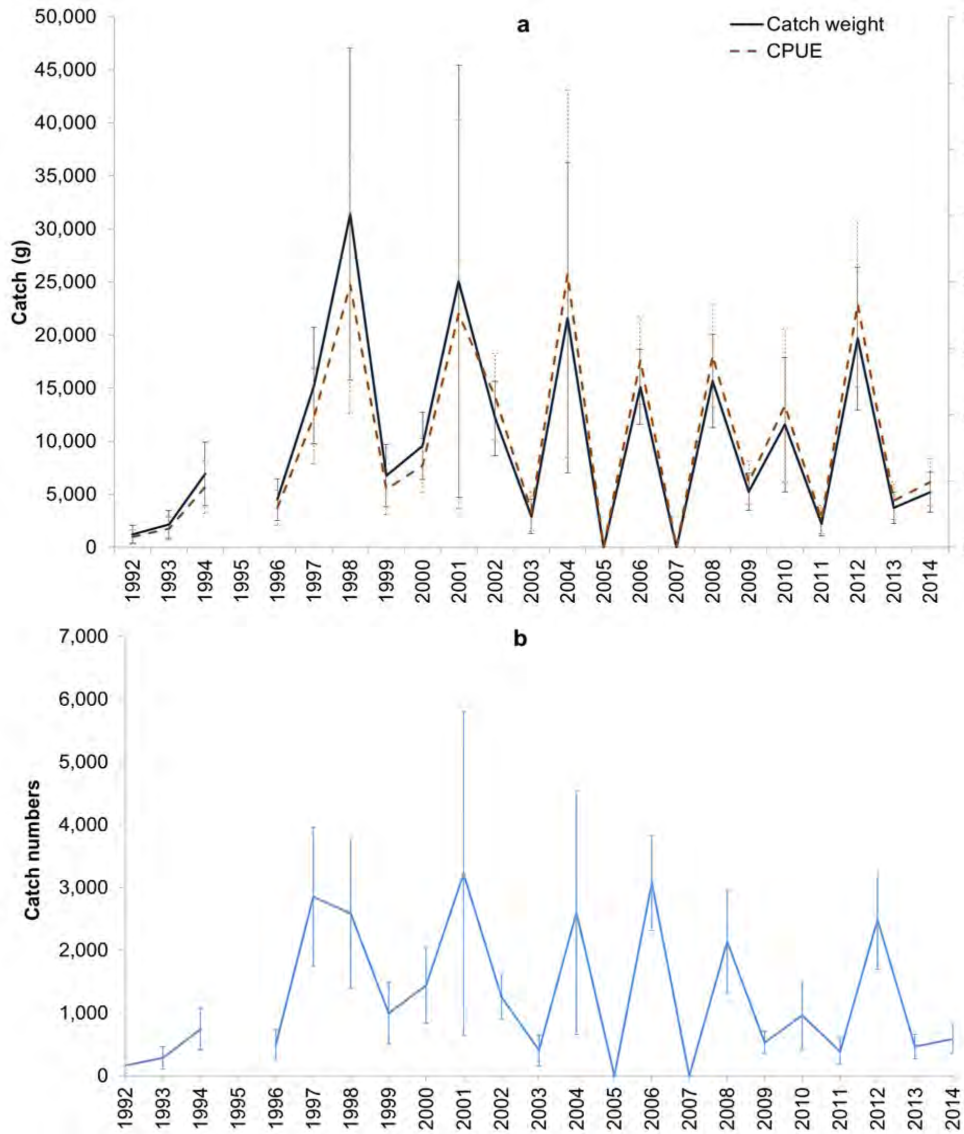

Figure 35-2. Preliminary estimates of catch weight (g) and catch-per-unit-effort (CPUE) (top panel, a) and catch numbers (bottom panel, b) of age-0 herring caught in the Strait of Georgia juvenile herring survey at core transects and stations during 1992-2014 (no survey in 1995). Estimates of catch weight (g) and CPUE were estimated using a two-stage design and bootstrapped data. Estimates of CPUE were calculated by dividing catch weight by the area fished by the net. Standard deviation bars are shown.

35.5. Implications of trends

Preliminary results and previous analyses (Schweigert et al. 2009) show that age-0 herring survey indices are correlated with the abundance of age-3 recruits (2.5 years later) as estimated by the age-structured stock assessment model (Cleary and Taylor in press), supporting the notion that age-0 herring indices may be indicative of the relative amount of herring in the SOG and the number of recruits joining the population 2.5 years later. Pacific Herring are prey for predatory fish, marine mammals, and seabirds and are important commercial species in British Columbia’s coastal waters. Changes in

herring abundance can affect availability to commercial fisheries and predators, such as salmon. Understanding trends in the populations of small pelagic fish species and factors that affect their abundance requires long-term monitoring of the nearshore pelagic ecosystem.

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36. STRAIT OF GEORGIA JUVENILE SALMON

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36.1. Highlights

- The survey catch of juvenile Coho Salmon in September 2014 remained above average (data collected since 1998 suggesting good returns in 2015. In addition, the average size was the largest observed in the time series and in combination with high salinities in February 2015 suggest a possible inside distribution of young adults in the spring of 2015.
- The catch of late ocean entrants (Harrison River Sockeye Salmon and Chinook Salmon from the South Thompson) in September 2014 was high and the fish were above average in size. This suggests continued good returns for these stocks.
- The projected returns based on these observations within the Strait of Georgia have to be taken with caution as the unusual conditions on the west coast of Vancouver Island during the winter of 2014/15 have not been observed previously and therefore it is not known how they will effect these salmon during their ocean rearing periods.

36.2. Introduction

Juvenile salmon generally enter the Strait of Georgia from April to June and many may remain and rear in the strait until the fall. The juvenile trawl surveys are designed to sample juvenile salmon throughout the Strait of Georgia during this first ocean summer and fall. In 2014 juvenile salmon were sampled during three trawl surveys (June 1-11, June 25-July 8 and September 17-October 12). These surveys fished standard track lines that have been fished since 1998 following the protocol in Beamish et al. (2010). In addition, additional sampling was conducted in the Discovery Islands, mainland inlets, Gulf Islands and Puget Sound. The June 1-11 survey was conducted using the chartered commercial trawl vessel *Viking Storm*. The subsequent two surveys were conducted with the Canadian Coast Guard research vessel *W.E. Ricker*.

Beamish et al. (2010) demonstrated that there was a good relationship between the catch rate of juvenile Coho Salmon in the September survey and returns of adults the following year. This work indicated that brood year strength for Coho Salmon from the Strait of Georgia was determined during their first summer in the ocean and within the Strait of Georgia region. In this report we make the assumption that early marine survival is a major component of determining overall marine survival for all salmon species in the Strait of Georgia. We examine the catch rates of juvenile salmon in 2014 in comparison to catch levels from 1998-2013, the condition of the juveniles and the general oceanographic conditions in the Strait of Georgia. We use the information collected in 2014 to estimate the relative strength of return in subsequent years (return year depends on the species).

The surface water temperature (SST) in May-June 2014 was above the average observed since 2000 and warmer than the previous 4 years (Chrome Island, Figure 36-1). Although the SST was not the highest on record there is indication that the survival of juvenile salmon may be inversely related to SST (Friedland et al. 2003, Beamish et al. 2009, Petrosky and Schaller, 2010). However, Mueter et al. (2005) suggested that these ocean conditions may only explain a small proportion of the variability in salmon survival driven by environmental factors. Therefore, the increase in the SST during the early summer 2013 and 2014 is a note of caution as we do not know the impact on the survival of juvenile salmon entering the ocean in these years.

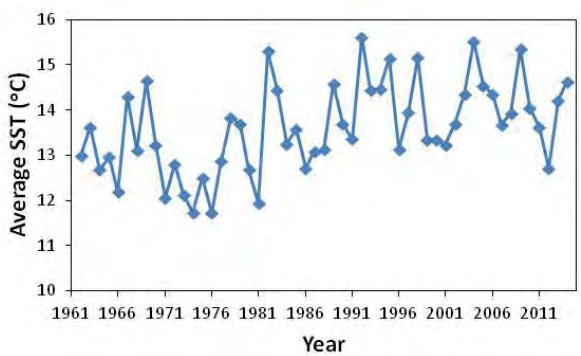

Figure 36-1. Average sea surface temperature (SST) in May and June at the Chrome Island light station 1962-2014.

36.3. Coho Salmon

Coho salmon generally spend one winter in the ocean, therefore, most juveniles that entered the ocean in 2014 will return to spawn in 2015. Chittendon et al. (2009) demonstrated that Coho Salmon from the Strait of Georgia remain and rear in the strait until late fall. Beamish et al. (2010) used the abundance and survival of Coho Salmon up to the annual September surveys to demonstrate that brood year strength for Coho Salmon was determined in the Strait of Georgia during the first marine summer. In 2014 the CPUE of Coho Salmon in the September survey was lower than 2013 and 2012 but continued to exceed the long term average (Figure 36-2). In addition, the average size of the juveniles was the largest observed in the 16 years of the survey. Based on the early marine index developed by Beamish et al. (2010) these conditions would suggest a **good** return of Coho Salmon in 2015. However, the increase in SST over the past few years in the strait and the warmer water temperatures on the west coast of Vancouver Island during the winter of 2014/15 (Chandler 2015) are not considered in the analysis and it is not known how these conditions may impact the Coho Salmon or other salmon species that entered the Strait of Georgia in 2014.

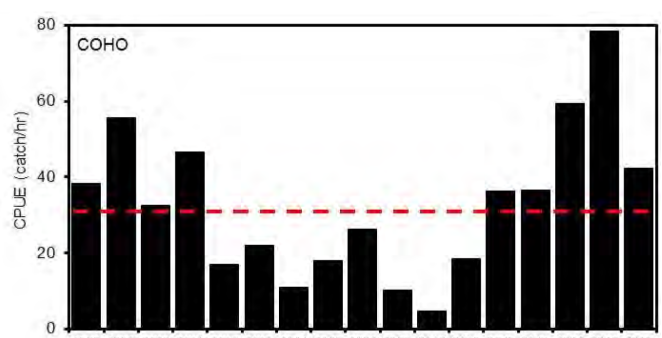

Figure 36-2. The CPUE of Coho Salmon in September trawl surveys in the Strait of Georgia 1998-2014. Red dashed line is the average catch over the time series.

In recent years there has been a change in the distribution of Coho Salmon after their first marine winter. Historically, Coho Salmon from this

region supported a recreational fishery in the Strait of Georgia in the early spring. However, in the mid-1990s, the behavior of Coho Salmon changed with the fish remaining off the west coast of Vancouver Island during this period and the early summer sport fishery in the strait collapsed. The cause for the change in behavior has not been determined although Beamish et al. (1999) suggested that there was a relationship with the winter (February) salinity in the strait. The salinity in February has been high over the past four winters, however, the pattern is not consistent over the past decade. Therefore, although the salinity may be an indicator, additional factors need to be examined. It is possible that the growth of the juveniles during the first summer may be a key factor. If this is the case, the large size of the juveniles in 2014 combined with the high salinity in February 2015 would suggest that Coho Salmon will be available to the sport fishery in the spring of 2015. This relationship has not been tested but the distribution of young adults in the spring of 2015 will help determine if there is value in exploring this hypothesis further.

36.4. Sockeye Salmon

Sockeye Salmon that entered the Strait of Georgia in 2014 were mostly progeny of the return to the Fraser River in 2012. This return was a sub-dominant year and therefore large numbers of juveniles were not expected in 2014. However, the CPUE of Sockeye Salmon in late June-early July was the lowest observed for this cycle year (Figure 36-3A). Catches were larger in the early June survey which was expected as this is generally the time of peak abundance for juveniles in the Strait of Georgia (Preikshot et al. 2012). Catch distribution in the trawl surveys and in purse seine surveys conducted in the Discovery Islands May-July 2014 suggested that the juveniles remained and reared in the Strait of Georgia until early June as was observed in 2010-2012 (Neville et al. 2013). Feeding (based on percent of empty stomachs) in 2014 was average. Therefore, except for the warming SST, the conditions within the Strait of Georgia appeared average for the juvenile Sockeye Salmon. However, this needs to be considered in combination with the warm waters that they may have encountered once they left this region. Therefore, with the low catch numbers in the standard survey and with the added notes of caution on marine conditions outside of the Strait of Georgia we would suggest below average returns for this cycle year in 2016.

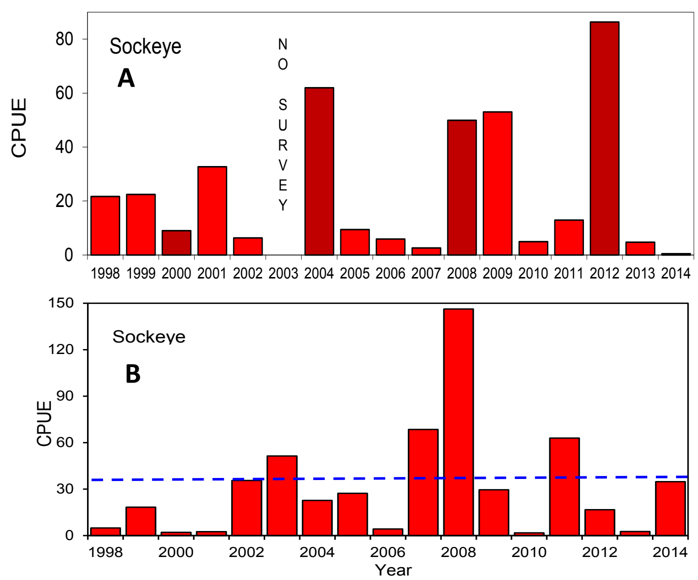

Figure 36-3. CPUE of Sockeye Salmon captured in the (A) June-July trawl survey and the (B) September trawl surveys 1998-2014.

Harrison River Sockeye Salmon are a Fraser River stock that does not spend one winter in lakes but migrates to the ocean in the spring in which they emerge and in general have had improved production over the past few years. Information that is known about their ocean entry suggests that they enter in late July and August. During the June/July survey small numbers of these fish are captured in Howe Sound but are rarely captured in the Strait of Georgia until August or September. In September, they are the dominant stock of Sockeye Salmon within the strait representing over 95% of the Sockeye Salmon captured (Beamish et al. 2012). In September 2014 the CPUE of Sockeye Salmon in the standard survey area was average (Figure 36-3B). In addition, large numbers of Sockeye Salmon remained in Howe Sound and mainland inlet regions that are not included in the CPUE calculation. The average size of the juveniles was above average. Overall, the catch and distribution of Sockeye Salmon in the September survey suggests good returns for Harrison River Sockeye Salmon in 2016 and 2017.

36.5. Chinook Salmon

Chinook Salmon early life history is complex with variation in life history type (ocean and stream-type, hatchery and wild), age at ocean entry and timing of ocean entry. Beamish et al. (2011) demonstrated that the catch of Chinook Salmon in the June-July surveys are a mixture of ocean and stream type fish. Neville et al. (2015) demonstrated that most of these juvenile fish present in the June-July survey either leave the strait or die before September. The CPUE of Chinook in the June-July survey continued a declining trend from 2006 and was below the long term average (Figure 36-4A). The average size of these fish was one of largest we had observed in the time series, however, additional analysis is required to determine if the change in size is due to a shift in the proportion of ocean and stream type fish in the catch. Overall, the continued decline in the CPUE in the early summer suggests continued poor returns for Chinook Salmon returning in 2015-2017. The continued decline in CPUE and the possible shift in stock composition (ocean and stream type) is also an indication that additional research on factors regulating survival during this early marine period is required.

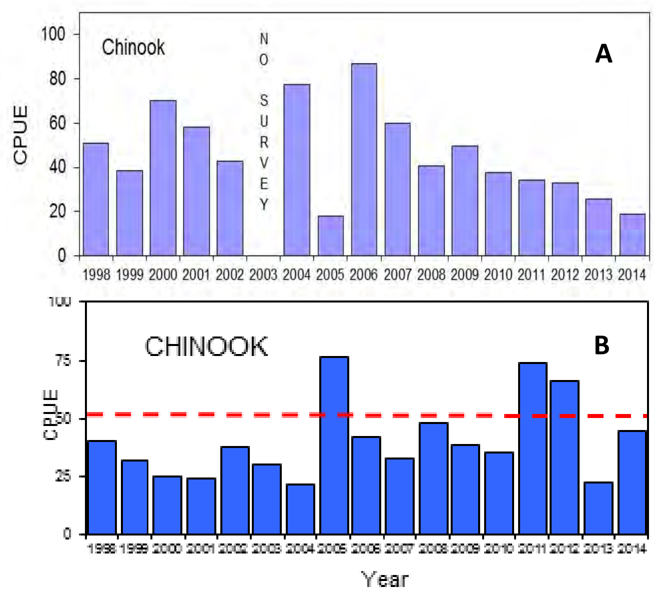

Figure 36-4. CPUE of Chinook Salmon captured in the (A) June-July trawl survey and the (B) September trawl surveys 1998-2014

In September the majority of the Chinook Salmon in the Strait of Georgia are from the South Thompson region (Beamish et al. 2011). These fish generally enter the ocean in

late July and August and, similar to Harrison River Sockeye Salmon, have had improved production over recent years. In September 2014 the CPUE of Chinook Salmon was average to above average (Figure 36-4B) and the average size of the fish was also above average. Therefore this would suggest continued good condition for these late ocean entrants.

36.6. Chum and Pink Salmon

Chum salmon enter the ocean in the year they emerge from the gravel and are produced in numerous rivers and stream around the Strait of Georgia. In 2014 the CPUE of Chum Salmon in the June-July survey was lower than 2013 and the fourth lowest in the time series (Figure 36-5). In addition, the average size of the juveniles remained small. These conditions would suggest a poor return of these fish as adults in 2016 and 2017.

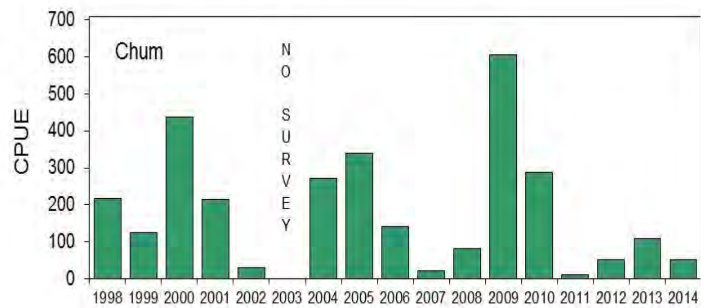

Figure 36-5. The CPUE of Chum Salmon in the June-July trawl survey in the Strait of Georgia 1998-2014

The primary producer of Pink Salmon in the Strait of Georgia is the Fraser River and this is an odd year run only. Therefore, juveniles enter the Strait of Georgia in even numbered years. In 2014 the CPUE of Pink Salmon was the second largest observed since 2008 suggesting continued good returns of Pink Salmon in 2015.

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37. TELEMETRY-BASED ESTIMATES OF EARLY MARINE SURVIVAL AND RESIDENCE TIME OF JUVENILE SOCKEYE SALMON IN THE STRAIT OF GEORGIA AND QUEEN CHARLOTTE STRAIT, 2014

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37.1. Highlights

- Survival rates and travel times for Sockeye salmon smolts from two B.C. lakes were estimated using internally-implanted acoustic tags.
- Mortality in clear freshwater tributaries leading to the mainstem Fraser River was high, but once in the Fraser River mortality is low, with rapid downstream migrations.
- Early marine survival was highest in the central Strait of Georgia but lower in the northern Strait of Georgia to Queen Charlotte Sound.
- Sockeye smolts took one month to migrate from the Fraser River mouth to the central B.C. coast where they occurred by the end of June.
- Marine survival of two-year-old Fraser River Sockeye to Queen Charlotte Sound in 2014 was similar to previous years.

37.2. Summary

From 2010-2014, we used a large-scale acoustic telemetry array to track two-year-old Chilko Lake Sockeye salmon smolts during the initial 1000 km of their freshwater and marine migration. Salmon smolts were surgically implanted with uniquely coded acoustic transmitters (“tags”) and then tracked with a network of acoustic sensors positioned within the Fraser River basin, the Salish Sea, and at the northern end of Vancouver Island (Figure 37-1).

By reconstructing the movements of each individual salmon from the data recorded by the array it was possible to estimate survival from Chilko Lake to the lower Fraser River, through the Strait of Georgia (SoG), and from the northern SoG to northern Queen Charlotte Strait using the Cormack-Jolly-Seber model (Cormack 1964, Jolly 1965, Seber 1965), as well as to determine residence time (travel time) in these key areas.

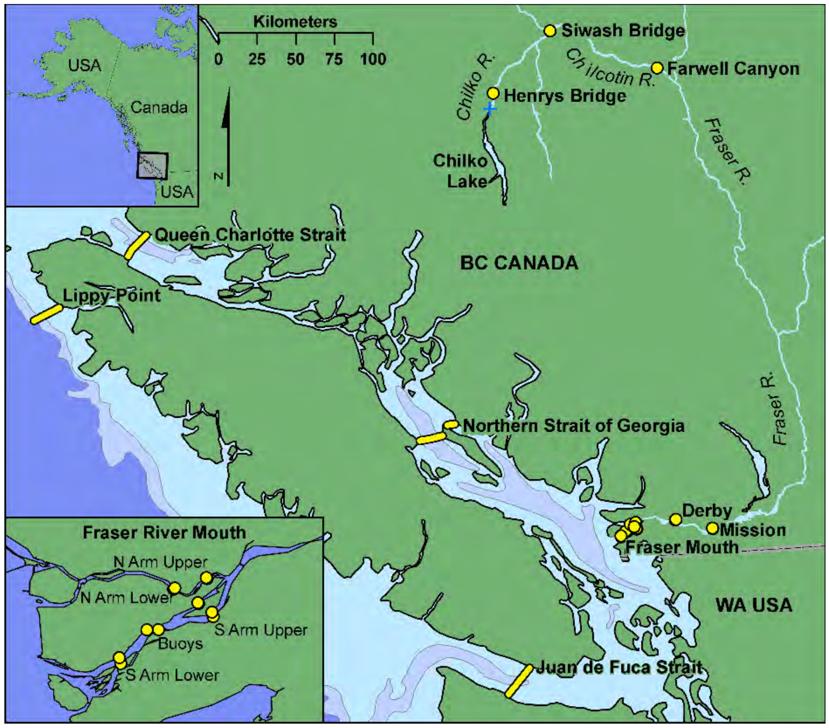

Figure 37-1. Map of the acoustic receiver array (yellow lines and dots) used to track juvenile Chilko Lake (Fraser River) Sockeye Salmon. Components of the array are variously managed by Kintama Research Services, the University of British Columbia and the Ocean Tracking Network (OTN). The blue cross represents the Chilko Lake release site in 2010-2014. Isobaths (200 and 500 meter) are coloured in pale blue. The Salish Sea includes Puget Sound to the south, the Strait of Georgia to the north and Juan de Fuca Strait to the west. The Lippy Point sub-array was not deployed in 2012-2014.

37.3. Chilko Lake Sockeye Early Migration Survival Estimates

Survival of Chilko Lake Sockeye in 2014 was average in each of the major migration segments relative to the time series. In 2014, freshwater survival from the DFO-managed enumeration weir at the outlet of Chilko Lake to the Fraser River mouth was 39% (SE=3%). This was consistent with previous years, when survival ranged between 21-48% in 2010-2013 (Table 37-1).

In those years when survival was estimable at the confluence of the Chilcotin and Fraser rivers, we found that most of the mortality occurred within the first 178 km (in the Chilko and Chilcotin rivers), and very little mortality occurred during the nearly 400 km migration through the Fraser River (see Figure 37-2; all 2011 treatment types and 2012 V5). This was further demonstrated by an additional treatment group released in 2011, where tagged smolts were transported 80 km downstream of the high mortality area in the Chilko River prior to being released. Subsequent mortality in the Chilcotin River of transported smolts was similar to the other treatment groups, but again very little mortality occurred once smolts reached the Fraser River (not shown). Extensive predation of smolts by bull trout (*Salvelinus confluentus*) in the Chilko River was observed during the study, and may account for a significant proportion of the post-release mortality observed for tagged fish (Furey et al. 2015).

Table 37-1. Survival of two-year-old Chilko Lake Sockeye smolts, 2010-2014. NSOG=Strait of Georgia sub-array, QCS=Queen Charlotte Strait sub-array, NA=not applicable because 180 kHz V5 and V6 transmitters could only be detected on freshwater receivers.

Year	Transmitter Type	n	Chilko Lake to Fraser River mouth	Fraser River mouth to NSOG	NSOG to QCS
2010	V7	199	0.21 (0.04)	0.76 (0.23)	0.17 (0.09)
2011	V7	254	0.31 (0.04)	0.38 (0.10)	0.61 (0.18)
2011	V6	200	0.32 (0.05)	NA	NA
2012	V7	386	0.29 (0.03)	0.77 (0.18)	0.31 (0.10)
2012	V5	199	0.34 (0.03)	NA	NA
2013	V7	203	0.48 (0.04)	0.82 (0.23)	0.24 (0.09)
2014	V7	236	0.39 (0.03)	0.57 (0.10)	0.28 (0.09)

Subsequent survival from the Fraser River mouth to the northern Strait of Georgia was 57% (SE=10%), which was also within the range of survival estimated in previous years (38-82%).

Survival from the northern Strait of Georgia through the Discovery Islands, Johnstone Strait and much of Queen Charlotte Strait was lower (28%; SE=9%), also consistent with previous years (17-61%). Survival estimates in this segment may potentially be somewhat underestimated due to weakening tag output by the time smolts reached the QCS sub-array, and although no mortality occurred in dummy-tagged smolts (held for eight days following tagging), the true effect of tagging is unknown. Should weakening tags or tagging-related mortality occur, it would bias our estimates of survival lower than the actual survival of untagged Sockeye smolts.

During the five year study, only three Chilko smolts were detected migrating via the southern route through Juan de Fuca Strait, all in 2011. Two of these three fish were later detected on the Lippy Point sub-array on the northwest tip of Vancouver Island.

Cumulative smolt survival from Chilko Lake to northern Vancouver Island, a distance of 1044 km, was similar to other years: 9% (SE=6%; Figure 37-2). In 2011-2013 cumulative survival ranged between 7-10%. In 2010, cumulative survival was only 3%; however, most of the additional mortality occurred in freshwater prior to entering the ocean (Table 37-1).

2014 was the fifth year for which we estimated survival of wild Chilko Lake Sockeye smolts. On average 1/3 of smolts survive the freshwater migration, of those fish about 2/3 survive the migration through the Strait of Georgia, and of those survivors about 1/3 survive the migration through the northern-most area between the NSOG and QCS sub-arrays.

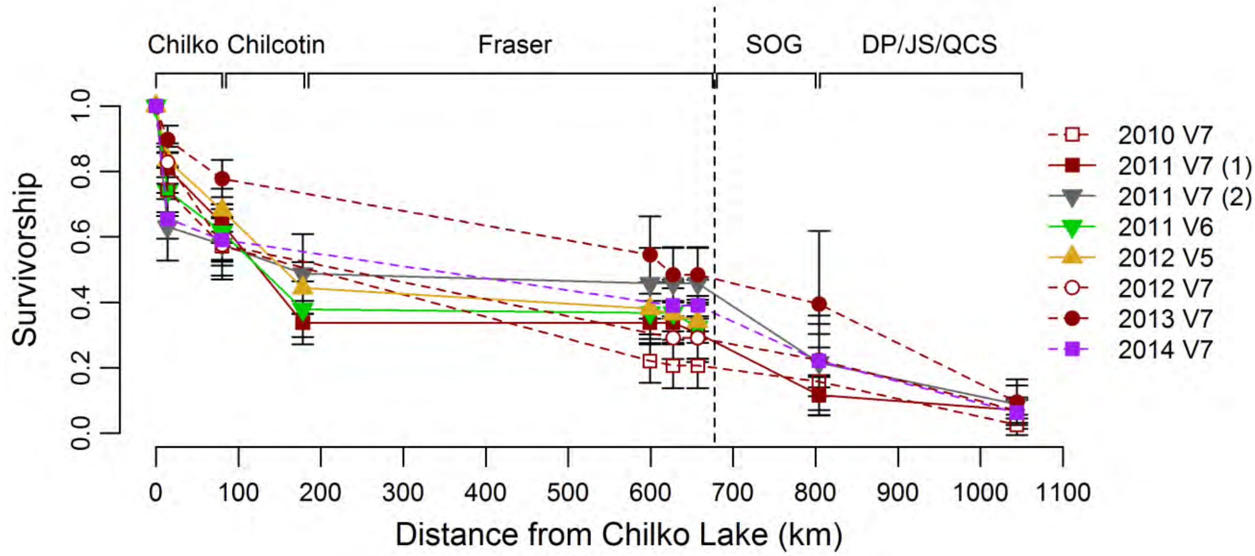

Figure 37-2. Cumulative survival of wild, two-year-old Chilko Lake Sockeye smolts from release at the DFO counting fence near the outlet of Chilko Lake to the Queen Charlotte Strait sub-array (QCS; NE Vancouver Island). SoG=Strait of Georgia, DP/JS/QCS=Discovery Passage/Johnstone Strait/Queen Charlotte Strait. Smolts were implanted with 5 mm, 6 mm, or 7 mm diameter VEMCO transmitters (5 mm and 6 mm tags could only be detected in freshwater). In 2011, smolts were released at the DFO fence (2011 V7 (1)), and a group of smolts was transported via truck and then released near the fence (2011 V7 (2)) as a control group for smolts that were transported downstream (not shown). The dashed vertical line represents the Fraser River mouth. Error bars are 95% confidence intervals. In 2010 and 2012-2014 we could not separate Chilcotin and Fraser River survival for smolts tagged with 7 mm tags because receivers were either not deployed (2010) or did not detect smolts at that location (2012-2014).

In 2004-07, we made similar measurements for hatchery-reared Cultus Lake Sockeye smolts migrating down the lower Fraser River, through the Salish Sea, and up to northern Vancouver Island, including the crucial 2007 smolt outmigration year which led to extremely low returns in 2009 (see Welch et al. 2009). Thus, we now have nine years of direct, telemetry-based survival measurements for Sockeye smolts along the inner coast of Vancouver Island. As with Chilko smolts, on average 2/3 of the Cultus Lake smolts survived the migration through the SoG (range=38-92%). Subsequent survival in the area to the north was higher for Cultus Lake smolts: about 1/2 survived this area (37-60%) vs. about 1/3 of Chilko lake smolts.

37.4. Sockeye Daily Survival Rates

Daily survival rates of Chilko Lake Sockeye in freshwater were lower than Cultus Lake Sockeye (Figure 37-3) due to the higher mortality experienced in the Chilko and Chilcotin rivers (Figure 37-2). Chilko Sockeye smolts had consistently higher daily survival rates in the SoG in all years than were experienced in freshwater, and these SoG survival rates were similar to survival rates measured for Cultus Lake Sockeye in prior years. Subsequent daily rates of survival during migration through the Johnstone

Strait, Discovery Passage, and Queen Charlotte Strait region were generally lower and more variable than in the SoG for both Chilko and Cultus Lake smolts.

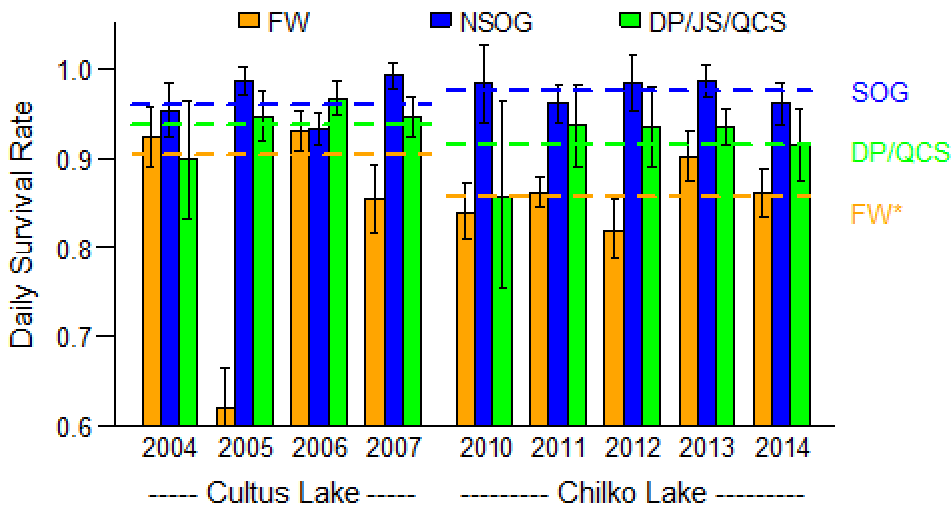

*Figure 37-3. Daily survival rate for two-year-old hatchery-reared Cultus and wild Chilko Lake Sockeye smolts in the Fraser River basin (FW), to the northern Strait of Georgia (NSOG) and through Discovery Passage/Johnstone Strait/Queen Charlotte Strait (DP/JS/QCS). The six dashed horizontal lines indicate the multi-year average survival rate for each population in each of three habitats. *The FW average excludes 2005 Cultus Lake Sockeye survival (see Welch et al. 2009). Error bars show 95% confidence intervals.*

37.5. Chilko Smolt Residence Time in the Strait of Georgia and Queen Charlotte Strait

Travel time from Chilko Lake to the Fraser River mouth was approximately one week in all years (median travel time ranged from 5-9 days). Median travel time from the Fraser River mouth to the Northern Strait of Georgia (NSOG) sub-array (4/5 of the Strait of Georgia, 147 km) ranged between 11-18 days among years (13 days in 2014; Figure 37-4). As the mean travel rate was 1 body length per second (BL/sec) from the Fraser River mouth to the NSOG sub-array, the travel time through the upper 1/5 of the SoG (about 40 km) is likely an additional four to six days. The maximum observed travel time to the NSOG sub-array ranged between 28-43 days in 2010-2014 and 95% of smolts had passed the NSOG sub-array by June 7 in 2014, June 10 in 2013, June 9 in 2012, June 12 in 2011 and June 16 in 2010, indicating that nearly all two-year-old smolts migrate through the SoG by mid-June. Assuming a migration rate of 1 BL/sec for smaller, one-year-old smolts, migration through the SoG may take an additional week to 10 days.

Median travel times from the NSOG sub-array to the QCS sub-array were similar to those in the SoG despite the longer distance (240 km): 9-15 days in 2010-2013, and 14 days in 2014 because mean migration speeds nearly doubled to 1.8 BL/sec. 95% of smolts had reached the Queen Charlotte Strait sub-array by June 19 in 2014, June 25

in 2013, June 16 in 2012, June 23 in 2011 and June 28 in 2010. Therefore, by early July most two-year-old smolts have reached the central coast of British Columbia. Smaller, one-year old smolts may take an additional 2-4 days to swim from NSOG to QCS, and thus they may reach the central coast by mid-July, consistent with Beacham et al. (2014).

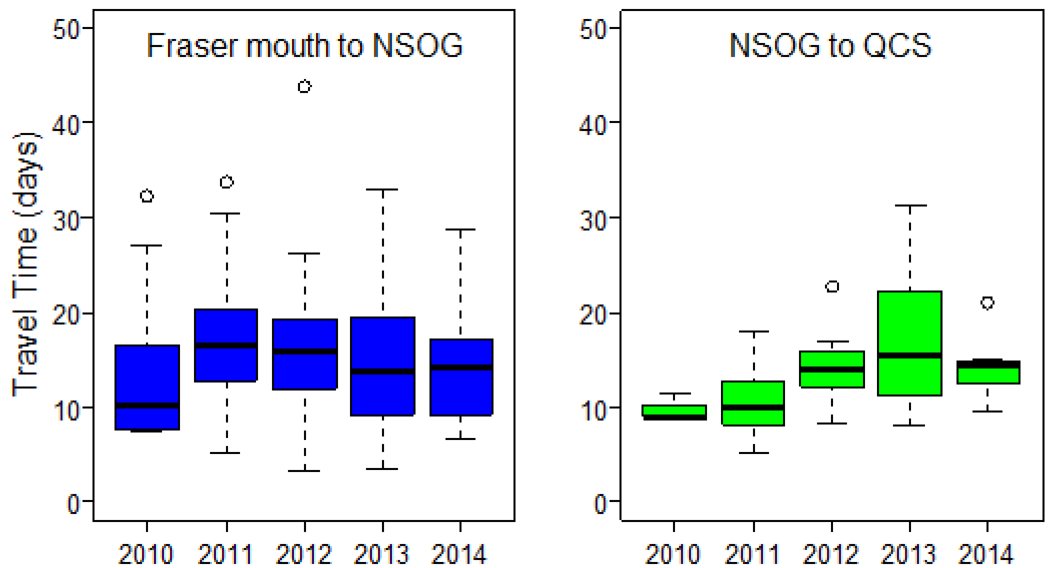

Figure 37-4. Annual travel times of acoustic tagged two-year-old Chilko Lake Sockeye smolts through (left) the Strait of Georgia (Fraser River mouth to NSOG sub-arrays) and (right) Discovery Islands/Johnstone Strait/Queen Charlotte Strait (NSOG to QCS sub-arrays), 2010-2014. The horizontal line within the box is the median, the top and bottom of each box shows the 25th and 75th percentiles, and the whiskers extend to the minimum and maximum values exclusive of outliers. Outliers are defined as exceeding 1.5 times the interquartile range and are shown as open circles.

37.6. Summary

Our multi-year results indicate that survival patterns of Chilko Lake Sockeye smolts are consistent among years, in that freshwater mortality appears to be largely confined to clearwater tributaries leading to the Fraser due to predation, and survival down the Fraser River mainstem is very high. Once in the ocean, daily survival rates are highest in the SoG and then decrease between NSOG and QCS. Travel times indicate that wild two-year-old Chilko Sockeye smolts and large hatchery-reared Cultus Lake smolts both migrate rapidly out of the SoG and Queen Charlotte Strait. Approximately one month after ocean entry, smolts are migrating along the central B.C. coast, consistent with findings from coastal trawl surveys (e.g. Beacham et al. 2014).

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38. FRASER RIVER SOCKEYE: ABUNDANCE AND PRODUCTIVITY TRENDS AND FORECASTS

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38.1. Highlights

- After a decade of declines in Fraser Sockeye total abundance and survival (recruits-per-spawner), which was the impetus for the Cohen Inquiry, Fraser Sockeye survival has been average in the past five years (2010-2014).
- Chilko marine survival, the only stock for which total survival can be partitioned into freshwater and marine over a long time series, has exhibited similar trends to the Fraser Sockeye aggregate; survival has been average in the past five years.
- Fraser Sockeye returns in 2015 are expected to be average, although the anomalously warm northeast Pacific and its effect on Fraser Sockeye survival is currently uncertain. Most fish returning in 2015 would have entered the ocean in the spring of 2013, when the northeast Pacific shifted to warmer than average temperatures.

38.2. Summary

Most Fraser Sockeye Salmon return to freshwater to spawn as four year old fish, after generally spending their first two winters in freshwater, and their last two winters in the ocean. After their second winter in freshwater, Fraser Sockeye smolts migrate downstream in the Fraser River, and enter the Strait of Georgia. They migrate rapidly northward in the Strait of Georgia (Preikshot et al. 2012; Rechinsky et al. 2015), and move into the North Pacific via the Johnstone Strait. Fraser Sockeye juveniles continue their northward migration along the continental shelf, move into the North-East Pacific in their first winter at sea (Tucker et al. 2009), and then spend one more winter in the marine environment before they return to their natal spawning grounds as adults.

Total Fraser Sockeye adult returns have historically varied (Figure 38-1A) due to the four-year pattern of abundances (cyclic dominance) exhibited by some of the larger stocks, and variability in annual survival (Figure 38-1A & B) and exploitation. After reaching a peak in the early 1990s, returns decreased to a record low in 2009 due to declines in stock survivals. In subsequent years, survival, and consequently, returns have increased. The 2010 and 2014 returns were particularly large since this is the dominant cycle line for the Late Shuswap stock, and the combination of above average escapements relative to other cycle lines and above average to average survivals resulted in large returns in these years. The aggregated Fraser Sockeye trend largely represents stocks that comprise the greatest proportion of total Fraser Sockeye abundance, namely Summer Run stocks (based on return timing of adults to their spawning grounds) such as Chilko and Quesnel.

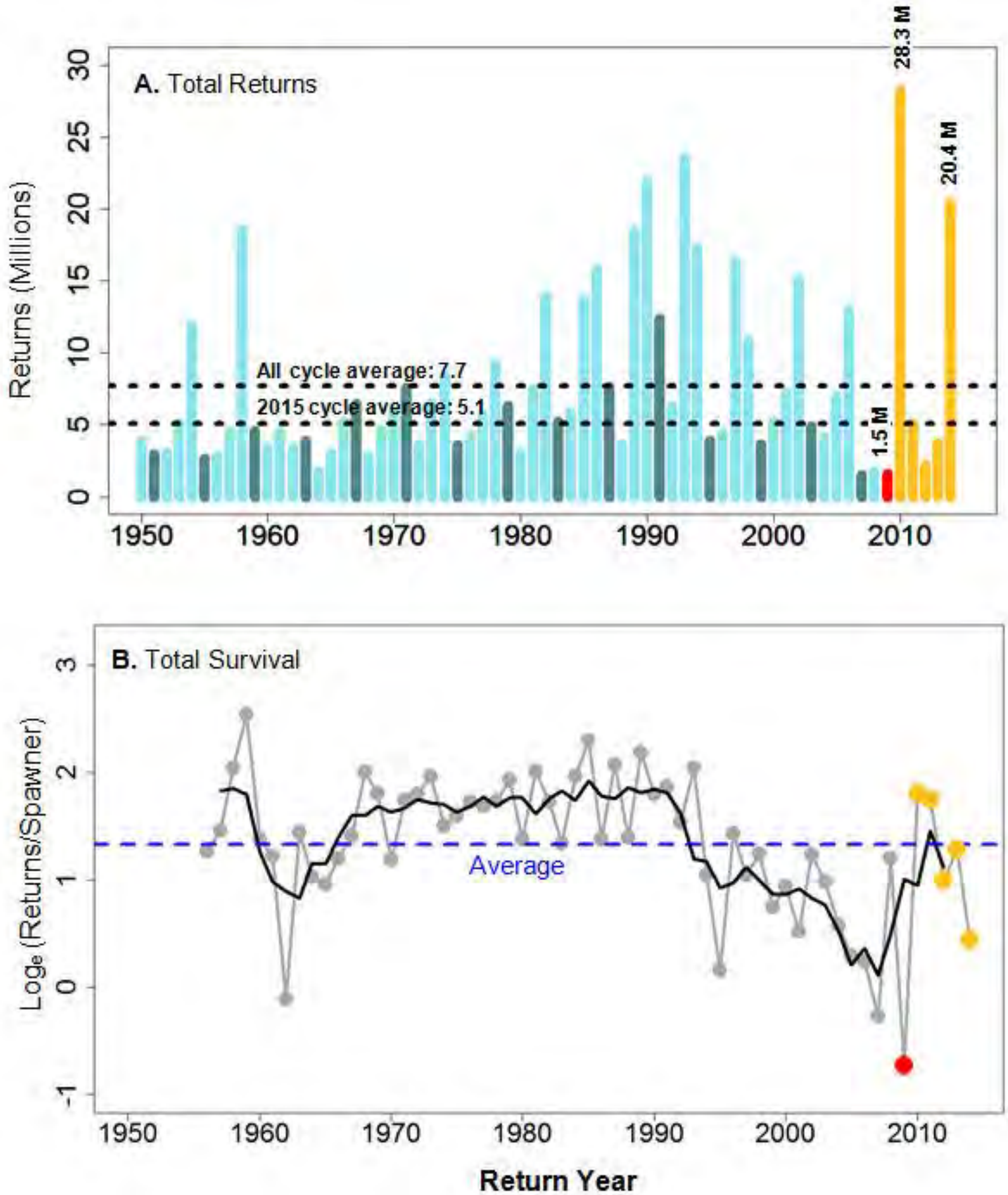

Figure 38-1. A) Total Fraser Sockeye annual returns (dark blue vertical bars for the 2015 cycle and light blue vertical bars for the three other cycles). Recent returns from 2012 to 2014 are preliminary. B) Total Fraser Sockeye survival ($\log_e$ (returns/total spawner)) up to the 2014 return year. The light grey filled circles and lines present annual survival and the black line presents the smoothed four year running average. For both figures, the blue dashed line is the time series average. The red vertical bar in panel A (or filled circle in B) represents the 2009 returns (low survival), and the yellow vertical bars in panel A (or filled circles in B) represent the 2010 to 2014 returns (average survival for the Fraser Sockeye aggregate).

Considerable Fraser Sockeye mortality occurs in the marine ecosystem, as indicated by Chilko River Sockeye (Fraser Sockeye indicator stock) marine survival data (Figure 38-2 and Figure 38-1). Chilko is the only Fraser Sockeye stock with a long and complete time series of smolt data (counted through an enumeration weir located at the outlet of Chilko Lake), which can be used with escapement and return data to partition total survival into freshwater and 'marine' components ('marine' survival includes their migration downstream from the counting weir to the Strait of Georgia). 'Marine' survival data for Chilko, similar to the aggregated Fraser Sockeye survival trend, exhibited declines in the 1990's, which culminated in the lowest survival on record in the 2005 brood year (2009 return year). Subsequently, marine survival has generally improved (Figure 38-2).

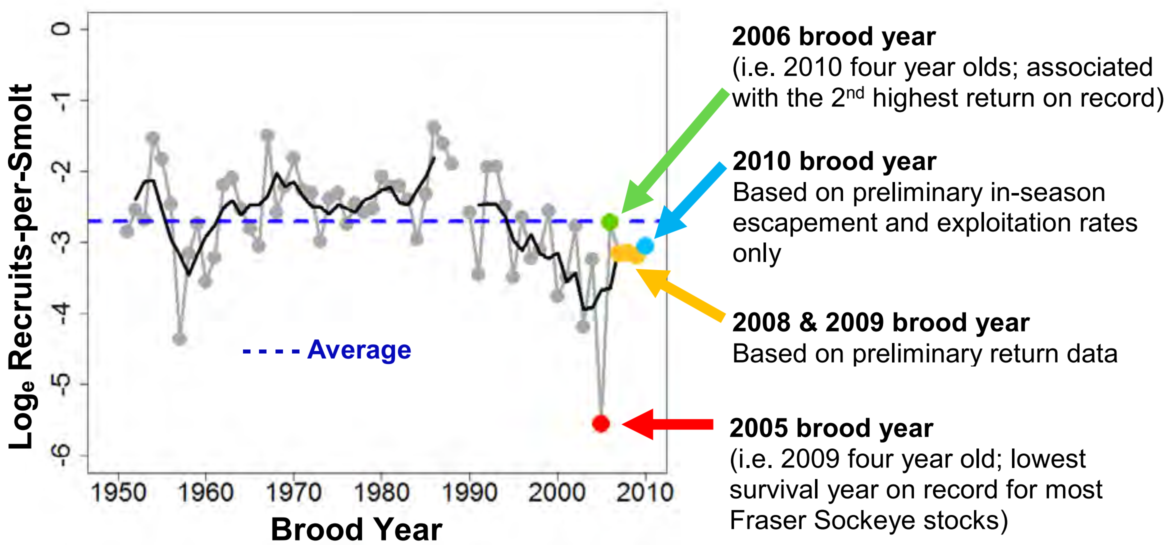

Figure 38-2. Chilko River Sockeye 'marine' (log_e recruits-per-smolt) annual survival (filled grey circles and grey lines) and smoothed four-year running average survival (black line). The 2005 brood year (2009 return year) was the lowest survival observed for Chilko Sockeye (red-filled circle) and the 2006 average survival was associated with the second largest return on record (2010). The 2007 to 2010 brood years (2010 to 2014 return years; amber-filled circles) exhibited closer to average survival. Note: Chilko 'marine' survival includes a freshwater period during their downstream migration as smolts from the outlet of Chilko Lake to the Strait of Georgia. The blue dashed line indicates average survival.

Across the individual Fraser Sockeye stocks, however, there has been considerable variability in survival. Although most stocks, such as Chilko and Stellako have exhibited declining trends in the 1990's, some stocks, such as Late Shuswap, have not exhibited any systematic trends, and one stock in particular (Harrison Sockeye) has increased in survival in recent years (Figure 38-3). The common feature amongst all stocks is that survival for the 2005 brood year was below average, and in many cases was the lowest on record, and survival in recent years has been close to average (Figure 38-3).

To capture inter-annual random (stochastic) uncertainty largely attributed to Fraser Sockeye survival, return forecasts are presented as standardized cumulative

probabilities (10%, 25%, 50%, 75%, and 90%), using Bayesian statistics, rather than as single deterministic point estimates (Grant et al. 2010, DFO 2015a). At the 25% probability level, for example, there is a one in four chance the actual return will fall at or below the specified return prediction, given the historical data. Fisheries and Oceans Canada (DFO) fisheries managers use these forecast probability distributions to frame out the range of fishing opportunities that stakeholders may expect in the upcoming year. These return forecasts are also applied, in concert with run timing forecasts, as additional information for test-fishery and hydro-acoustic models, used to manage the fisheries in-season. As the fishing season proceeds and more in-season data become available, the pre-season forecasts have a diminishing influence on in-season return estimates.

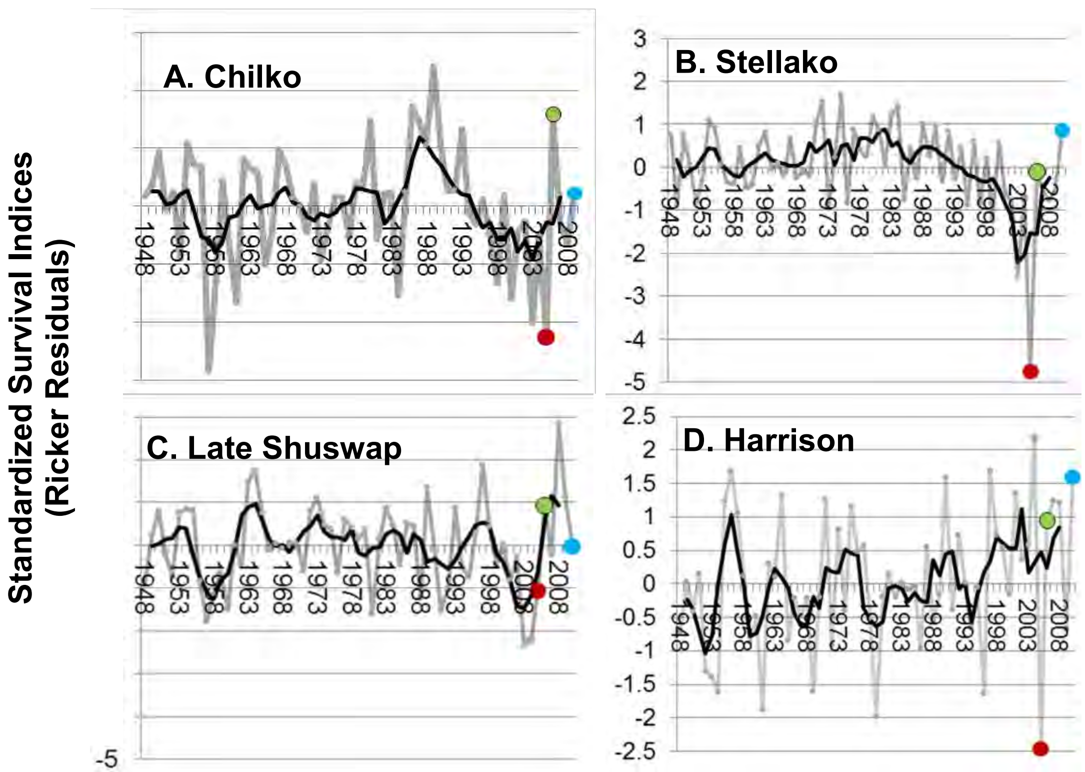

Figure 38-3. Fraser Sockeye survival (standardized z-scores of Ricker model residuals) up to the 2014 return year for A) Chilko Sockeye; B) Stellako Sockeye; C) Late Shuswap Sockeye; and D) Harrison Sockeye. The grey filled circles and line presents annual productivity and the solid black line presents the smoothed four-year running average. The 2005 brood year (2009 return year) (red circle), the 2006 brood year (2010 return year) (green circle) and 2010 brood year (2014 return year) (blue circle) are indicated; these recent data are preliminary.

The 2015 return forecast indicates a one in four chance (25% probability) the total Fraser Sockeye return will be at or below 3,824,000 (lowest observed on this cycle) and a three in four chance (75% probability) it will be at or below 12,635,000, assuming

survival is similar to past observations (DFO 2015a). The mid-point of this distribution (50% probability) is 6,778,000 (there exists a one in two chance the return will be at or below this value). The 2015 forecast falls close to the cycle average at these probability levels. Chilko and Harrison Sockeye contribute the greatest percentage (60%) to this total forecast. Given the larger escapements in the 2010 brood year (five year olds returning in 2015) compared to the 2011 brood year (four year olds returning in 2015) for a number of stocks, five year olds are predicted to occur in much higher percentages than average (average five year olds in total returns: 12%): Early Stuart (95% five year olds), Nadina (78%), Pitt (63%), Late Stuart (52%), Quesnel (56%), and Stellako (52%).

Similar to the previous year's forecast (DFO 2014a, DFO 2014b), a supplement Canadian Science Advisory Secretariat (CSAS) paper was produced as part of the 2015 forecast process (DFO 2015b). This supplement provides additional information on the condition and abundance of various stocks from the 2011 brood year escapement through to 2014 jack returns. Generally, Chilko dominated the stock composition across the various life-history stages assessed, including the adult escapements in 2011, downstream migration of smolts at Mission from April to May 2013, and Strait of Georgia in 2013. Harrison, given this stock has a different age structure and life-history stage, was not included in these comparisons of relative stock proportions. Forecasts generated using jacks (three year old) returns in 2014 to predict four year old returns in 2015 indicated a lower return for Chilko Sockeye relative to the official forecasts (DFO 2015a); given the lower predicted abundances in the 2015 returns only a few stocks had large enough jack abundances to be used in sibling forecasts. Information on ocean conditions was also provided in the supplement (DFO 2015b), which highlighted the anomalously warm northeast Pacific in the second half of 2013 through to present. It is currently unclear how these warm conditions have effected Fraser Sockeye survival from the 2013 ocean entry year through to the 2015 returns.

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Topical reports on Ocean Acidification

39. OCEAN ACIDIFICATION ON THE PACIFIC COAST OF CANADA

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39.1. Highlights

- Ocean acidification is becoming an increasing concern in coastal NE Pacific, but few data are available.
- The outer coast of B.C. waters have naturally high acidity, which may make this region more vulnerable to increased acidification.
- All marine organisms in outer coast B.C. waters experience (for at least part of their lives) pH that is lower than the current global average, although little is known of the impacts of ocean acidification to mid- and upper trophic level species.

39.2. Summary

Ocean acidification (OA) is becoming an increasing concern in the coastal northeast Pacific and yet few measurements of carbon parameters (from which acidity – pH can be estimated) have been made in the region compared with other hydrographic parameters like oxygen and nutrients. In the coastal zone of British Columbia there is no funded routine monitoring of carbon parameters by DFO at present. Data are few in part because quantifying pH and the carbon system in seawater is challenging (Brewer 2013).

Locally, concern over OA is particularly high because the shellfish aquaculture industry has experienced significant difficulty (Saunders 2015). These difficulties, and their association with OA, are well-documented in the neighbouring US waters (e.g. Washington State Blue Ribbon Panel 2012, Barton et al. 2012). In the Strait of Georgia in 2015, local shellfish farmers have had to rely on Chilean sources to obtain about half the oyster seed necessary for their season (Roberta Stevenson, BC Shellfish Growers Association, Comox, B.C., pers. com.). In addition, while many aspects of climate change remain uncertain, the chemistry of increasing CO_2 in the ocean is certain (Doney et al. 2009).

On the outer B.C. coast, local waters tend to have high acidity naturally because the subsurface North Pacific waters are ‘old’, i.e. they have had a lot of time to accumulate organic matter, which becomes CO_2 and so increases acidity when it decays (e.g. Feely et al. 2012). Therefore, this region may be more vulnerable to OA (Feely et al. 2008). Because of the highly dynamic circulation, these waters also experience large variability in carbon content and pH (Ianson and Allen 2002, Haigh et al. 2015). Given that our first data in the region were collected in 1998 (Ianson et al. 2003) we do not have a long enough time series to elucidate trends (Ianson 2013, Christian 2014).

Since variability is so high and subsurface pH is generally low, all marine organisms in B.C. waters currently experience pH values that are significantly lower than the present-day surface global average of 8.1 (Raven et al. 2005) at least some of the time (Figure 39-1). In fact many organisms spend their entire time below the benchmark level of 8.1 (e.g. Rockfish, Haigh et al. 2015).

Some organisms have been relatively well studied with respect to effects of increased acidification, e.g. calcifying phytoplankton (Riebesell and Tortell 2011). However, many other organisms have not been well-studied. In B.C. waters, little is known about the impacts of OA on organisms above a trophic level of two or three (Figure 39-2).

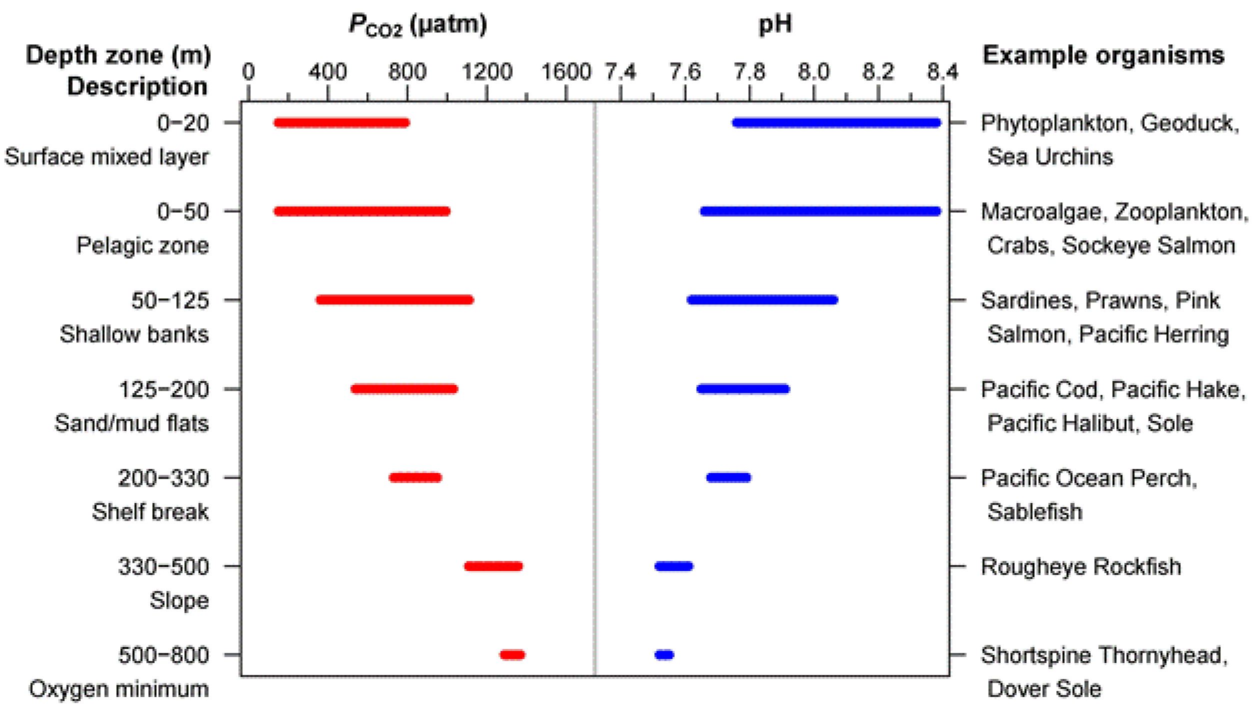

Figure 39-1. Estimated present-day ranges of P_{CO2} (red) and pH (blue) during spring and summer for various depth zones along the outer B.C. continental shelf, with typical species found in each zone. There are numerous data above 50 m and few below 125 m. The number of values in each depth zone from top to bottom are: 70, 116, 33, 45, 5, 4 and 2, respectively. Above 50 m, the distributions of values are skewed, such that high P_{CO2} (low pH) extremes occur less often than the low P_{CO2} (high pH) extremes (figure from Haigh et al. 2015; see paper for original figure and caption, detailed explanations, data, code and references).

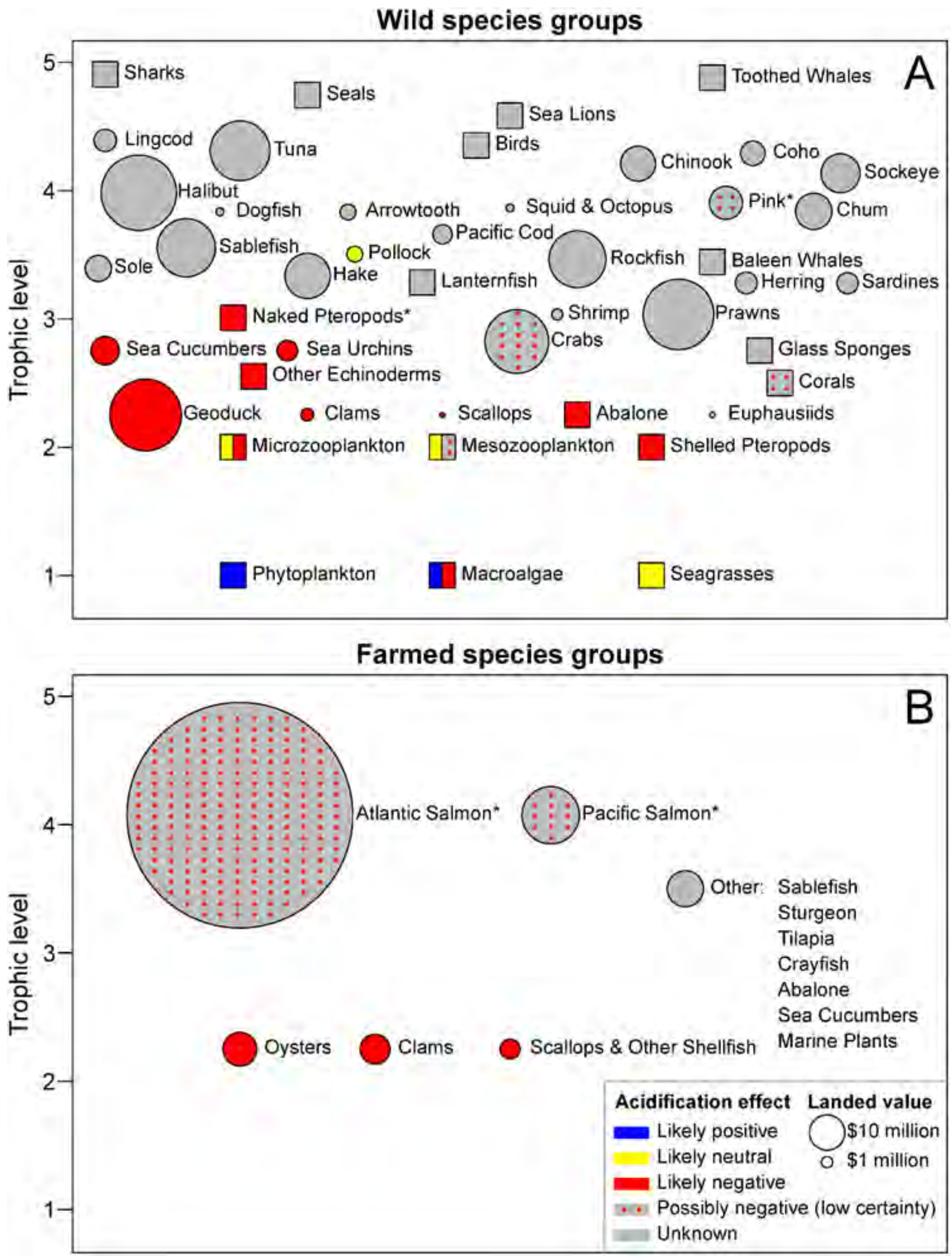

Figure 39-2. Summary of ocean acidification effects on (A) wild, and (B) farmed species groups in B.C. waters, including landed value for those that are fished or farmed. Species groups are arranged vertically by trophic level. Areas of circles are proportional to the landed values in 2011. Squares represent species groups that are not commercially harvested. Solid colours represent the likely direct effects of ocean acidification. Stippling refers to possible effects. For species marked by an asterisk (*), colours represent indirect effects (figure from Haigh et al. 2015; see paper for original figure and caption, detailed explanations, data, code and references).

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40. ACIDIFICATION OF COASTAL WATERS AND THE IMPACTS ON COMMERCIAL SCALLOP PRODUCTION

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40.1. Highlights

- Conditions persist that threaten the viability of commercial scallop aquaculture in the Strait of Georgia.

40.2. Summary

Island Scallops Ltd (ISL) was established in 1989 as an economic entity to produce seed and harvest cultured adult Pacific Scallop. Its research and production facility on the east coast of Vancouver Island draws bottom water from a depth of 25 m in the Strait of Georgia (Qualicum Bay) and the properties of this water has a direct impact on the viability of its operations.

Since 2009 additional monitoring has been required to examine the causes of mass mortalities of immature scallops. Low pH of the source water has been the focus of this research. It is generally understood that acidification of the water is more corrosive to the shells of young scallops and requires them to use more energy to extract what they need from the water to build their shells and avoid predators and infection. In the larval stages pH less than 7.8 and pCO_2 less than 750 ppm will result in high mortality within eight days.

Experimentation to mechanically vary the concentrations of pCO_2 at different life stages (and lower the pCO_2 levels to below 400 ppm in nursery tanks) has verified the link between pCO_2 concentration and scallop health.

Natural variability in the source waters (temperature, salinity, dissolved oxygen concentration and pH) continues to be monitored. A Pro-Oceanus Mini-Pro Membrane Analyser is used for field measurements and a LICOR 840A in combination with an equilibrium chamber for hatchery water.

40.3. References

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41. VANCOUVER AQUARIUM DATA ON OCEAN ACIDIFICATION

Jeffrey B. Marliave[1], Laura A. Borden[2], Skip Young[3] and Jessica A. Schultz[4]

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41.1. Highlights

- Local upwelling can create markedly different oceanographic conditions over very small spatial scales.
- There may be a step-function decrease in pH in response to climate regime shifts (with regime shifts defined based on ONI/ENSO data, not PDO).

41.2. Summary

Seabed monitoring by the Vancouver Aquarium's Howe Sound Research dive team has in the last two years included oceanographic monitoring of seawater conditions approximately 1 m off bottom at 16 m depth (zero tide) on two sides of a barrier reef between Howe Sound and Strait of Georgia, separated by only 74 m (Figure 41-1). Tide-forced upwelling on the Howe Sound side of this reef yields consistently cooler temperatures than the Strait of Georgia side, using temperature data from benthic temperature loggers at 16 m (Figure 41-2). Data on pH monitoring at these reef sites is not included here, as only one sonde buoy was available and its deployment on the Howe Sound side in winter 2013/2014 yielded very different results from the deployment on the Strait of Georgia side in winter 2014/15, two winters that markedly contrast in terms of surface temperatures that relate to the North Pacific "warm blob" discussed elsewhere in this State of the Pacific Ocean report. Future work will require two buoys simultaneously at the two sites in order to determine whether pH also varies over such small spatial scales.

Long-term pH records for the seawater intake at the Vancouver Aquarium (also at approximately 16 m depth at zero tide) have been reported for 1968-2010 (Marliave et al. 2011). The Aquarium's pH data for 2011-2015 are graphed on a bimonthly basis in Figure 41-3. Extending the modal/range pH graph for 1968-2010 (Marliave et al. 2011) to include 2011-2015 is depicted in Figure 41-4, together with arrows for possible regime shifts defined by the Oceanic Nino Index (ONI).

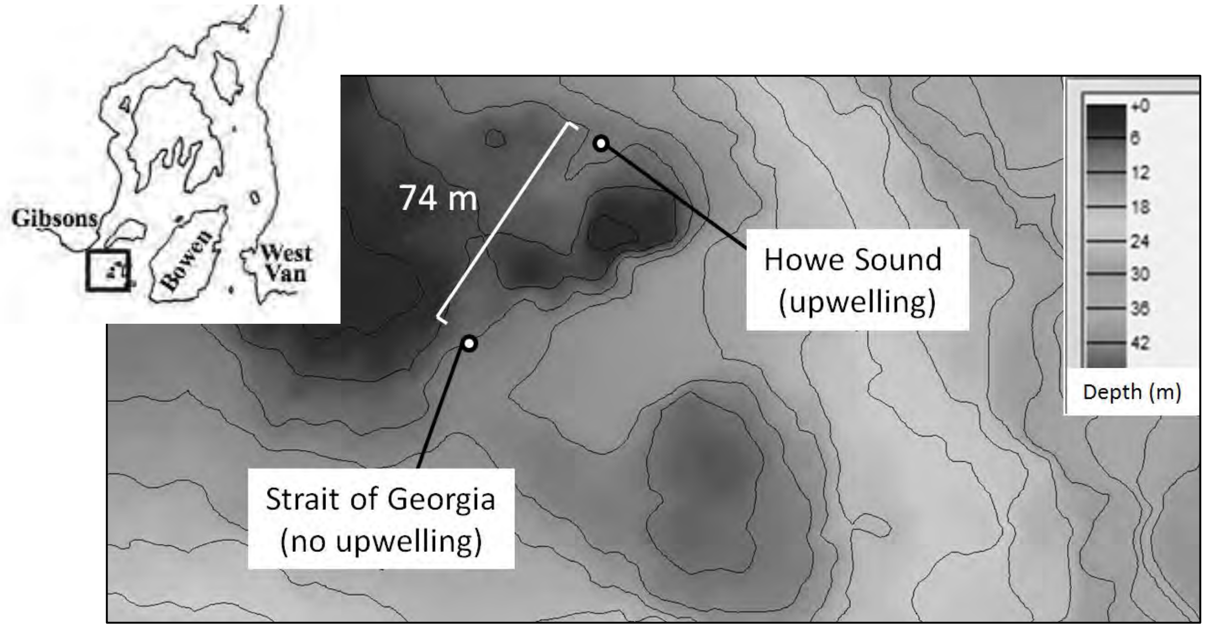

Figure 41-1. Depth contour map of the "Mystery Reef" study site. Oceanographic parameters were measured both on the Howe Sound side, where water movement is most influenced by tidal upwelling, and the Strait of Georgia side, where water movement is most influenced by counter-clockwise net transport.

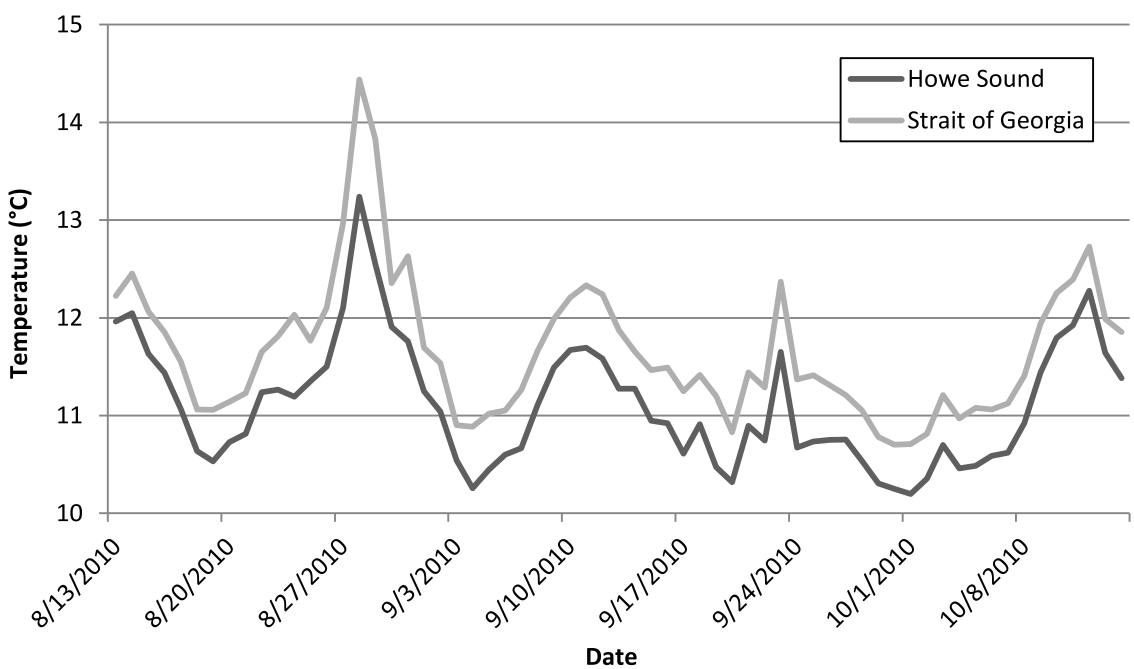

Figure 41-2. Mean daily temperature recorded simultaneously at both the Howe Sound and Strait of Georgia side of the Mystery Reef using benthic temperature loggers at 16 m (zero tide). Although variable, the Howe Sound side, where upwelling is common, is consistently colder than the Strait of Georgia side.

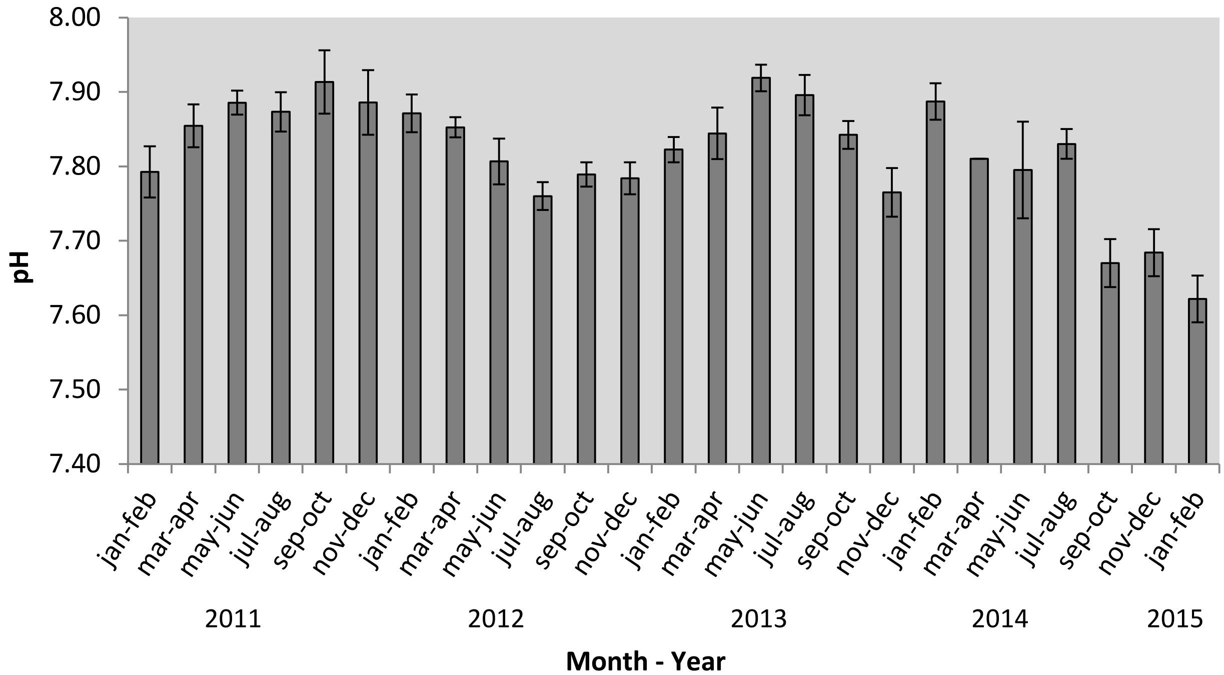

Figure 41-3. Mean bi-monthly pH recorded at the Vancouver Aquarium intake reservoir for seawater pumped from Burrard Inlet First Narrows at 16 m in depth from January 2011 to February 2015. Error bars represent standard error.

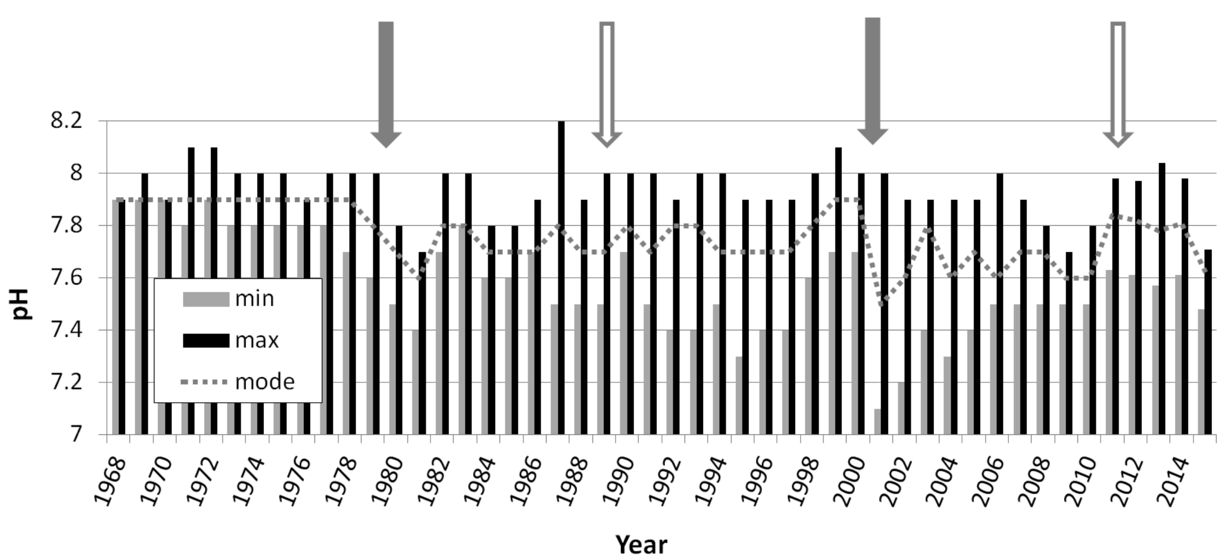

Figure 41-4. The minimum (grey bars), maximum (black bars) and modal (dotted line) pH, as recorded from the Vancouver intake reservoir from Burrard Inlet First Narrows from 1968 to 2015. Solid arrows indicate commonly agreed upon climate regime shifts while hollow arrows indicate climate regime shifts that are contentious.

The possible ONI (El Niño Southern Oscillation [ENSO]) climate regime shifts in Figure 41-4 include a proposed 2011 shift that is indicated by unpublished observations of seabed life by the Aquarium's Howe Sound team. What stands out in the graph is the appearance of drops in modal pH after the major 1978 and 2000 climate regime shifts, followed by a plateau at lower modal pH values. Note as well that recently the minimum pH values have varied more interannually than the maximum values. Preceding the drop after 2000 was a spike in pH during 1999 and 2000. Similarly, there has been an elevation of pH in 2011-2014, followed by an abrupt drop to pH 7.6. If it turns out that 2011 was indeed another climate regime shift, then the drop from elevated pH should decline and then plateau at an even lower modal pH. What had appeared to be noise in the data for an apparent straight-line reduction of pH over time may somehow relate to biological responses to climate regime shifts so that there is a step-function reduction that yield plateaus at successively lower modal pH levels.

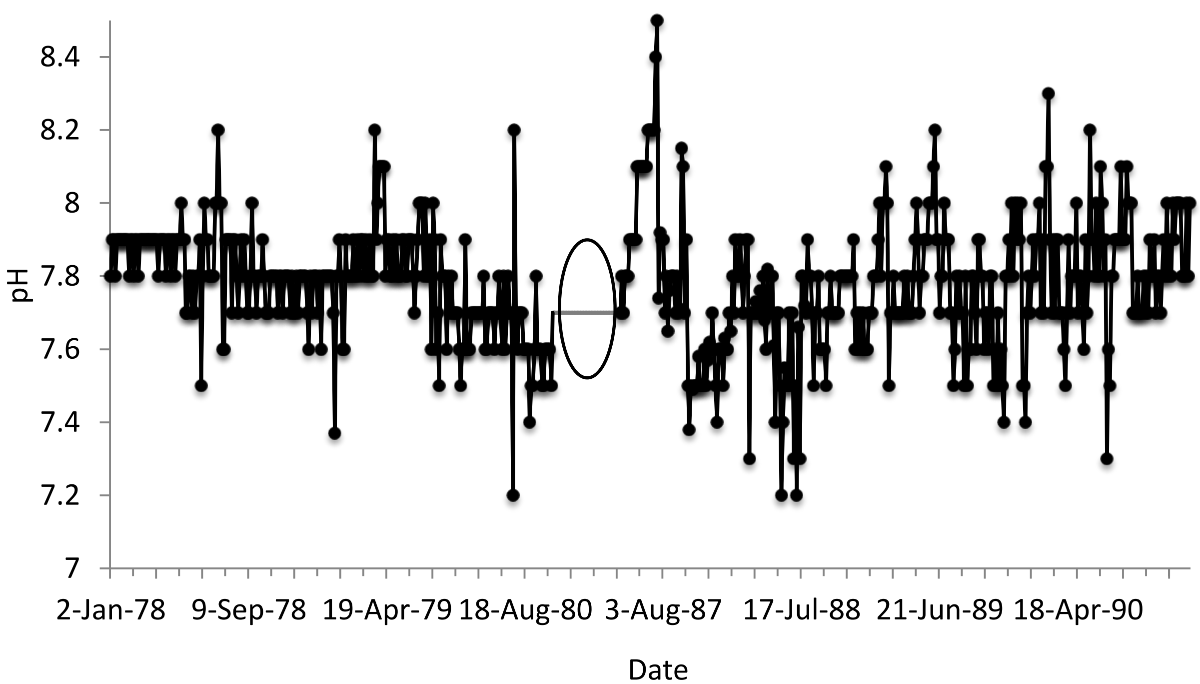

Figure 41-5. Seasonal variation in pH at the Vancouver Aquarium seawater intake in the First Narrows for selected years between 1978 and 1990. Ellipse indicates years for which inadequate data were recorded.

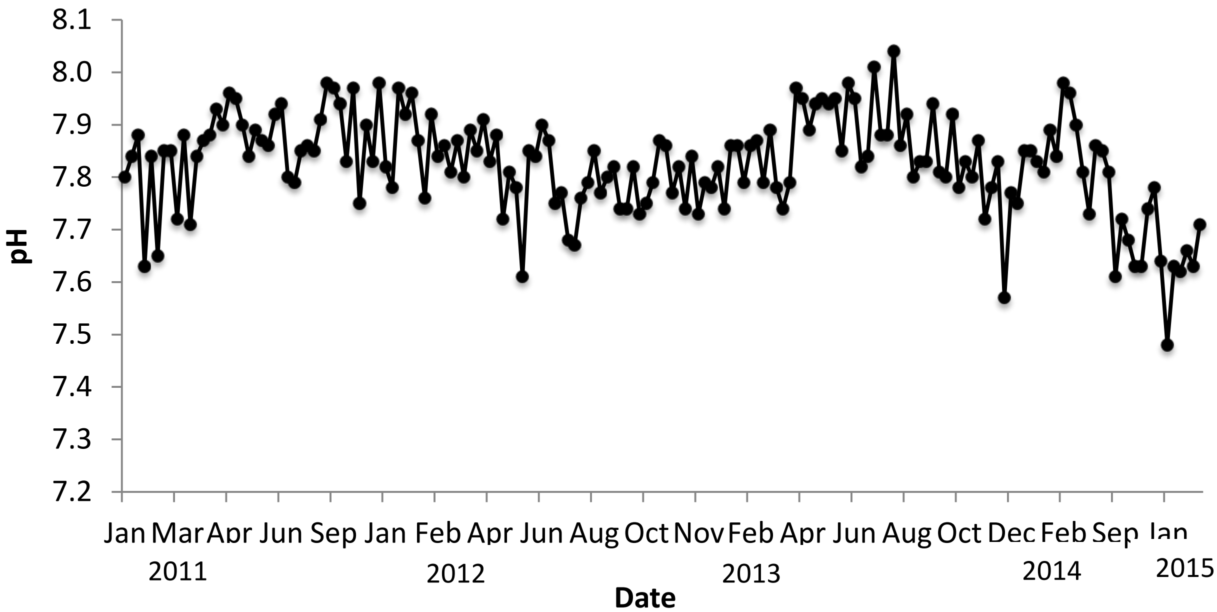

Figure 41-6. Vancouver Aquarium First Narrows intake seawater pH for 2011-2015 (N.B. fewer months of data in 2014), showing upward and downward trends in minimum and maximum pH values.

The trends in pH minima and maxima for the First Narrows (Figures 41-5 and 41-6) demonstrate trends that are out of synch between years, in terms of season. There was a downward trend in pH from January through June of 2012 (Figure 41-6), then a comparable downward trend from July through December of 2013, after a rise during February through June of 2013. The second half of 2012 had seen relatively stable pH. There was another rise in late 2013/early 2014, followed by a drop through to early 2015, as reflected in Figure 41-4.

Discussion at the State of the Pacific Ocean meeting involved queries about variation within seasons for different years. Figure 41-5 presents variations for selected years following the 1978 climate regime shift. Note that 1987 was an El Niño year and had elevated pH during spring and early summer.

41.3. References

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42. DEVELOPING A CANADIAN OCEAN ACIDIFICATION PROGRAM

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42.1. Highlights

- Roughly one-third of the carbon dioxide emissions from burning fossil fuels since 1750 have ended up in the oceans, lowering the pH of open ocean surface waters by about 0.1 units. The 2007 International Panel on Climate Change (IPCC) Fourth Assessment report forecasts that the pH would decrease by a further 0.14 to 0.35 units by the year 2100 (e.g. Denman et al. 2011).
- There are no ‘dense’ long time series of pH in the NE Pacific Ocean or in B.C. coastal waters. There are even less data for the saturation state for aragonite, the less stable mineral form of calcium carbonate which is used in the skeletal structures of corals, oysters, pteropods and other marine organisms.
- One decade-long time series (2001-2011) from Tatoosh Island, at the southern seaward end of the Strait of Juan de Fuca, estimates the mean surface pH has decreased from 8.3 to 7.7, with annual peak to peak variation of about 1 unit, i.e. a factor of 10 in H^+ ion concentration (Wootton and Pfister 2012).
- The Canadian Network of Centres of Excellence MEOPAR (Marine Environmental Observation, Prediction and Response) network has funded (March 2015) two initial projects towards establishing a national ocean acidification program.

42.2. Need for a Canadian national program on ocean acidification

Canada is lagging many other nations in setting up a national program to address the risks to commercial fisheries and coastal ecosystems from the ongoing and future increasing acidification of the ocean. In 2012, the US formed an extensive observation, research and management program on ocean acidification (OA) in its coastal regions (NOAA 2012), with states such as Washington State taking considerable action (Feely et al. 2012, Scigliano 2012). Also in 2012, after considerable urging by the European Union, the International Atomic Energy Agency established the Ocean Acidification International Coordination Centre (OA-ICC) at their laboratories in Monaco, *“… to communicate, promote and facilitate global activities on ocean acidification. It will serve the scientific community and science users (policy makers, the general public, media and other stakeholders)* “ (IAEA 2012). DFO considers ocean acidification as a priority issue, but implementing a national program to address OA has been slow due to lack of funding and not having an academic partner (such as MEOPAR).

In November 2013, MEOPAR issued its second open call for proposals to address scientific issues relevant to the MEOPAR goal of *" … building partnerships and a team of Canadian researchers to address critical issues related to human activity in the marine environment, and the impact of marine hazards on human activities in coastal regions."* In the autumn of 2014, after receiving two proposals to set up ocean

acidification research networks that were favourably reviewed, MEOPAR set up an Ocean Acidification Coordinating Committee (OACC) to coordinate these two initial projects and possibly additional projects in a MEOPAR Ocean Acidification Program.

42.3. Elements of a Canadian ocean acidification program

First, the OACC developed a list of essential elements for a Canadian OA program:

- Develop a 'Climatology' of pH and pCO_2 in Canadian coastal waters
- Identify key species (and ecosystems) at risk and potential impact on coastal communities and industries
- Strong collaboration with the Department of Fisheries and Oceans (research and management), other Canadian research networks, (e.g. Ocean Networks Canada, ArcticNet), and the international community
- Develop tools to predict probable extent and impacts on economically and culturally important marine species in Canada over the next few decades

The OA program is intended to be ‘porous’ – a collaboration between DFO, the MEOPAR community and relevant industrial partners. The MEOPAR OACC consists initially of:

- Ken Denman, University of Victoria
- Maurice Levasseur, Laval University
- Paul Lyon, Department of Fisheries and Oceans
- Ron Pelot, Dalhousie University

The two initial projects consist of 18 Prinicipal Investigators + 17 Collaborators:

i. Karen Kohfeld, Simon Fraser University, Leader

Themes

- Field observations – *Atlantic:* Gulf of St Lawrence, Scotian Shelf, and Labrador and Newfoundland Shelves; *Pacific:* Strait of Georgia – emphasis on northern Strait
- Biological interactions and impacts
- Biogeochemical impacts
- Socio-economic risks

Universities to receive funds

- SFU, UBC, Dalhousie, Rimouski, St. Mary's

ii. Helmuth Thomas & Peter Tyedmers, Dalhousie, Leaders

Themes

- Natural variability vs long-term secular trend in pH – Scotia Shelf, Brier Island(NS), Gulf of St. Lawrence, Hudson Bay (Belcher Islands), Cambridge Bay, Pacific Line P
- Do current monitoring activities reflect OA conditions where shellfish production and harvesting occur?
- Socio-economic implications of current and future OA

Universities to receive funds

- UBC, Dalhousie, Manitoba, St. Francis Xavier, Calgary, McGill

The MEOPAR Observation Core will contribute up to 10 pH and/or pCO_2 sensors and operate a sensor calibration centre at Dalhousie.

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43. DFO'S PACIFIC OCEAN ACIDIFICATION WORKING GROUP

Karen Hunter[1] and Andrew Ross[2]

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[2]Ocean Sciences Division, Fisheries & Oceans Canada, Institute of Ocean Sciences, Sidney, B.C., Andrew.Ross@dfo-mpo.gc.ca

43.1. Highlights

- The Pacific Ocean Acidification Working Group (POAWG) was formed in 2014 to review ocean acidification (OA) globally and regionally, and to establish minimum requirements for monitoring and studying changes in the ocean carbonate system that may impact aquatic species, fisheries, and the aquaculture industry in Pacific Region. POAWG's key recommendations are:
  - Ensure sufficient monitoring to document OA dynamics and promote understanding of the primary mechanisms that govern OA variability in B.C. coastal waters.
  - Integrate new infrastructure for coastal monitoring of key OA parameters near aquaculture sites in Pacific Region.
  - Partner with key regional researchers and, potentially, the aquaculture industry to widen monitoring networks in coastal areas.
  - Build human resources capacity for OA monitoring and research within DFO.

43.2. Ocean Acidification in Pacific Region

Approximately one quarter of the anthropogenic carbon dioxide (CO_2) released into the atmosphere is absorbed by the oceans, causing rapid and persistent changes in ocean chemistry, including a 30% increase in acidity during the last century (Solomon et al. 2007). Though there are few local data to support trend analysis at this time, open ocean observations of the decline in ocean pH in the Northeast Pacific are consistent with the global trend (Wong et al. 2014). Such changes in both oceanic waters and coastal zones are likely to have negative impacts on marine ecosystems and organisms that contribute significantly to the economy and ecology of the Pacific Region, particularly those living in nearshore environments where ocean acidification (OA) and its biological effects remain largely unmonitored and unstudied (Haigh et al. 2014).

43.3. POAWG Mandate

Research is underway in various government and university research laboratories across Canada to model, measure and understand the extent and impact of acidification in Canadian oceans. Washington and Maine have recently released detailed reports to support OA risk management within their jurisdictions (e.g., Washington State Blue

Ribbon Panel 2012; State of Maine 2014). Not unlike B.C., these States have strong seafood sectors that rely heavily on key shellfish species. The Pacific Ocean Acidification Working Group (POAWG) was formed in 2014 with the relatively modest aim of initiating discussions between OA experts in DFO and academia as to the resources needed to maintain, and support the appropriate expansion of, ocean acidification monitoring and research in Canada's Pacific Region. A DFO Technical Report (Hunter et al.), which documents the meetings and findings of the POAWG, is currently in preparation.

43.4. Strategy and Action

The following Strategies and Action were developed during a POAWG workshop on January 8, 2015 to identify and address the minimum requirements for an OA monitoring program Canadian Pacific waters (Table 43-1).

Table 43-1. Minimum requirements for monitoring and studying ocean acidification in Pacific Region.

	Strategies	Actions
WHERE	**AT** existing study and survey locations. **AT** surface and at depth. **AT** economically vulnerable locations (e.g. particularly Baynes Sound, and other shellfish growing areas). **AT** sites that capture the range of pCO_2 variability, establish the coastal oceanographic context, and support investigation of biological responses to 'extremes'. **IN LABORATORY** for experimental study of biological effects.	Include carbonate system parameters as DFO core measurements in Pacific coastal waters; POAWG members to connect with existing survey managers; Provide sampling training and equipment (2 additional surveys per year until coverage is complete). Secure funding for staff and training to operate a continuous pCO_2 monitoring system, with bottle sample processing capacity. Work with academic partners (VIU/U.Alaska) to develop a network of ocean monitoring sites in B.C. Secure funding to support nearshore research and monitoring, linked to laboratory experiments (PBS/UBC).
WHEN	**DURING** existing surveys and cruises. **DURING** seasons with overlapping detrimental impacts (e.g. harmful algal blooms) on key organisms. **DURING** times that capture system variability and key life-cycle stages for organisms of concern.	(Link to WHERE) POAWG to work with other DFO staff, aquaculture industry representatives, and academia to establish collaborations. Propose a joint industry-POAWG meeting in 2015.
HOW	**BY** using known calibration procedures and standardized field methods. **BY** installing and maintaining pCO_2 monitoring systems at fixed locations. **BY** increasing HR capacity. **BY** supporting collaborations between POAWG members and industry.	POAWG familiar with most recent methodologies. ½ FTE OA technician + ½ FTE POAWG Coordinator. Work with non-DFO colleagues to support coast-wide efforts; Potential for greater involvement of DFO Aquaculture staff.
WHAT	**CONTINUE** research and monitoring of OA extremes in the Georgia Strait. **CONTINUE** measuring at least 2 of the 4 key carbonate system parameters, along with temperature and salinity at the same time/location. **INITIATE** assessments of the potential biological impacts of ocean acidification in B.C. on commercially important fishery and aquaculture species.	Secure funding to support and improve existing discrete (bottle) and continuous (sensor) field-based OA monitoring. Work with POAWG coordinator and biological experts to develop and propose a collaborative work plan. Ensure future funding to support experiments on biological impacts.

43.5. 2014-15 POAWG Membership

Kumiko Azetsu-Scott (DFO), Jim Christian (DFO), Lyanne Curtis (DFO), Wiley Evans (UAlaska), Helen Gurney-Smith (VIU), Chris Harley (UBC), Karen Hunter (DFO), Debby Ianson (DFO), Sophie Johannessen (DFO), Kristi Miller (DFO), Lisa Miller (DFO), Tammy Norgard (DFO), Chris Pearce (DFO), Ian Perry (DFO), Andrew Ross (DFO).

43.6. References

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Appendix 1. Review Meeting Agenda

DFO State of the Pacific Ocean Meeting: Assessing NE Pacific ocean conditions in 2014

Auditorium, Institute of Ocean Sciences
9860 West Saanich Road, Sidney, B.C.
10th and 11th March 2015

Co-Chairs: Ian Perry and Peter Chandler

Day 1- Tuesday March 10th - (Mostly) Global, Deep-Sea, West Coast Vancouver Island

Start time	*Speaker*	*Topic*
9:30	Peter Chandler	Welcome, introductions, purpose of meeting
9:45	Bill Crawford/ Skip McKinnell	Global temperatures and anomalies, and related large-scale atmospheric indices in the Gulf of Alaska
10:00	Howard Freeland	The “Blob” or Argo and other views of a large anomaly in the Gulf of Alaska in 2014/15
10:15	Jim Gower	West coast satellite and wave buoy data
10:30	Frank Whitney	Anomalous winter winds decrease 2014 transition zone productivity in the NE Pacific
10:45	Sonia Batten	Status of lower trophic levels offshore in 2014
11:00	Mike Lapointe /Michael Folkes	Sockeye salmon diversion rate
11:15	Doug Yelland/Marie Robert	Line P / LaPerouse hydrographic survey
11:30	Bill Crawford	Subsurface oxygen concentration along the West Coast
11:45	Peter Chandler	Sea surface temperature and salinity at BC lighthouses, 2014
12:00		**lunch**
13:00	Dave Jackson	Canadian Hydrographic Service sea level data
13:15	Angelica Peña	Phytoplankton on the BC continental shelf
13:30	Moira Galbraith	Zooplankton update: WCVI, QCS and SoG
13:45	Ian Perry	Small mesh multispecies trawl survey results for 2014 along WCVI
14:00	Jennifer Boldt	Update on pelagic fishes
14:15	Linnea Flostrand	Nighttime pelagic trawl surveys off WCVI
14:30	Roy Hourston	Upwelling along the West Coast: magnitude and timing
14:45		**break**
15:00	Kim Hyatt	Coast-wide status of sockeye indicator stocks in 2014 and trends expected from 2015-2016
15:15	Greg Workman	Groundfish survey
15:30	Mark Hipfner	Seabirds along the outer coast of Vancouver Island
15:45	Linda Nichol	Marine mammals
16:00	Susan Allen and Maycira Costa	Timing of the Spring phytoplankton bloom in the Strait of Georgia and chlorophyll dynamics in the SoG based on MODIS imagery
16:15	Ian Perry	General discussion of overall trends and events; end of day 1

Day 2- Wednesday March 11th - Strait of Georgia and Ocean Acidification

Start time	*Speaker*	*Topic*
9:30	Peter Chandler	Reflections on Day 1, key highlights, new ideas
9:45	Sophia Johannessen	Oxygen in Douglas Channel 2013-2014.
10:00	Peter Chandler, Diane Masson, Angelica Peña	SoG water properties survey 2014
10:15	Chrys Neville	Juvenile salmon in the Strait of Georgia
10:30	Sue Grant	Forecasts and Fraser Sockeye survival trends
10:45	Erin Rechisky/David Welch	Telemetry-based estimates of survival and residence times of juvenile sockeye in the Strait of Georgia and to Queen Charlotte Sound
11:00	Richard Dewey	ONC (Venus/Neptune) observations off the west coast of Vancouver Island
11:15	Akash Sastri	Venus in the Strait
11:30	Peter Chandler	General discussion of overall trends and events; end of SoG session
12:00		**lunch**
	(Ocean Acidification)	
13:00	Ian Perry	Introduction to ocean acidification session
13:20	Debby Ianson	Overview of NE Pacific Ocean acidification
13:40	Jeff Marliave/Jessica Schultz	Vancouver Aquarium ocean acidification studies
14:00	Rob Saunders	Ocean acidification: an industry perspective
14:20	Ken Denman	Developing a Canadian Ocean Acidification Network
14:40	Andrew Ross/Karen Hunter	POAG working group report
15:00	Ian Perry	Ocean acidification discussion and overall meeting wrap-up

POSTERS (unscheduled)

- Brian Hunt — The Hakai Institute marine monitoring program
- Lingbo Li — Are euphausiids resilient to low oxygen in the Salish Sea?
- Nina Bednaršek — Pteropods as Bioindicators for Ocean Acidification

Appendix 2. Review Meeting Participants

First and last name	Affiliation
Mack Adamson	DFO, Institute of Ocean Sciences, Sidney
Scott Akenhead	Ladysmith Institute, Ladysmith
Susan Allen	University of British Columbia, Vancouver
Sandy Argue	Argus Bio-Resources, Victoria
Hal Batchelder	PICIES, Victoria
Sonia Batten	Sir Alister Hardy Foundation for Ocean Science, Nanaimo
Nina Bednarsek	University of Washington, Seattle
Douglas Bertram	Environment Canada, Institute of Ocean Science, Sidney
Lyle Berzins	
Michelle Bigg	DFO, Fisheries Protection Program, Nanaimo
Jennifer Boldt	DFO, Pacific Biological Station, Nanaimo
Wendy Callendar	DFO, Institute of Ocean Sciences, Sidney
Barron Carswell	Province of British Columbia
Dennis Chalmers	Province of British Columbia
Peter Chandler	DFO, Institute of Ocean Sciences, Sidney
Sean Cheesman	Province of BC
Bill Crawford	DFO (retired), Institute of Ocean Sciences, Sidney
Beth Currie	
Ken Denman	University of Victoria , Victoria
Richard Dewey	Ocean Networks Canada
John Dower	University of Victoria , Victoria
Linnea Flostrand	DFO, Pacific Biological Station, Nanaimo
Michael Folkes	DFO, Pacific Biological Station, Nanaimo
Howard Freeland	DFO (retired), Institute of Ocean Sciences, Sidney
Moira Galbraith	DFO, Institute of Ocean Sciences, Sidney
Germain Gatien	DFO, Institute of Ocean Sciences, Sidney
Steve Gormican	Camosun Collage, Victoria
Jim Gower	DFO, Institute of Ocean Sciences, Sidney
Sue Grant	DFO, Delta
Corly Haycroft	Province of BC
Joy Hillier	DFO, Prince Rupert
Mark Hipfner	Canadian Wildlife Service, Delta
Roy Hourston	DFO, Institute of Ocean Sciences, Sidney
Brian Hunt	Hakai Institute
Karen Hunter	DFO, Pacific Biological Station, Nanaimo
Kim Hyatt	DFO, Pacific Biological Station, Nanaimo
Debby Ianson	DFO, Institute of Ocean Sciences, Sidney
Rob Irwin	University of British Columbia, Vancouver
Dave Jackson	CHS, Institute of Ocean Sciences, Sidney
Wayne Jacob	Hakai Institute, Calvert Island, BC

Marlene Jeffries	Ocean Networks Canada, Victoria
Sophia Johannessen	DFO, Institute of Ocean Sciences, Sidney
Greg Jones	Environment Canada, Institute of Ocean Sciences, Sidney
Stephanie King	Sea This Consulting, Nanaimo
Mike Lapointe	Pacific Salmon Commission, Vancouver
Lingbo Li	University of Washington, Seattle
Jie Liu	University of British Columbia, Vancouver
Joanne Liutkus	BC Salmon Farmers Association
Eddie Loos	ASL Environmental Sciences, Sidney
Jeff Marliave	Vancouver Aquarium, Vancouver
Eduardo Martins	U. Waterloo/DF0
Diane Masson	DFO, Institute of Ocean Sciences, Sidney
Jim McIsaac	T. Buck Suzuki Foundation, Vancouver
Skip McKinnell	PICES (retired)
Steve Mihaly	Ocean Networks Canada, Victoria
Kristi Miller	DFO, Pacific Biological Station, Nanaimo
Ben Moore-Maley	University of British Columbia, Vancouver
Larry Neilson	Province of BC
Chrys Neville	DFO, Pacific Biological Station, Nanaimo
Linda Nichols	DFO, Pacific Biological Station, Nanaimo
Byron Nutton	DFO, Ecosystems and Fisheries Management, Nanaimo
Miriam O	DFO, Institute of Ocean Sciences, Sidney
Patrick O'Hara	Environment Canada, Institute of Ocean Sciences, Sidney
Tom Okey	Ocean Integrity Research, Victoria
Elise Olson	University of British Columbia, Vancouver
Rick Page	
Evgeny Pakhomov	University of British Columbia, Vancouver
Tim Parsons	Institute of Ocean Sciences, Sidney (emeritus)
Isobel Pearsoll	Pacific Salmon Foundation, Vancouver
Angelica Peña	DFO, Institute of Ocean Sciences, Sidney
Ian Perry	DFO, Pacific Biological Station, Nanaimo
Eric Peterson	Hakai Institute, Calvert Island, BC
Matthew Poirier	DFO, Institute of Ocean Sciences, Sidney
Erin Rechisky	Kintama Research Services
Katie Reid	Province of British Columbia
Dave Riddell	Ocean Networks Canada, Victoria
Marie Robert	DFO, Institute of Ocean Sciences, Sidney
Steve Romaine	DFO, Institute of Ocean Sciences, Sidney
Andrew Ross	DFO, Institute of Ocean Sciences, Sidney
Chelsea Stanley	DFO, Institute of Ocean Sciences, Sidney
Akash Sastri	Ocean Networks Canada, Victoria
Rob Saunders	Island Scallops Ltd., Qualicum Beach, BC
Jessica Schultz	Vancouver Aquarium, Vancouver

Kyle Sha	University of British Columbia, Vancouver
Marc Trudel	DFO, Pacific Biological Station, Nanaimo
Peter Van Buren	Province of British Columbia
Antonio Velez	DFO, Pacific Biological Station, Nanaimo
Kang Wang	University of British Columbia, Vancouver
David Welch	Kintama Research Services, Nanaimo
Frank Whitney	DFO (retired), Institute of Ocean Sciences, Sidney
Greg Workman	DFO, Pacific Biological Station, Nanaimo
Doug Yelland	DFO, Institute of Ocean Sciences, Sidney
Kelly Young	DFO, Institute of Ocean Sciences, Sidney
Cindy Yu	University of British Columbia, Vancouver