STATE OF THE PACIFIC OCEAN 2010

Context:

Pacific Canadian waters lie in a transition zone between coastal upwelling (California Current) and downwelling (Alaskan Coastal Current) regions, and experience strong seasonality and considerable freshwater influence. Variability is closely coupled with events and conditions throughout the tropical and North Pacific Ocean, experiencing frequent El Niño and La Niña events particularly over the past decade. The region supports important resident and migratory populations of invertebrates, groundfish and pelagic fishes, marine mammals and seabirds.

Monitoring the physical and biological oceanographic conditions and fishery resources of this region is done semi-regularly by several government departments, to understand the natural variability of these ecosystems and how they respond to both natural and anthropogenic stresses. Support for these programs is provided by Fisheries and Oceans Canada (DFO), and Environment Canada. Contributors to this report are members of the Fisheries Oceanography Working Group of the DFO Centre for Science Advice Pacific Region (CSAP), with additional contributions from other Canadian and American fisheries and climate scientists.

This Science Advisory Report has resulted from a Fisheries and Oceans Canada, Canadian Science Advisory Secretariat Regional Advisory Process. Additional publications resulting from this process will be posted as they become available on the DFO Science Advisory Schedule at http://www.dfo-mpo.gc.ca/csas-sccs/index-eng.htm.

SUMMARY

- The near-record high number of returning Sockeye Salmon to the Fraser River was the good news story for 2010. Approximately 30 million adults returned, and of these about 17 million were headed for Shuswap Lake. These returns contrast with 2009 when fewer than 2 million sockeye migrated back to the Fraser. With such wide changes between years it is difficult to predict returns for 2011 with high certainty. The DFO prediction for 2011 is between 1.0 and 12 million (10% and 90% probabilities) if the low recent productivity persists. If, on the other hand, salmon have the long-term average productivity seen last year and in previous decades, between 1.7 and 15 million sockeye are predicted to return.

- The story was reversed for Humboldt squid. Squid were found in record-high numbers in summer 2009 along the west coast, but in 2010 not even one was observed in British Columbia waters. Several causes have been proposed, but none proven.

- The year 2010 started with extreme El Niño weather along the west coast, with strong southerly winds bringing warm, fresh ocean waters to the Oregon and British Columbia coast. These winds weakened in April and by summer the winds blew much more strongly than normal from the north, upwelling cool salty water along the outer coast. Waters of the Strait of Georgia shifted from cool to normal or even warm in 2010. La Niña conditions of late 2010 and early 2011 were linked to stronger westerly winds in the Pacific Ocean and cooler ocean waters along the coast. Overall the cool conditions prevailed in 2010, and this year was the third consecutive year with cooler than normal ocean temperatures along the Pacific Canadian coast.

- Over the past decade and a half both the Pacific Decadal Oscillation (PDO) and ENSO (El Niño – La Niña) have shifted phase together and reinforced the impact of each one on west coast ocean temperature. Whereas in the 1990s, scientists would attribute changes in ocean temperatures and species compositions to changes in PDO or ENSO, they have recently been able to use these indices almost interchangeably in local waters to link physical changes in the ocean to shifts in abundance of one or several marine species.

- Scientists monitor abundance and species of plankton in local waters to determine the quantity and quality of prey for larger species. Phytoplankton can be tracked by measuring chlorophyll in the ocean. Summer 2010 chlorophyll concentrations were often low in the southern Strait of Georgia and Juan de Fuca Strait, while fall chlorophyll concentrations were higher in Juan de Fuca Strait and slightly lower in the Strait of Georgia compared with previous years. The timing of the spring bloom in the Strait of Georgia is considered important for juvenile herring and salmon survival. Numerical models suggest that this bloom occurred in mid-April in 2010, compared to March to early April for most years. Bloom timing depends on local winds and cloud cover. A study of Rivers Inlet of Central BC discovered the spring bloom could be blown completely out of this short inlet by outflow winds. Its late development in 2009 could have been due to these winds. Studies of impacts of this outflow on local sockeye juveniles are ongoing.

- Zooplankton species tend to shift from cold-water to warm-water types with corresponding shifts in local ocean temperature. Monthly surveys found the 2010 composition of cold-water copepods (a type of zooplankton) off Oregon was 4th highest in 15 years of observations. However, the species richness, which usually correlates with ocean temperature, was also high in 2010. These contrasting observations might be attributed to a warm ocean waters in winter and cool summer of 2010. Similar surveys in British Columbia observed more cold-water copepods species.

- Recent surveys found the biomass of *Pandalus jordani* shrimp off central west coast Vancouver Island had increased in 2008, 2009, and 2010 from very low levels during 2004-2007. Such increases appear related to colder waters in 2006, 2007, and 2008 during the larval stages of the shrimp (this species has a 2-yr time lag from hatch to recruitment at age 2) and to low abundances of Pacific hake (a potential shrimp predator) in May surveys in 2008, 2009, and 2010. This survey in May also provides insight into populations of resident flatfish, such as sole, Pacific cod, halibut, and arrowtooth flounder. Biomass trends of key flatfish indicator species all increased in 2010, as did the biomass of the "cold water indicator" species walleye pollock.

- Offshore Pacific hake (*Merluccius productus*) is a trans-boundary stock that exhibits seasonal migratory behavior, ranging from offshore and generally southern waters during the winter spawning season to coastal areas between northern California and northern British Columbia from spring to fall. In 2011, spawning biomass is estimated to have rebounded rapidly from a low in 2007 based on the strength of recent year classes (2005, 2006 and particularly 2008). However, estimates of spawning biomass are highly uncertain. The most recent coast-wide survey in 2009, using ship-based sonar sampling, was difficult to interpret due to large numbers of Humboldt squid among the hake.

- Coastwide, herring adult biomass is generally low in all areas except the Strait of Georgia, where the stock remains somewhat high due to its near-record high biomass several years ago and indications of strong returns in 2011. Sardine numbers went from zero to many thousands of tonnes in the 1990s, but have declined since 2006. Eulachon have experienced long-term declines in many rivers throughout their distribution from California to Alaska. Indices of eulachon abundance in central and southern British Columbia rivers remain at low levels. COSEWIC recently assessed eulachon, and designated stock from some BC rivers as Threatened and in others as Endangered.

- The abundance of albacore tuna in BC coastal waters in 2010 was the second highest since 1990, and those caught were in cooler water than in previous years.

- Counts of seabirds in Pacific Rim Marine Reserve on the west coast of Vancouver Island revealed many species increased in number over the past five years. However, on Triangle Island where seabird breeding depends critically on ocean conditions in April, the mean growth rate for chicks of Cassin's auklet was extremely low in 2010 – in fact, the lowest in the 15-year time series by quite a wide margin. This poor growth is linked to late arrival of spring weather.

- A Pacific North Coast Integrated Management Area (PNCIMA) Groundfish overview revealed several general trends. Gadoid (Pacific Cod, Walleye Pollock, Pacific Hake) stocks are stable or increasing. Most rockfish species are at low abundance with some being listed as Special Concern or Threatened by COSEWIC. Flatfish stocks appear to be stable. Sablefish stocks appear to be stable at low abundance. Lingcod and Elasmobranch (e.g. Spiny Dogfish) stocks appear stable.

- Sockeye ocean survival was high for stocks in Barkley Sound on the west coast of Vancouver Island, attributed to cool ocean waters when they entered the ocean two years earlier. An assessment of ~60 years of escapement and catch data of five salmon species to the central and north coast suggests that Pink Salmon, with significant increases in escapements, are doing relatively well. Coho and Chinook Salmon are doing relatively poorly - declines over the time series were significant for Coho Salmon catches, escapements, and returns; and for Chinook Salmon catches and returns. ,A different picture can emerge from shorter-term studies. For example, the Chinook Abundance Index for stocks between SE

Alaska and Oregon has increased and declined over 10 to 15 year cycles since 1979, and this index is presently increasing from a low in 2008.

- The numbers of some baleen whales have increased following the end of whaling in the 1960s. Humpback whales are now most frequently sighted. Fin, blue and sei whales are observed much less frequently.

- Oxygen concentrations in bottom waters at 150 metres depth in late summer dropped to lowest observed values in 2006 and 2009 off southwest Vancouver Island. Normal concentrations were observed in 2010. Lower oxygen concentrations were observed off the coast of Oregon and Washington in most summers since 2002, perhaps due to stronger upwelling winds there in summer.

INTRODUCTION /BACKGROUND

This report is the twelfth in an annual series on the state of physical, biological, and selected fishery resources of Canadian Pacific marine ecosystems. The region supports important resident and migratory populations of invertebrates, groundfish and pelagic fishes, marine mammals and seabirds. Monitoring the physical and biological oceanographic conditions and fishery resources of the Pacific Region is done semi-regularly by scientific staff in several government departments, to understand the natural variability of these ecosystems and how they respond to both natural and anthropogenic stresses. Support for these programs is provided by Fisheries and Oceans Canada, Environment Canada, Parks Canada and various other agencies. Additional information is provided by the US National Oceanographic and Atmospheric Administration (NOAA), University of Victoria, Simon Fraser University, and the University of British Columbia.

Information for this report was presented at the annual meeting of the Fisheries Oceanography Working Group (FOWG) at the Institute of Ocean Sciences, Sidney, BC, on Feb. 24 to 25, 2011 chaired by Jim Irvine and Bill Crawford, both of Fisheries and Oceans Canada. This summary report is based on contributions by participants.

More details are provided in Crawford, W.R. and J.R. Irvine. 2011. State of physical, biological, and selected fishery resources of Pacific Canadian marine ecosystems in 2010. DFO Can. Sci. Advis. Sec. Res. Doc. 2011/054 available at http://www.pac.dfo-mpo.gc.ca/science/psarc-ceesp/osrs/index-eng.htm.

ASSESSMENT HIGHLIGHTS

2010 – Warm and Fresh, then Cool and Salty

After a cool ocean year in 2009, Coastal Pacific Canadian waters were warmer and fresher than normal in the first three to four months of 2010, due to stronger southerly winds of the El Niño winter. Conditions shifted to cool and salty at Langara and Kains Islands (Fig. 1 below) and at other outer coast stations in April through September 2010, due to strong winds from the north along the west coast. Temperatures at Race Rocks and Departure Bay in the Salish Sea in summer 2010 were warmer than average (Chandler RD2011, p127). Temperatures at Langara and Kains warmed somewhat through autumn, then turned cool in late 2010 and into 2011.

Waters of the nearby Strait of Georgia warmed at most depths through the first half of 2010, from relatively cool temperatures of previous years. (Masson RD2011, p111; Dewey RD2011, p107).

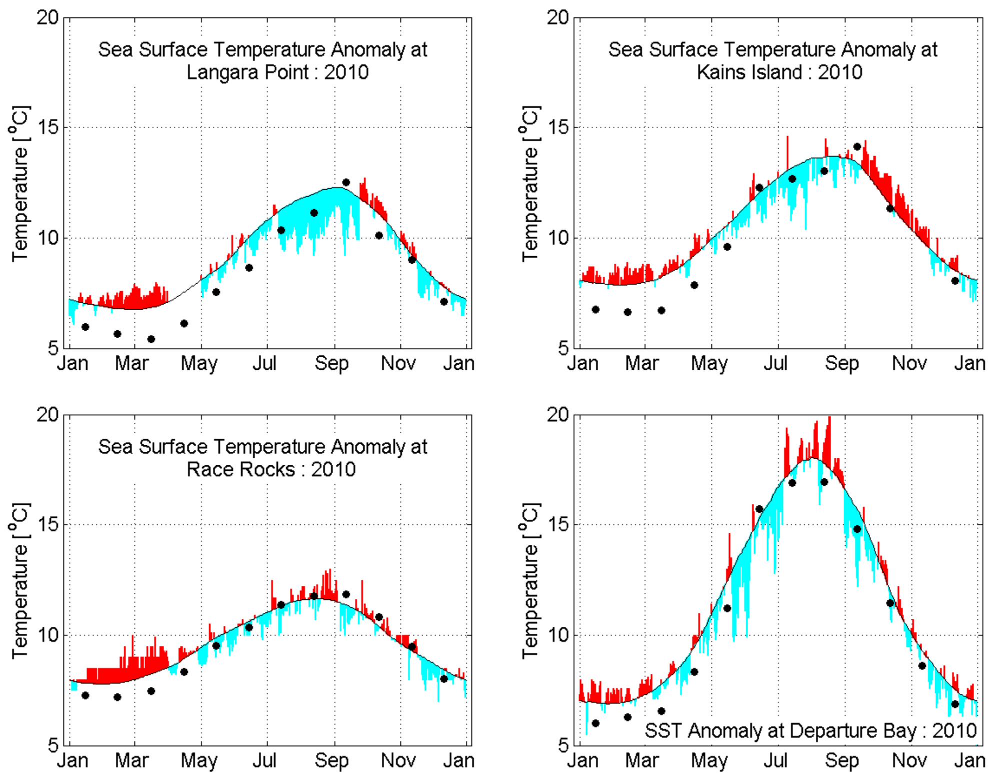
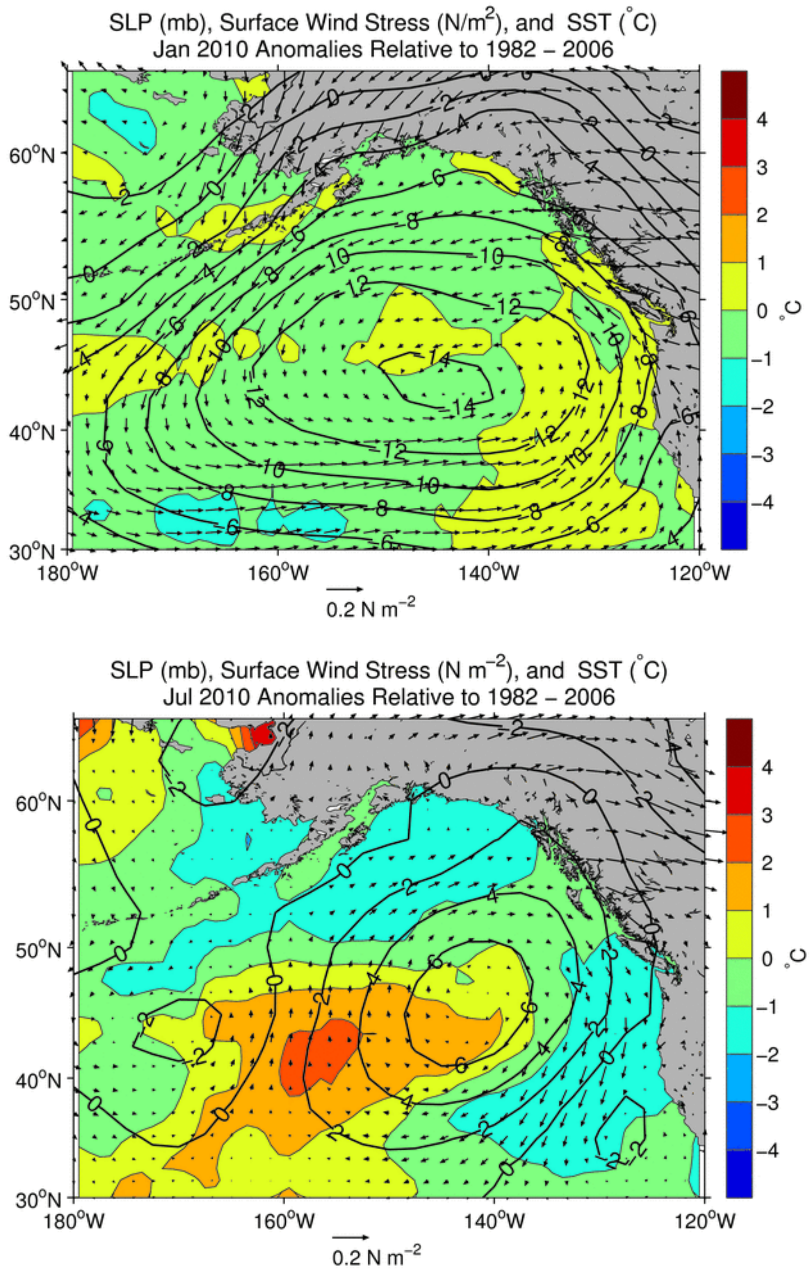


Figure 1. Sea surface temperature measured at lighthouses and shore stations (Chandler RD2011, p127). Langara Island is off the northwest tip of Haida Gwaii; Kains Island is off northwest Vancouver Island; Race Rocks is on the north side of Juan de Fuca Strait; and Departure Bay is in Nanaimo in the Strait of Georgia. Red denotes temperature above normal for the time of year; blue denotes temperature below normal while black dots represent the monthly temperature anomalies observed in 2009.

The 2010 winter and summer weather patterns (Fig. 2) included formation of a very intense Aleutian Low Pressure system in January and February (Hourston and Thomson RD2011, p40). The lowest air pressure in its centre was almost 14 millibars lower than typical for January. Because winds flow counter-clockwise around this low pressure system, coastal winds were much stronger than normal, and pushed relatively warm fresh water toward shore.
It was the warm air of this weather system that melted so much snow in January and February, just before the 2010 Winter Olympics in Vancouver.



The stronger, counter-clockwise rotating winds in winter in the centre of the Aleutian Low drew cold and salty waters closer to the ocean surface of the centre of the Gulf of Alaska. These formed a layer of salty water between 90 and 150 metres depth across this gulf (Freeland RD2011, p28; Robert, Crawford & Bolingbroke RD2011, p31).

Figure 2. (from Hourston and Thomson RD2011, p40) Anomalies of air pressure, winds and ocean temperature in Jan. 2010 (top) and July 2010 (bottom). Black contours denote air pressure anomalies in millibars. Arrows show wind stress anomalies in Nm^{-2}. Colours show sea surface temperature anomalies in °C.

The opposite weather system took over in July 2010. Normally the North Pacific High Pressure System extends northward into the Gulf of Alaska in summer. In July this system moved even farther northward than normal, and strengthened, so that the normally gentle winds from the north were much stronger along the BC and northern USA coast, as can be seen in Fig. 2, bottom panel. By early 2011 the winds had shifted into a typical La Niña weather pattern, with much stronger winds from the west in the Gulf of Alaska, and cooler coastal ocean temperatures.

2010 – Some Biological Surprises

Fraser River Sockeye Salmon

The biggest event in 2010 was the large return of Sockeye Salmon to the Columbia/Okanagan and Fraser rivers. The Fraser Sockeye Salmon return was amongst the largest observed in the past 100 years, bringing a bonanza Sockeye fishery to southern British Columbia in summer and early autumn 2010, with commercial, sports and First Nations all benefiting. Preliminary estimates indicate 30 million Fraser Sockeye Salmon returned (i.e. catch plus escapement) in 2010, with 17 million of these from the Shuswap Lake populations alone. The 2010 Fraser Sockeye returns contrasted significantly with the previous year's (2009) near-record low (~1.3 million) returns that fell at the extreme low end of the forecast distribution.

Fraser Sockeye productivity in 2009 had been amongst the lowest on record, following over a decade of systematic decreases in productivity exhibited by most stocks. Most Fraser Sockeye

Salmon take four years from egg to their return as adults to spawn. During these years there are very few observations of these fish as they hatch, grow in fresh water, enter the ocean and circle the Northeast Pacific Ocean. Scientists typically use the number of spawners four years earlier to predict the numbers returning. The uncertainty surrounding predictions would be reduced if the ratio of adult returns to their previous (parental) generation spawners (i.e. productivity) remained constant over the years. However, starting as early as the 1950's and 60's, this ratio has systematically decreased for many stocks and was particularly low in 2009.

Given the systematic decreases in productivity over time and the particularly low productivity in 2009, DFO recommended a forecast that assumed recent lower stock productivity for 2010; a forecast that assumed long-term average productivity for 2010 returns was also presented but had a lower degree of belief. The 2010 Fraser Sockeye returns fell at the high end of the recommended forecast distribution. Most stocks were in the middle of the forecast distribution that assumed long-term average productivity. Notable exceptions included Shuswap Lake stocks that had exceptionally high productivity in 2010 (Grant RD2011, p125).

The recommended forecast for Fraser Sockeye Salmon returns in 2011 again assumes that recent lower productivity conditions will persist. Under this scenario there is a one in ten chance (10% probability) that returns will be at or below 1.0 million, and a nine in ten chance they will be at or below 12.1 million. The mid-point of this distribution is 3.2 million (one in two chance returns will be above or below this value). Under the alternate, and presumably less likely, assumption that long-term average productivity conditions will persist, there is a 10% probability returns will be at or below 1.7 million, a 90% probability they will be at or below 15.1 million and a 50% probability they will be at or below 4.6 million (Fig. 3).

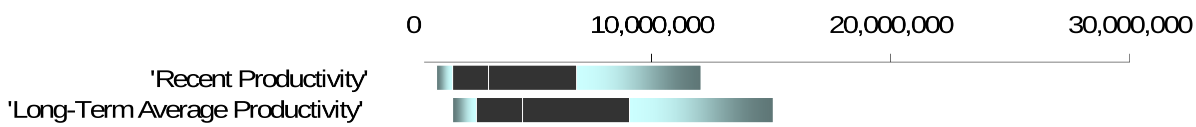


Figure 3. (from Grant RD2011, p125) 2011 forecast probability distributions for all Fraser Sockeye Salmon stocks. Black horizontal bars represent the 25% to 75% probability distribution range, the 50% probability level is indicated by the white vertical line and the blue (lighter) horizontal bars represent the 10% to 90% probability distribution range. Separate distributions are provided for the two forecast scenarios: 'Recent Productivity' and 'Long-Term Average Productivity.'

Clearly we are in an era of very uncertain times for predicting Sockeye Salmon returns to the Fraser River. The Cohen Commission is investigating all aspects of Fraser River Sockeye Salmon health, especially the low returns of 2009 and high returns of 2010.

Humboldt Squid

The second major surprise was the complete absence of Humboldt Squid in BC (Forrest et al. RD2011, p89). These invaders arrived from the south in summer in the early 2000s and reached maximum numbers in the summer of 2009, extending all along the continental shelf of BC, where they were caught by the tonne in many of the test trawls of the summer hake survey. In previous decades they were confined mostly to Central American and Mexican waters. Their sightings in 2010 were confined to waters south of Oregon, and ocean features such as ocean oxygen concentrations and temperatures are considered as factors in their distribution.

Biological Linkages between Spring Bloom Timing and Fish and Bird Production

Phytoplankton are a major source of food for zooplankton, which in turn are fed upon by many species in the ecosystem including salmon and birds. In some coastal areas of BC a spring phytoplankton bloom is closely followed by a zooplankton bloom (Allen et al. RD2011, p116). The relative role of nutrients, temperature, light, and wind in determining the timing and intensity of spring blooms and linkages further up the food chain are areas of active research reported on at this year's State of Ocean Workshop.

Chlorophyll concentrations can be measured from research ships and provide a reliable estimate of the concentration of phytoplankton in the ocean. Peña (RD2011, p113) reports that chlorophyll concentrations in the Strait of Georgia are generally high and variable in spring, low during the summer and fall, and lowest during winter. Spring concentrations in Juan de Fuca Strait are usually lower than in the Strait of Georgia, perhaps due to strong vertical mixing, but are similar at other times of the year. In 2010 chlorophyll concentrations were generally close to the average from 2004-2009. However, summer chlorophyll concentrations were often low in the southern Strait of Georgia and Juan de Fuca Strait while fall chlorophyll concentrations were higher in Juan de Fuca Strait and slightly lower in the Strait of Georgia compared with those observed in previous years. Ship-based sampling reveals that diatoms tend to dominate the phytoplankton populations in the Strait of Georgia in spring and dinoflagelates in summer.

Allen et al. (RD2011, p116) used a biophysical model to predict spring blooms in the Strait of Georgia. They defined the spring bloom to be the time of the peak of the bloom, which occurs as the nitrate at the surface drops to zero, which in 2010 was 16 April (Fig. 4). This figure is instructive as it shows that chlorophyll concentrations over time can be multi-modal, and bloom timing dates can vary depending on how one defines the bloom and collects data. On several occasions during 2010, strong winds deepened the mixed water layer, postponing the development of the bloom.

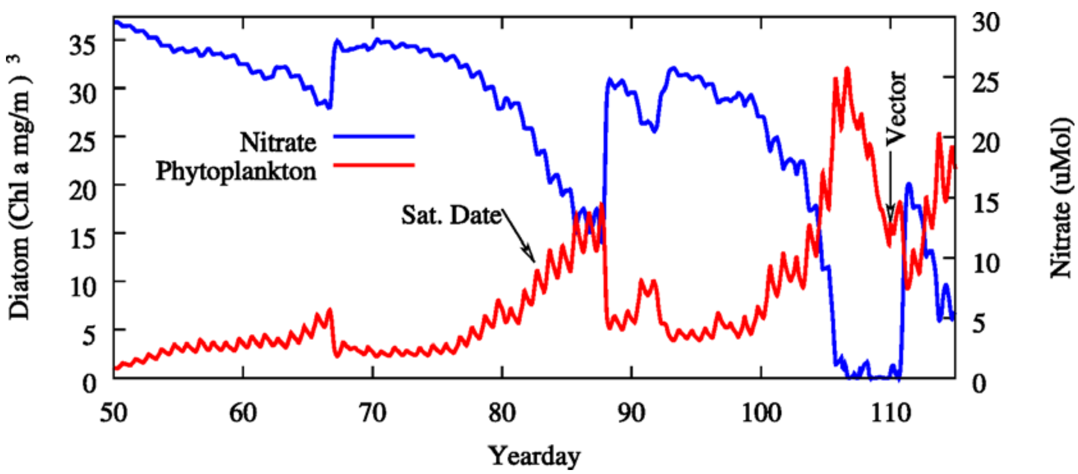


Figure 4 (from Allen et al. RD2011, p116): Modelled time series for spring 2010 in Strait of Georgia showing phytoplankton chlorophyll a (in red) and nitrate (in blue). The spring bloom peaked on day 106, April 16. Marked are day 82, March 23, the date that satellite data show the start of the spring bloom, and day 110, April 20, when, sampling from the Vector (Peña RD2011, p113), showed that the spring bloom was over.

Pawlowicz et al. (RD2011, p137) applied the same model further north in Rivers Inlet. Here the timing of the spring bloom is less governed by variations in available light, and can be inhibited by wind-driven mixing and advection. For instance, the 2009 spring bloom was two weeks later than 2008, apparently the result of strong late outflow winds moving surface currents containing phytoplankton out of the fjord, delaying the onset of the bloom within the inlet. In 2010, lower than normal spring and summer river flows in the area (Morrison RD011, p131) may have been partly responsible for the early large spring bloom reported by Pawlowicz et al. (RD2011, p137).

Interestingly, advection of plankton-rich water from Rivers Inlet might provide needed prey for seabirds and salmon in Queen Charlotte Sound. Hipfner (RD2011, p142) found the mean growth rate for the zooplanktivorous Cassin's auklet on Triangle Island was extremely low in 2010 – in fact, the lowest in the 15-year time series by quite a wide margin. In general, the auklets' offspring grow more quickly and fledge at heavier masses in cold-water years, because timing of their hatching is strongly temporally matched with the phenology of an important prey species, the copepod *Neocalanus cristatus*.

Using chlorophyll measurements from SeaWiFS satellite, Borstad et al. (2011) linked the survival of Rhinoceros auklets on Triangle Island and Sockeye Salmon from nearby Smith Inlet to spring chlorophyll concentrations measured by satellite. Irvine et al. (2010) predicted marine survivals for Chilko Lake Sockeye Salmon returning in 2010 and 2011 using a strong correlation between spring chlorophyll concentrations and marine survivals of Chilko Lake Sockeye Salmon from previous years. Measured survivals for fish that returned in 2010 were within the prediction interval; predicted survivals for fish returning in 2011 are low (~2%).

Gower (RD2011, p26) tracked the phytoplankton concentrations in surface waters of the Gulf of Alaska with satellite imagery of chlorophyll. Measurements over the past 13 years revealed a massive bloom in phytoplankton in late summer 2008. Growth of phytoplankton in the Gulf is normally limited by availability of iron, and an Alaskan volcano whose iron-carrying dust spread over the gulf is believed to have triggered this bloom in 2008 (Hamme et al. 2010). This bloom did not return in the summers of 2009 or 2010.

In conclusion, the timing of the spring bloom plays a major role in our coastal marine ecosystem, although the relative importance of light, wind, and discharge can vary among regions.

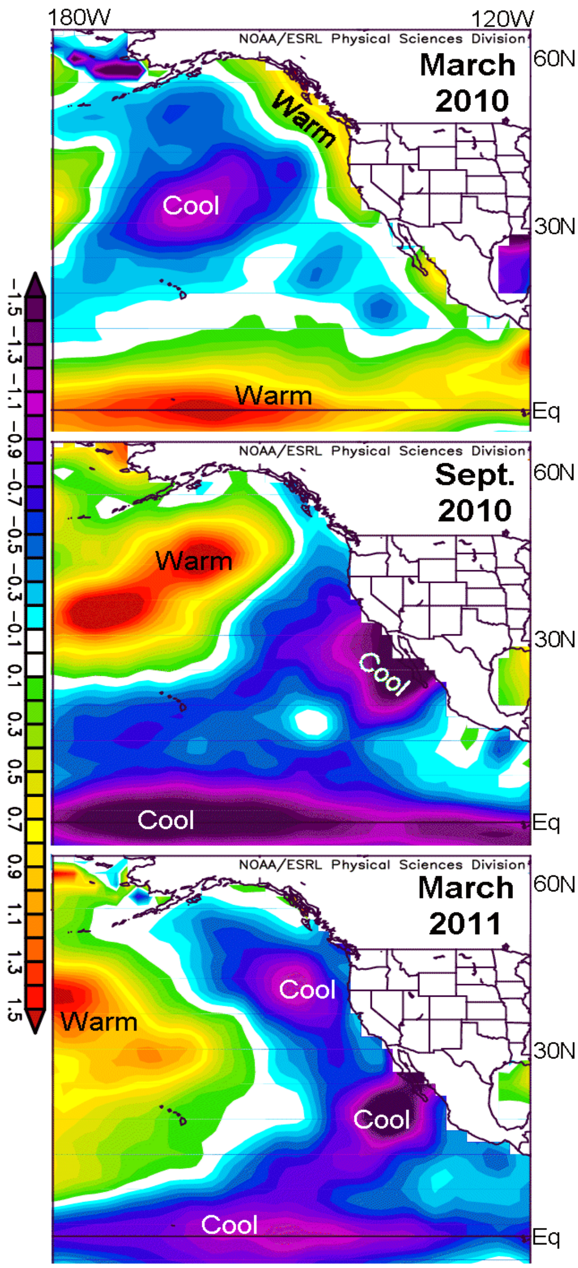
Linking Climate Changes to Lower Trophic Levels

Rapid shifts in Pacific Ocean Temperature

Recent ocean temperature changes in the eastern Pacific Ocean can be seen in the three panels of Fig. 5. The colour shading indicates the temperature relative to the 1971-to-2000 average of that month. Note that the absolute surface temperature of BC waters in a warm March is still cooler than the ocean temperature in a cool September. The relatively warm oceans west of North America in March 2010 were part of the coastal warming due to stronger southerly winds of this El Niño winter. The warm anomalies gave way to cooler anomalies in September 2010, due to persistent and strong northerly winds along the west coast in summer. By March 2011 relatively cool waters were present all along the west coast and Equator, in response to La Niña winds (Crawford, Hourston, Thomson RD2011, p18).

El Niño is part of a Pacific-wide pattern of winds and temperatures. It is formally defined by the ocean temperature along the Equator in the Pacific Ocean and is present when these temperatures exceed 0.5°C above normal for several seasons. This warming is present in the top panel of Fig. 5, showing temperature anomalies of March 2010. La Niña events take place when temperatures fall to more than 0.5°C below normal, as in September 2010 and March 2011 in the bottom two panels of Fig. 5.

Temperatures along the Equator and west coast in March 2011 were similar to those of March 2008 and 2009, and were typical of La Niña winters. These ocean temperatures are usually set up by stronger northeast trade winds over the tropical North Pacific Ocean and stronger westerly winds in the subarctic Pacific. Similarly, Pacific Ocean temperatures of early 2010 were typical of El Niño winters, with warm oceans along the North American west coast. As of early April 2011 the existing La Niña was predicted to continue into late spring 2011. Readers can track future La Niña conditions and predictions at this site: NOAA ENSO News.



The link between ENSO events (a term that includes both El Niño and La Niña) and winds and temperatures in the Gulf of Alaska has become stronger in the past decade. Another index of North Pacific climate is the Pacific Decadal Oscillation (PDO), which is a measure of changes in temperature all across this ocean. Both ENSO and the PDO have varied together in the past decade, allowing use of either index to relate ocean changes to changes in marine resources in west coast waters. Time series of these indices are presented in Fig. 6.

Figure 5. (from Crawford, Hourston, Thomson RD2011, p18) Ocean temperature anomalies in the Pacific Ocean for March 2010 (top), September 2010 (middle), and March 2011 (bottom). The map extends from North America westward to 180°West, and from 5° South to 65° North. The Equator is marked by the horizontal black line near the bottom of each panel. The temperature anomaly scale in °C is at left. Positive and negative temperature anomalies are labelled warm and cool, respectively. Images provided by NOAA.

Zooplankton

Juvenile Barkley Sound Sockeye Salmon can consume euphausiids 3 to 5 mm long in May when these Sockeye enter the ocean. Low biomass of 3 to 5 mm *Thysanoessa spinifera* in May 2010 could result in low returns of age 4 Sockeye Salmon in 2012 and age 5 fish in 2013 relative to the time series (Tanasichuk RD 2011, p65).

The Oregon coast saw an increase through the middle of 2010 in the total number of copepod species (a type of zooplankton), in response to the warming in early 2010 (Peterson RD2011, p61). These warm waters, in turn, were set up by El Niño winds of winter 2010. This increase in copepod species richness in 2010 is seen in Fig. 6, which also reveals the past 15 years of changes as measured by monthly ocean surveys.

The PDO of Fig. 6 is the Pacific Decadal Oscillation, and MEI is an index of El Niño intensity in the tropical Pacific. Copepod Species Anomaly is based on the number of copepod species in monthly net surveys. These graphs reveal that the anomaly of ocean temperature at NOAA Buoy 46050 tends to change with changes in both PDO and MEI. The number of copepod species on the Oregon shelf increases with local ocean temperature, which in turn changes with both PDO and MEI.

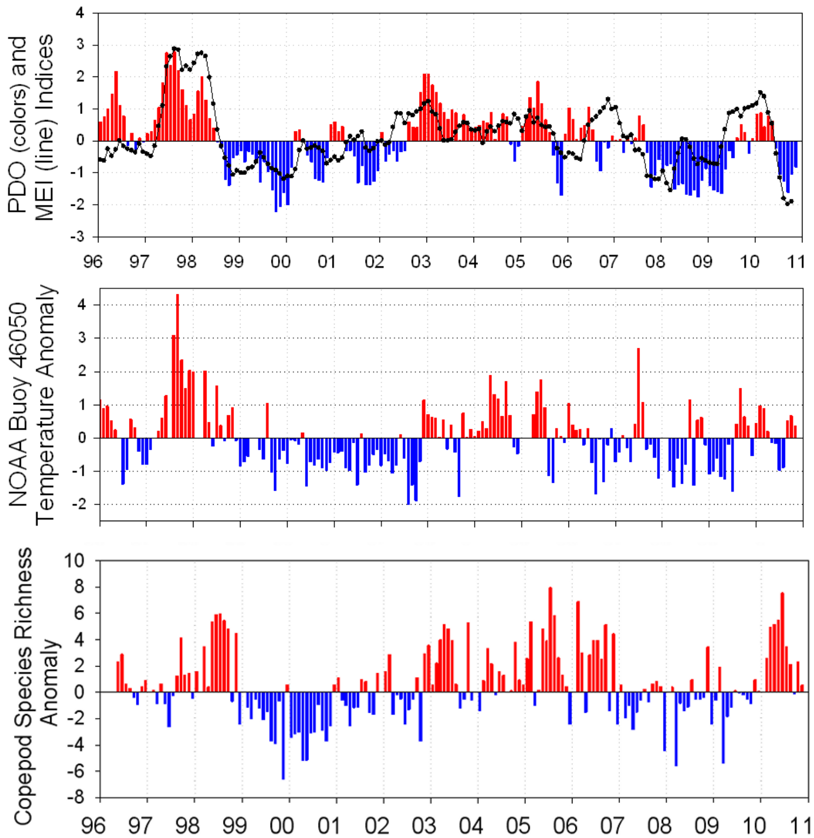


Figure 6. Indices of the ocean and copepods on the Oregon continental shelf (from Peterson RD2011, p61).

Oddly, despite a warm spring and high copepod species richness, the biomass of cold water, (or northern) species was high, ranking 4th out of 15 years (1996-2010). Much of the high biomass was due to the copepod *Pseudocalanus mimus*.

Zooplankton survey data from the outer coast of Vancouver Island and in the Pacific North Coast Integrated Management Area (PNCIMA) region (Mackas, Galbraith and Young. RD2011, p57) also reveal temperature as an ongoing cause of species changes. The positive anomalies of the cool-water zooplankton community off the west coast of Vancouver Island are associated with good local survival and growth of juvenile salmon, sablefish, and some seabirds. Annual-average anomalies of the cool-water copepod and chaetognath species groups on the Vancouver Island continental shelf remained positive in 2010, following generally warmer waters of the previous three seasons, but trended downward from their higher levels in the colder years 2007 and 2008. Conversely, the warm-water, southern-origin copepods and chaetognaths shifted to positive anomalies, continuing an upward trend that began midway through 2009 with the onset of El Niño related warming. Another strong and ongoing signal in the zooplankton time series since about 2000 has been increasing incidence of strongly positive annual anomalies of one or more gelatinous zooplankton taxa. In 2010, the gelatinous zooplankton were dominated by salps (herbivores) in spring, and by medusae (predators on crustacean zooplankton) in mid-late summer.

The open ocean zooplankton community in the Gulf of Alaska, sampled by a Continuous Plankton Recorder towed behind commercial ships, had a relatively normal year of species composition and timing of their spring bloom in 2010 (Batten RD2011, p55). However, preliminary results indicate that 2010 was a year of low biomass of zooplankton.

Zooplankton time series from the Strait of Georgia are being reconstructed from samples collected by various shorter-term research programs. Sampling methods and spatial coverage have been relatively consistent since about 1990. Analyses reveal responses that are surprisingly different from those off the outer coast (Mackas, Galbraith, Young, Dower, and Li RD2011, p118), although they appear to maintain a close relationship to subsurface water temperatures. In particular, there is less evidence of recent rapid alternations between warm- and cool-water, shelf-resident copepod communities. Instead, the dominant signals in the Strait of Georgia have been the declines, after about 1999, in the biomass of large deep-migrating copepods and of euphausiids. Both taxa had a prolonged minimum from about 2003-2008, but also show a partial recovery in 2009 and 2010.

Shrimp on the Vancouver Island Shelf

An annual DFO survey in May samples for *Pandalus jordani* shrimp (Perry RD2011, p69). Recent surveys found their biomass off central Vancouver Island had increased in 2008, 2009, and 2010 from very low levels during 2004-2007. Such increases appear related to colder waters in 2006, 2007, and 2008 during the larval stages of the shrimp (this species has a 2-yr time lag from hatch to recruitment at age 2) and to low abundances of Pacific hake (a potential shrimp predator) in May surveys in 2008, 2009, and 2010.

Clams and oysters in Pacific Rim National Park Reserve

All clam species in Pacific Rim Park displayed globally and/or recently declining trends for at least some size cohorts (Zharikov et al. RD2011, p95). 2010 in particular, and the last 4 to 5 years in general, have had very low stock abundances for all three species. The introduced Japanese oyster remained stable through the past 6 years and 2010 was about average. Native Olympia oyster abundance hasddeclined precipitously but during the past 5 years numbers fluctuated at low levels and in 2010 were about average.

Abundance Variations of Fish, Birds and Mammals

Pacific Hake

Offshore Pacific hake form the largest biomass of any groundfish species on the continental shelf of BC (Forrest et al. RD2011, p89). The 2009 acoustic survey data were re-analyzed in 2010 due to problems caused by the record incursion of Humboldt squid into BC waters and these revised estimates were included in 2011 stock assessment. The stock reconstruction indicates that offshore Pacific hake experienced a long period of decline from the late 1980s to a low in 2000, followed by a brief increase to a peak in 2003 as the exceptionally large 1999 year class matured. The stock again declined from 2003 to 2007, but in 2011 spawning biomass is estimated to be rebounding rapidly based on the strength of recent year classes (2005, 2006 and particularly 2008). Hake spawned during the cool La Niña winter of 2008 is now estimated to form the largest year-class along the entire west coast. However, this assessment is quite uncertain, particularly with respect to the size of the 2008 year-class.

Pacific Herring

Pacific herring comprise an important component of commercial fisheries in British Columbia (Schweigert et al. RD2011, p78). Projected biomass estimates of the Strait of Georgia and Prince Rupert herring stocks were above the fishery threshold or cutoff values and were therefore open to commercial fishing in the 2010/2011 fishing season. Biomass estimates for the Haida Gwaii, Central Coast, and West Coast Vancouver Island herring stocks were projected to be below 2011 fishery cutoff values; therefore these three areas were not open during the 2011 roe herring fishery.

Off the west coast of Vancouver Island (WCVI), fish predator abundance has decreased in recent years, while the abundance of most marine mammal predators has increased. This has resulted in a relatively stable or slightly decreasing trend in the amount of herring consumed by predators since 1973 (Schweigert et al. RD2011, p78). In the shorter term, WCVI herring recruitment should remain low in 2011 because, although the biomass of hake which prey on fishes was low in 2008, *T. spinifera* prey biomass was low during the first three years of life; lower *T. spinifera* prey biomass in 2010 could continue to depress recruit and adult growth; adult survival rates in 2010 could decline because of lower *T. spinifera* biomass (Tanasichuk RD2011, p65).

The biomass of herring in the Strait of Georgia reached near historic high levels in 2002 to 2004 at over 100,000 tonnes (Schweigert et al., RD2011, p78). They feed in summer along the southwest coast of Vancouver Island. The summer off-shore trawl survey and the juvenile herring survey indicated good recruitment for 2011, and initial indications from the 2011 test fishery suggest recruitment was very high. However, their weight-at-age has declined since the mid-1970s.

Sardine

In 1992, after a 45 year absence, sardine returned to southern Vancouver Island from their southern base off California and expanded their distribution northward throughout the west coast of Vancouver Island, Hecate Strait and Dixon Entrance by 1998 (Flostrand et al. RD2011, p84). The most recent U.S. sardine assessment suggests that coast-wide abundance off Canada and the U.S. peaked in 2000 and has declined since, decreasing to approximately 700,000 tonnes in 2010. The estimated migration rate into Canadian waters has also decreased since 2006.

Eulachon

Eulachon have experienced long-term declines in many rivers throughout their distribution from California to Alaska (McCarter et al. RD 2011, p87). Abundance indices in central and southern British Columbia rivers remain at low levels. The estimated eulachon spawning stock biomass in the Fraser River decreased in 1994 and has consistently been below the 150-tonne fishing reference point since 2004. COSEWIC recently designated eulachon as Threatened in some BC rivers, and others as Endangered. The biomass in the Fraser River will be estimated by an egg and larval survey in April-May 2011.

Albacore Tuna

Albacore tuna, like Pacific hake, sardines, and most recently Humboldt squid, migrate into BC waters in summer. Annual albacore Catch Per Unit Effort (CPUE) in BC coastal waters averaged 87 fish per vessel-day for 2000-2009 and in 2010 was well above average at 113 fish per vessel-day (Holmes RD2011, p76). The 2010 CPUE was the second highest since 1990; the highest was in 2006 at 129 fish per vessel-day. Temperature does not appear to be the major driver of this recent increase. Coastal BC waters in 2010 were 0.1 to 0.45 C° cooler than normal (based on Amphitrite Point data) during the fishing season (July-Oct) and more than 80% of the catch was made at temperatures of 14 to 16 °C, in contrast to temperatures between 16 and 18 °C in previous years.

Flatfish along the West Coast of Vancouver Island

The annual shrimp survey in May also provides insight into populations of resident flatfish, such as sole, Pacific cod, halibut, arrowtooth flounder, and of midwater species such as Pacific hake

(Perry RD 2011, p69). Biomass trends of key flatfish indicator species all increased in 2010, as did the biomass of the "cold water indicator" species walleye pollock.

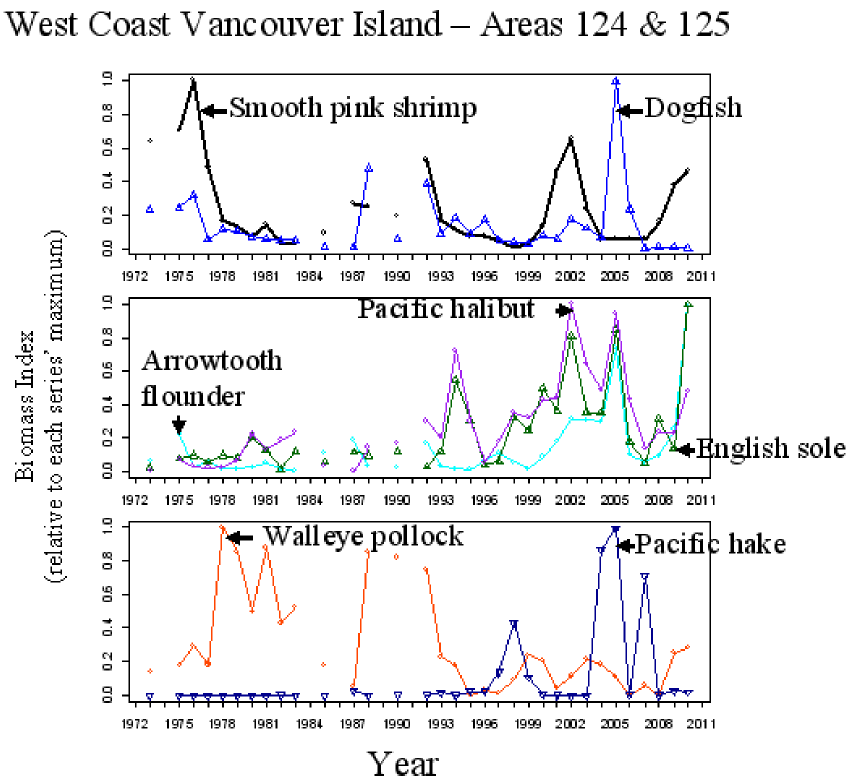


Figure 7. (from Perry RD2011, p69) Time series of normalized (to maximum biomass) survey catches of smooth pink shrimp, dogfish, Pacific halibut, Arrowtooth flounder, English sole, Pacific hake and walleye pollock. Sampling was conducted in May of each year.

Seabirds in Pacific Rim National Park Reserve

Parks Canada scientists discovered that 2010 experienced one of the highest abundances of most seabirds in this reserve (Zharikov RD2011, p95). Most species responded positively to the cooler local oceanic conditions observed during 2007 to 2009. Cooler coastal waters in BC are generally thought to result in increased energy flows through phyto- and zooplankton to juvenile fish to seabirds. The steep increases in abundance in the past few years and 2010 in particular suggest that we are mostly observing aggregative responses – birds congregate in areas with abundant food sources.

Groundfish

During the last 4 years roughly 51% of BC's trawl and 67% of BC's non-trawl catch has come from PNCIMA, which includes all waters in Canada north of Brooks Peninsula and Campbell River in northern Strait of Georgia. Recent groundfish catches, stock status and trends in abundance within the PNCIMA region were summarized by Workman and Rutherford (RD2011, p144). Gadoid (Pacific Cod, Walleye Pollock, Pacific Hake) stocks are stable or increasing. Most rockfish species are at low abundance with some being listed as Special Concern or Threatened by COSEWIC. Flatfish stocks appear to be stable. Sablefish stocks appear to be stable at low abundance. Lingcod and Elasmobranch (e.g. Spiny Dogfish) stocks appear stable.

The following statements can be made about species group status for British Columbia as a whole. Where possible, stock status for groundfish species are now characterized relative to fishery reference points usually related to the target biomass at maximum sustained yield, BMSY. For BMSY-based reference points, Critical, Cautious and Healthy Zones of stock abundance are delimited by a limit reference point (e.g. 0.4BMSY) and upper stock reference point (e.g., 0.8BMSY) based on the DFO Sustainable Fisheries Framework (DFO 2009). Recent stock assessments for inside and outside populations of Spiny Dogfish (*Squalus acanthius*) (DFO 2010) and Sablefish (*Anoplopoma fimbria*) (DFO 2011) are available on the DFO Science Advisory Schedule at http://www.dfo-mpo.gc.ca/csas-sccs/index-eng.htm. Those pertaining to Pacific Ocean Perch (*S. alutus*), the inside population of Yelloweye rockfish, and four outside stocks of Lingcod (*Ophiodon elongatus*) will be posted shortly.

The status of the inside Yelloweye rockfish population in 2010 was estimated to be well below the limit reference point of 0.2 of the unfished biomass following a long period of decline since the mid-1980s, and therefore very likely to be in the Critical Zone. The 2010 abundances of four offshore Lingcod stocks were estimated to be above the target reference point of BMSY, and therefore likely to be in the Healthy Zone. Stock assessment model fitting to historical data suggests that the sablefish spawning stock biomass is currently estimated to be below BMSY, and in the mid- to upper-Cautious Zone to low-Healthy Zone. The harvest rate of legal-size sablefish is close to the harvest rate at maximum sustained yield, UMSY, due to the series of quota reductions from 4,600 t to 2,300 t between 2007 and 2010 in response to declining abundance. The spawning biomass of Pacific Ocean Perch has increased modestly from a historical low in 2006; spawning biomass at the start of 2011 has a high probability being above the limit reference point of 0.4BMSY and is likely in the Cautious to low - Healthy zone. No immediate conservation concerns were identified for the inside and outside populations of Spiny Dogfish; proxy reference points based on historical catches were applied rather than BMSY-based reference points.

Basking shark is the only Groundfish species listed by COSEWIC as Endangered. Species listed as Threatened include Bocaccio rockfish (*Sebastes paucispinous*), Canary rockfish (*S. pinniger*), Quillback rockfish (*S. maliger*) and Yellowmouth rockfish (*S. reedi*). Species listed as Special Concern include Darkblotched rockfish (*S. crameri*), the inside and outside populations of Yelloweye rockfish (*S. ruberrimus*), Longspine thornyhead (*Sebastolobus altivelis*), and the sibling species Rougheye (*S. aleutianus*) and Blackspotted rockfish (*S. melanostictus)* (COSEWIC 2011)*.*

Indicator Stocks of Sockeye Salmon

Fraser River Sockeye Salmon returns were the big event of 2010 and are discussed at the beginning of this report. Hyatt et al. (RD2011, p157) provide information on non-Fraser Sockeye Salmon. Each of five regions of British Columbia has at least one Sockeye stock that has been closely monitored over many decades and serves as an indicator for that region. Two of these regions lie on the outer coast of British Columbia in Eastern Queen Charlotte Sound and along the west coast of Vancouver Island, and in both regions the ocean survival tends to be best when La Niña conditions and cool ocean waters are present in the first months that juveniles enter the ocean.

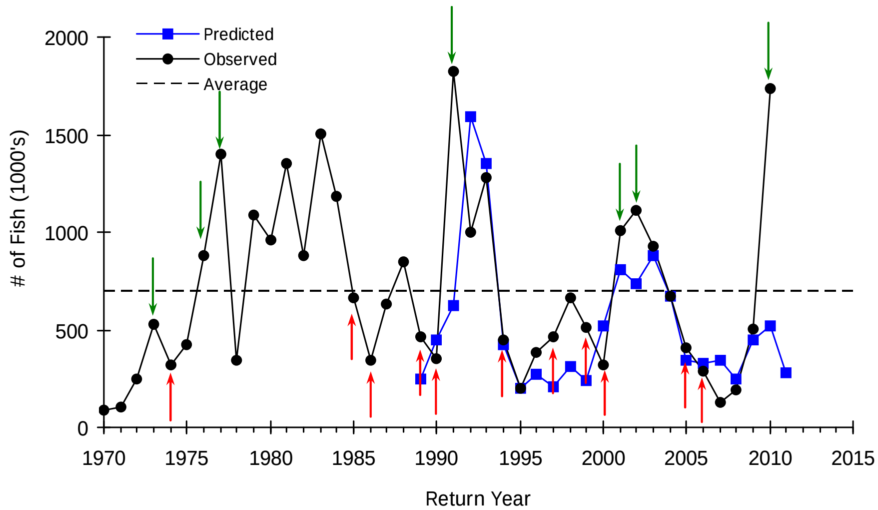


Figure 8 (from Hyatt et al. RD2011, p157). Observed and predicted returns of Barkley Sound Sockeye Salmon 1970-2011. Arrows indicate La Niña (green, cool ocean) or El Niño (red, warm ocean) events classified by NOAA as moderate to strong (www.ggweather.com/enso/oni.htm). Arrows are aligned with adult returns two years after the sea entry year in which juvenile salmon experienced a given ENSO event.

The sockeye indicator stock of Barkley Sound in Vancouver Island reveals this response in Figure 8, where returns were high two years after La Niña events and extremely high following the strong 1989 and 2008 La Niña events. The prediction formula might need to be adjusted for strong La Niña years when local waters are especially cool. Smith Inlet Sockeye are the indicator stock in Queen Charlotte Sound. Their numbers crashed in the early 1990s, and although the fresh water survival has been much higher since 1995 than in the twenty years before, the marine survival dropped in the early 1990s, has remained low, and this stock has not rebounded.

Salmon in the Central and North Coast (PNCIMA)

Temporal abundance patterns and status were examined for PNCIMA salmon (Irvine et al. RD2011, p154). To reduce the influence that non-PNCMIA salmon migrating through PNCIMA might have on the analyses, catch data were excluded from areas known to include large portions of migrating salmon. Escapement data were from all watersheds within PNCIMA. Analysis of data for salmon returning to PNCIMA revealed interesting differences in total returns (i.e. sum of catches and escapements scaled for missing streams and years) among species (Fig. 9).

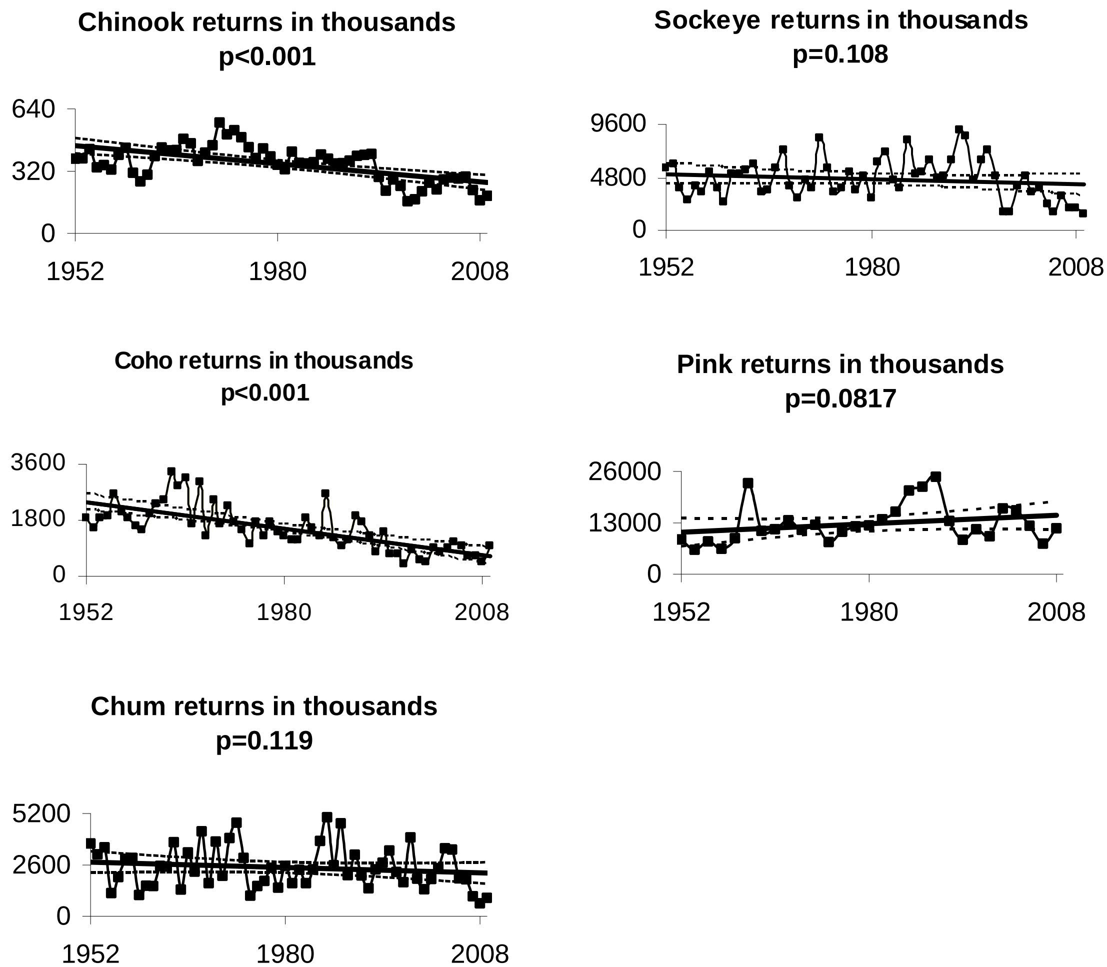


Figure 9. (from Irvine et al. RD2011, p154) Return estimates (i.e. catch plus escapement) for Chinook, Sockeye, Coho, Chum, and Pink Salmon in PNCIMA. Solid lines are linear regression lines (time series slopes) with probability that slope is 0 and dashed lines are 95% confidence limits for these lines.

It appears that Pink Salmon are doing relatively well in this area, and Coho and Chinook Salmon relatively poorly. Pink Salmon was the only species with significant increases since 1952 (spawner numbers only). When scientists compared mean values during the most recent decade with historical means, recent catches and returns were lower for each species except Pink Salmon. Pink Salmon was also the only species with significantly higher escapements during the most recent decade compared to earlier. Declines since 1952 were significant for Coho Salmon catches, spawning escapements, and returns, Chinook Salmon catches and returns, and Chum Salmon escapements (Irvine et al. RD2011, p154).

Chinook Salmon

Under the jurisdiction of the Pacific Salmon Treaty (PST), 30 Chinook Salmon stock aggregates and 25 fisheries distributed between southeast Alaska and northern Oregon are managed annually to either projected landed catch targets or are limited by maximum allowed exploitation rates. Estimates of escapements or terminal runs of mature fish for each of the stock aggregates and estimates of numbers of Chinook landed or released in the PST fisheries are assembled annually and provide some of the crucial inputs to the calibration of the Coast-wide Chinook Model (CM). The Chinook stocks (consisting of both wild- and hatchery-origin fish) and fisheries represent nearly all Chinook and fishing-related impacts known to occur within the PST jurisdiction (Brown et al. RD2011, p92). Time series of abundance indices are annually derived and reported to the Pacific Salmon Commission in technical reports available at http://www.psc.org/publications_tech_techcommitteereport.htm#TCCHINOOK).

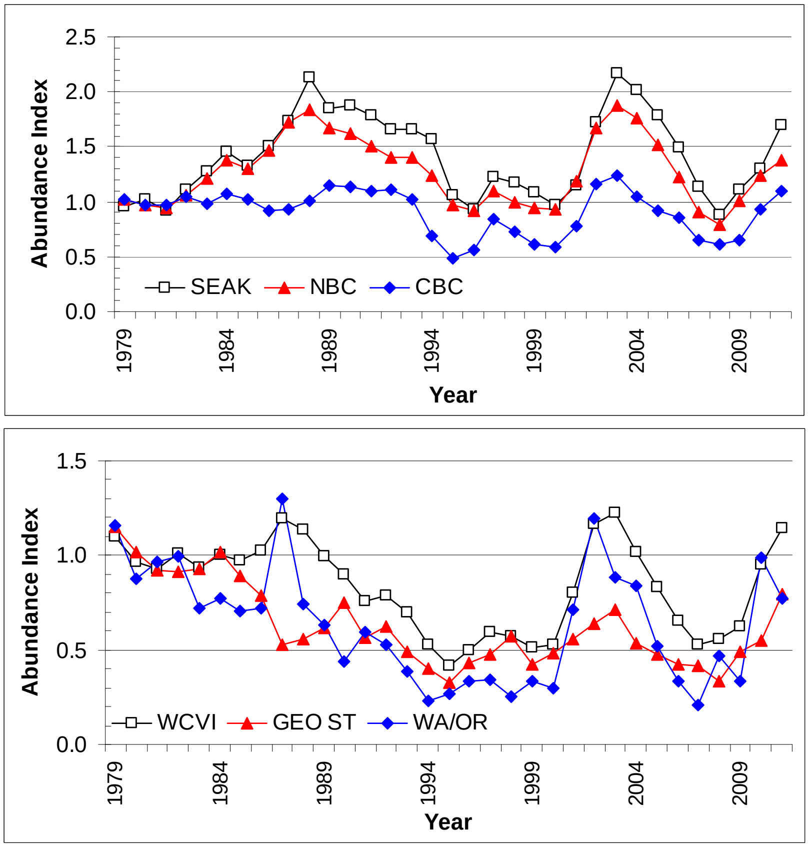


Figure 10. (from Brown et al. RD2011, p92) Time series of Chinook Salmon abundance indices. Top panel: Three major northerly PST fisheries, 1979-2011. These are southeast Alaska troll (SEAK), northern BC troll in statistical areas 1-5 (NBC) and central BC troll in statistical areas 6-12 (CBC). Bottom panel: Three southerly PST fisheries, 1979-2011. These are west coast Vancouver Island troll (WCVI), Georgia Strait and Juan de Fuca Sport (GEO ST), and Washington and northern Oregon ocean troll (WA/OR). Values for 2011 are forecasts resulting from the March 2011 calibration of the coast-wide Chinook model.

The abundance indices are derived by dividing the annual estimated Chinook abundance in any one fishery by the average from the 1979-1982 'base period'. These provide a means to assess temporal and spatial trends in the relative abundance of Chinook stocks contributing to regional fisheries. The 2011 report projects increases in Chinook abundance for most fisheries but a modest decrease for the Washington/Oregon troll fishery. The modest increases are due to expectations for large abundances of Lower Fraser River and most Columbia River stocks that entered the sea in 2008 and produced record high, or nearly so, returns of jack Chinook (the youngest age class maturing which has spent time in the ocean) to spawning grounds in 2009 and age-3 Chinook to spawning grounds in 2010.

Long-Term Trends

Many features of the ocean change slowly over several years or decades. Although they need not be reported annually, they do need updates from time to time. The status of some of these features is reported below.

Recovery of Populations of Large Baleen Whales

Seven species of baleen whales (blue, fin, sei, humpback, North Pacific right, minke and grey) inhabit Canadian Pacific waters and the Northeast Pacific. Shore-based whaling in BC (1905 to 1967) focused on the blue, fin, sei and humpback whale (as well as sperm whales), killing at least 18,316 baleen whales during this period (Gregr *et al.* 2000) and greatly reducing their numbers (Nichol et al. RD2011, p100).

Presently, the humpback whale is the most frequently encountered baleen whale in BC, with a population of about 2,100 whales estimated in 2006 (by photo-identification and mark recapture analysis) and a growth rate of 4% per year (Ford *et al.* 2009). Fin whales remain relatively uncommon in BC waters, at least when compared to sighting rates obtained for humpback whales during DFO ship surveys.

Blue whales remain relatively rare in BC even with the cessation of whaling, but there is evidence of recovery of this Northeast Pacific population with movements of individuals between California/Mexico and historic feeding grounds in the waters of BC/Alaska in late summer (Burtenshaw *et al.* 2004; Calambokidis *et al.* 2009).

There have been only two recent sightings of sei whales in BC, both since 2004, yet during the BC whaling era 3,779 sei whales were taken offshore of west coast Vancouver Island, mostly during the 1960's (Gregr *et al.* 2000).

The North Pacific right whale is an endangered species and there have been no sightings in Canadian Pacific waters since 1951, although there have been a few sightings in areas adjacent to Canadian waters.

Ocean Oxygen Concentrations

Scientists have reported alarmingly low oxygen concentrations in near-shore waters of the Oregon coast in summer, beginning in 2002 and most severely in 2006. High crab mortalities on the ocean bottom took place in these summers. Low oxygen concentrations (less than 1 ml/L) have also been observed on the continental shelf of southwest Vancouver Island since 2002, with concentrations of 0.7 ml/L at 150 metres depth recorded in 2006 and 2009, the lowest in the 50 year record (Crawford RD2011, p47). Although the frequency of observations of low oxygen concentrations has increased since 2002, hypoxia on the Canadian shelf is much less severe than off Oregon and Washington, and mortality of bottom life has not been reported.

Ocean Acidification

Ocean acidification is an alarming ocean feature of global climate change. It is expected to become a major problem impacting our local waters in the latter half of this century (Ianson 2008).

Global oceans are becoming more acidic due to increasing carbon dioxide. Much of the extra CO_2 released by burning fossil fuels ends up in the oceans, increasing the dissolved inorganic carbon concentration (DIC). The North Pacific Ocean already has the most acidic water in the Pacific, Atlantic and Indian Oceans, due to its relatively cool and fresh waters. At present the pH of seawater has decreased by about 0.1 due to oceanic uptake of anthropogenic carbon dioxide and is projected to decrease by 0.4 by the year 2050 (Orr et al. 2005). The decrease in pH (and concurrent decrease in carbonate ion concentration) is a great threat to organisms that produce calcite and aragonite shells or structures, such as pteropods, corals and shellfish. The Royal Society (2005) provides more information on this disturbing trend.

Mapping of the BC coast.
Over the past few years a project team has undertaken a thorough analysis of British Columbia's marine regions, including adjacent lands (Bodtker RD2011, p134). Products include an online marine atlas and data library (www.bcmca.ca/data) and various workshop reports generated during data collation and review (www.bcmca.ca/document-library/.

SOURCES OF INFORMATION

This Science Advisory Report has resulted from a Fisheries and Oceans Canada, Canadian Science Advisory Secretariat, Regional Advisory meeting of February 23-24, 2011 on the State of the Pacific Ocean 2010. Additional publications from this process will be posted as they become available on the DFO Science Advisory Schedule at http://www.dfo-mpo.gc.ca/csas-sccs/index-eng.htm.

All references cited as (Name RD2011, pxxx) are in the appendix of the following research document as separate reports:

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As well, reports dating back to 1999 can be found at:

English: http://www.pac.dfo-mpo.gc.ca/science/psarc-ceesp/osrs/index-eng.htm
French: http://www.pac.dfo-mpo.gc.ca/science/psarc-ceesp/osrs/index-fra.htm

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