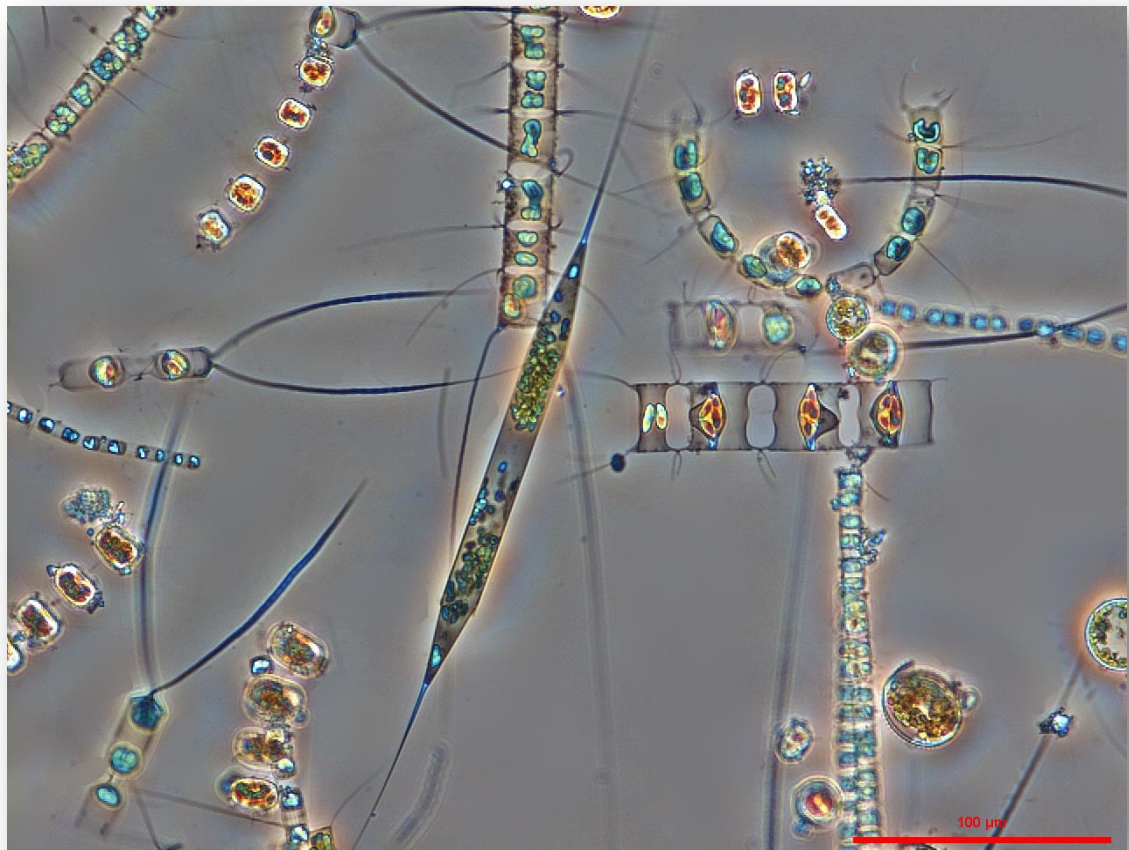


Potential Impacts of Oil on Plankton and the Planktonic Larvae of Commercial Fisheries Species



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Barb Faggetter, Ph.D., R.P.Bio
Ocean Ecology

1662 Parmenter Ave.

Prince Rupert, BC V8J 4R3

Telephone: (250) 622-2501

Email: blueseas@oceanecology.ca

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Prepared for: Joy Thorkelson, Northern Representative
United Fishermen and Allied Workers' Union - CAW
869 Fraser Street
Prince Rupert BC V8J 1R1

Prepared by: Ocean Ecology

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Executive Summary

- 1 Plankton are often referred to as the “lower trophic levels” of the ocean. These lower trophic level organisms play an extremely vital role in ocean ecosystems, and in the biosphere as a whole. In spite of their importance, we know relatively little about the spatial and temporal distribution of plankton in many regions of the ocean or their relationship to the commercial fisheries that exist in those regions.
- 2 We can characterize our limited knowledge of the temporal and spatial distribution of plankton in the Hecate Strait region as follows:
 - 1) For the overall PNCIMA region, there is a definite mean annual pattern in phytoplankton productivity, with low chlorophyll concentrations in the winter and higher concentrations in the summer. There is generally a spring bloom and a fall bloom; however, the timing and relative strength of these blooms can be locally and annually variable. In many areas within the PNCIMA region, high phytoplankton abundance may persist from June through to early fall.
 - 2) Overall, phytoplankton biomass is highest at the southeast end of Dixon Entrance, where the freshwater input of the Skeena and Nass Rivers is highest, and in the entrance to Queen Charlotte Sound in the south where the high-nutrient inflow from Queen Charlotte Strait mixes with fresher runoff from Fitz Hugh and Smith Sounds. Several localized areas around the perimeter of the Queen Charlotte Basin sustain high phytoplankton biomass throughout much of the spring, summer and fall (particularly Dogfish Banks, Chatham Sound, and off of Fitz Hugh and Smith Sounds). These areas have large and sustained nutrient supply, either from freshwater river runoff and deep-water entrainment, from strong tidal mixing in shallow areas, or from wind-driven upwelling in the summer.
 - 3) The phytoplankton community composition varies seasonally in PNCIMA. In general, the spring bloom is composed largely of small, fast-growing diatoms. As these species deplete surface nutrients, larger diatoms and dinoflagellates gain in abundance. In the summer, a variety of flagellates numerically dominate, but diatoms continue to dominate the biomass. In fall and winter, the diatom contribution drops below 50%. Small flagellates then dominate the relatively low winter phytoplankton productivity and biomass. However, this generally pattern may not be reflected locally. For example, in northern Hecate Strait, diatoms numerically dominated the population throughout the year, with centric diatoms making up greater than 50% of the total phytoplankton during most of the year.
 - 4) The “average” temporal distribution of zooplankton is similar to that of the phytoplankton on which they feed. Minimum annual zooplankton densities occur in winter. In spring, many species of zooplankton spawn, and total numbers follow the upward trend in the phytoplankton population with a short time lag.
 - 5) The spatial distribution of zooplankton is determined by a combination of nutrient enrichment, which stimulates phytoplankton blooms, localized concentrating effects (e.g., along bathymetric edges), and the retention of critical life stages. The seasonal cycle of zooplankton is subject to significant within-region and within-season variability. This is caused in part by spatial patchiness and in part by interannual variability.
 - 6) Small to medium-sized copepods tend to be the most common zooplankton. Euphausiids, another of the crustacean zooplankton, are a key prey for some fish, birds, and whales. Euphausiid biomass reaches a maximum in autumn at most locations. The dominant carnivorous zooplankton in the Hecate Strait region are chaetognaths, which are most abundant during fall and winter, and jellyfish, which reach their maximum abundance at mid-summer. Other important non-crustacean herbivorous zooplankton include shelled pteropods, salps and doliolids. These groups are occasionally abundant in Hecate Strait, but on average make up less of the total biomass than they do off the

outer coast of Vancouver Island. Several ciliate species can be very abundant numerically during June and July. Compared to the continental margin off Vancouver Island (both south and north), Hecate Strait has lower total zooplankton biomass, smaller amounts of deep-water oceanic species (pteropods, subarctic oceanic copepods, salps), and larger amounts of meroplanktonic larvae.

- 7) Many of the larval invertebrate meroplankton are most abundant in the springtime following a spring spawning event; however, spawning for some species also occurs in the summer and early fall.
- 8) For most species of ichthyoplankton, abundance is greatest in winter and spring. Wind-driven displacement of surface water can be large in the winter, resulting in dispersal of surface plankton and decreased retention of larvae. Poor larval retention within coastal waters may significantly limit the abundance of adult fish in subsequent years. There appears to be a spatially dependent trophic linkage from phytoplankton to fish in the PNCIMA region. Thus, areas of high phytoplankton productivity support high biomasses of groundfish and pelagic fish.
- 9) In early spring and summer, juvenile salmon of all species are found aggregated in nearshore inlets and estuaries serving as their points of sea entry. However, by October, juvenile salmon of all species are found somewhat further offshore concentrated in pelagic, surface waters located over the continental shelf. All Pacific salmon species, whether rearing in or migrating through the QCB, tend to aggregate in the nearshore waters of the continental shelf. The virtual absence of juvenile salmon in the offshore waters of PNCIMA serves to emphasize the importance of nearshore areas to salmon populations originating from watersheds within and external to the QCB.
- 10) Ecologically or biologically significant areas (EBSAs) for salmon exist in the PNCIMA region. These regions would be particularly sensitive to impacts by oil.

3 While a number of laboratory and mesocosm studies have been carried out to examine the effects of oil on plankton, the overall impact on the entire plankton community in its natural environment, both in the short term and over a number of years, is relatively poorly understood. There are many environmental variables which change both spatially and temporally, making each spill event a unique impact on the ecosystem where it occurred. While studies from the Deepwater Horizon spill have shown that the plankton community appears to have recovered relatively quickly, we are still waiting to learn about the impacts to sensitive species and long term effects. This lack of understanding regarding the long term effects of changes in species composition and impacts on organisms with multiyear life cycles, combined with our limited knowledge of the PNCIMA region, particularly the northern reaches of Hecate Strait, mean that the use of the precautionary principle is essential in assessing the degree of risk that an oil spill represents for this region.

1 Introduction

- 4 In 1998, Enbridge Northern Gateway Pipelines started an analysis of the need for, and feasibility of, a new pipeline to transport future oil sands production to existing and new markets (Gateway Pipeline Inc. 2005). By 2005, Enbridge released a preliminary proposal for a project to construct and operate two pipelines, 1,170 km in length, between an inland terminal at Bruderheim, Alberta and a marine terminal near Kitimat, British Columbia. The marine component of the project will include: (1) an export oil sands product pipeline; (2) an import condensate pipeline; (3) a tank terminal, including hydrocarbon tanks, pump facilities and other land facilities; (4) two marine loading and unloading berths; and (5) marine transportation of oil and condensate within a defined area (CEAA 2011).
- 5 On September 29, 2006, the Honourable Rona Ambrose, the Minister of the Environment and Minister responsible for the Canadian Environmental Assessment Agency (CEAA) at that time, announced that the proposed Enbridge Gateway Pipeline and Marine Infrastructure project had been referred for assessment by an independent review panel. Minister Ambrose stated "*Public discussion and debate are crucial elements in the review process. The public process will help Albertans and British Columbians to understand the potential impacts of this complex project which passes through diverse ecological regions and zones.*" CEAA then made \$600,000 available under its Participant Funding Program to assist groups and individuals to participate in the environmental review of the proposed Northern Gateway Pipeline Project on December 4, 2009. On March 25, 2010, CEAA awarded \$64,665 to the United Fishermen and Allied Workers' Union – CAW to support their participation in the environmental assessment process for the Northern Gateway Pipeline Project (CEAA 2011). The UFAWU-CAW application proposed additional studies on (1) the spatial and temporal variations in plankton, including the larvae of commercial species (2) the impact of oil on plankton, including both food chain impacts and impacts on the larvae of commercial species; (3) the fate and toxicology of oil as it relates to commercial species; and (4) the socioeconomic impacts associated with the potential loss of fisheries as a result of an oil spill, including long-term impacts. It was felt by the UFAWU-CAW that these issues had not been adequately addressed by the original impact assessment studies conducted by the proponent (Beckett & Monro 2010; Enbridge Northern Gateway Project 2010; Stephenson *et al.* 2010; Watson & Vaughan 2010). Ocean Ecology has been engaged by UFAWU-CAW to assist them in these studies.
- 6 The objectives of this report are (1) to review our current knowledge of the temporal and spatial distribution of plankton in the Hecate Strait region; (2) to describe, where known, the food preferences and early life history, including spatial and temporal distribution, of commercial species with planktonic larvae; (3) to discuss potential impacts of oil on plankton, with emphasis on particularly sensitive species, times of the years, and locations; and (4) to highlight gaps in our knowledge and understanding of the marine ecosystem where the application of the precautionary principle is extremely important.

2 Temporal and Spatial Distribution of Plankton in Hecate Strait

- 7 Plankton are organisms which drift in the ocean currents. While many plankton have some capacity to swim vertically in the water column, their swimming velocity is low relative to the horizontal currents of the ocean, and thus their spatial distribution is determined largely by the ocean current patterns. Plankton range in size from less than 2 μm (bacteria and viruses) to greater than 20 mm (jellyfish and salps). Although marine bacteria play an essential role in the degradation of oil after a spill, and marine viruses are important in species shifts following stressor events, for the purposes of describing the potential impacts of oil on the planktonic food chain and the early larval stages of commercial fisheries species, this report will focus on species in the size range between 2 μm and 20 mm. This size range has traditionally been divided into the phytoplankton, the “plant-like” or photosynthetic plankton which form the base on the food chain, and the zooplankton, the “animal-like” or heterotrophic plankton. Plankton may also be described according to their life histories. Holoplankton are those organisms which are planktonic for their entire life cycle, and include many phytoplankton, copepods, and krill. Meroplankton are those organisms which are planktonic for only a part of their life cycle, usually the larval phase. Meroplankton include sea urchins, sea stars, crustaceans, some marine gastropods, and many fish species. While plankton can be found throughout the oceans, plankton productivity is generally highest along the continental margins where nutrients are most plentiful.
- 8 Plankton are often referred to as the “lower trophic levels” of the ocean. Since plankton are small and not readily visible to most people, and are not often commercially valuable in and of themselves, studies on plankton often do not receive the same levels of funding as studies on visible iconic species, such as whales, or commercially valuable species, such as salmon. However, these lower trophic level organisms play an extremely vital role in ocean ecosystems, and in the biosphere as a whole. As an example, phytoplankton in the open ocean produce approximately 110% of the annual primary production, or plant growth, of tropical rainforests. In spite of their importance, we know relatively little about the spatial and temporal distribution of plankton in many regions of the ocean. Hecate Strait is part of the PNCIMA (Pacific North Coast Integrated Management Area) region. Examination of the data sets available from DFO show that the zooplankton data for PNCIMA is almost all located at the north end of Vancouver Island, very close to the data sources for WCVI (West Coast Vancouver Island). To quote from DFO, “*We do not have sufficient data elsewhere in the PNCIMA areas to assess whether this is representative of PNCIMA as a whole*” (Brown 2008).
- 9 Our lack of data with respect to the lower trophic levels and their relationship to commercial fisheries is further emphasized by Biodivcanada.ca, the website of the federal, provincial and territorial working group on biodiversity, which was established following Canada's ratification of the Convention on Biological Diversity in December, 1992. This working group makes the following comments regarding research and monitoring needs for marine biodiversity in Canada (biodivcanada.ca 2011):
- Information needs common to all marine ecozones:
 - Status and trends related to coastal biomes
 - Long-term trends in fish and zooplankton, and their food web linkages
 - Accurate population abundance estimates
 - Accurate status and trends estimates lacking for many species, particularly benthic and non-commercial species
 - Information needs specific to the North coast and Hecate Strait ecozone:
 - Source of excessive marine mortality of some fish, including salmon, eulachon, and herring
 - Trends in plankton (only available for the southern edge of the ecozone)

2.1 Phytoplankton

2.1.1 General Observations

- 10 Phytoplankton carry out photosynthesis - the process by which plants and plant-like organisms convert carbon dioxide and water into organic compounds, such as sugars, using a chemical pigment called chlorophyll to capture energy from sunlight. Globally, phytoplankton are thought to be responsible for 40% of all the photosynthesis on Earth (Garrison 2002). In the open ocean, they are responsible for essentially 100% of all photosynthesis, and in many coastal areas, they carry out over 90% (some photosynthesis is done by the benthic macrophytes and seagrasses in these regions) (Mackas *et al.* 2007).
- 11 In the Hecate Strait region, there are three main “ecological” groups of phytoplankton:
- *Diatoms* - diatoms are encased within a unique cell wall made of silica (hydrated silicon dioxide) called a frustule. Diatoms may have radial symmetry (centric diatoms) or bilateral symmetry (pennate diatoms). They may occur either singly or in chains. Diatoms account for much of the spring and summer season biomass and productivity (Perry 1984).
 - *Dinoflagellates* - dinoflagellates are characterized by having two flagella, transverse and longitudinal, which allow them to have limited vertical migration in the water column. They usually occur singly, although a few species can form chains. Many dinoflagellates are photosynthetic, although a large fraction of these are in fact mixotrophic, combining photosynthesis with ingestion of prey. Other dinoflagellates are colorless predators on other protozoa, and therefore function ecologically as microzooplankton. Dinoflagellates may be “armoured” by a thick cellulose cell wall, or “naked”. Dinoflagellates tend to be most abundant during the mid to late summer (Perry 1984; Forbes and Waters 1993).
 - *“Phytoflagellates”* - phytoflagellates are a diverse group containing members from ten taxonomic classes of algae. Their shared characteristics are motility and small size. Phytoflagellates are most abundant in offshore regions and in the winter when larger phytoplankton, such as diatoms and dinoflagellates, are low in concentration. Coccolithophorids are a sub-group within the phytoflagellates. They have plates or scales called coccoliths that are made of calcite, which are important microfossils. When they produce dense blooms, they turn the water a milky turquoise color (Mackas *et al.* 2007). They are responsible for the occasional “unique” bloom in the region.

2.1.2 Temporal Distribution

- 12 The natural progression and abundance of phytoplankton species in temperate waters, such as those of the North Coast and Hecate Strait, are described by Margalef (1958) and Guillard and Kilham (1977). The increased availability of nutrients and light in springtime, both necessary for photosynthesis, results in higher rates of primary production and higher phytoplankton biomass. While light availability (“top-down” control determined by day length, cloudiness and mixed-layer depth) is the over-riding variable driving the spring bloom, the timing and magnitude of bloom dynamics can be strongly modulated by zooplankton grazing (“bottom-up” control). Throughout the summer and fall, diatom and dinoflagellate populations respond to the physical conditions that control light and nutrient availability, and to grazing by micro- and macrozooplankton. A short fall bloom of diatoms often occurs in the late summer/fall as grazing pressure decreases and increasing seasonal winds mix deeper nutrients up to the surface. During the winter, phytoplankton production and biomass tend to be low in response to low light conditions (Cummins and Haigh 2010).

- 13 Since the pigment chlorophyll is essential to the process of photosynthesis, one of the ways of observing increases in the abundance of phytoplankton is by measuring the amount of chlorophyll present in the seawater at a given time and location. McQueen and Ware (2006) have summarized all of the available chlorophyll data for "Hecate Strait", which they have defined to include Dixon Entrance, Hecate Strait, Goose Island Bank, and Queen Charlotte Sound. This summary was based on five data sets (Dilke *et al.* (1979), Perry *et al.* (1981), Forbes and Waters (1993), Denman *et al.* (1985), and an unpublished data set from Ware and Thomson as cited by McQueen and Ware (2006)). Comparisons of chlorophyll concentrations measured from surface waters (<10 m deep) at three locations (Dixon Entrance, Hecate Strait, and Queen Charlotte Sound) suggested that the differences between years and between sites were small (McQueen and Ware 2006). However, there was a very definite mean annual pattern (see Figure 1), with low chlorophyll concentrations in the winter and higher concentrations in the summer. In addition, there was a strong spring bloom and a weaker fall bloom (McQueen and Ware 2006).

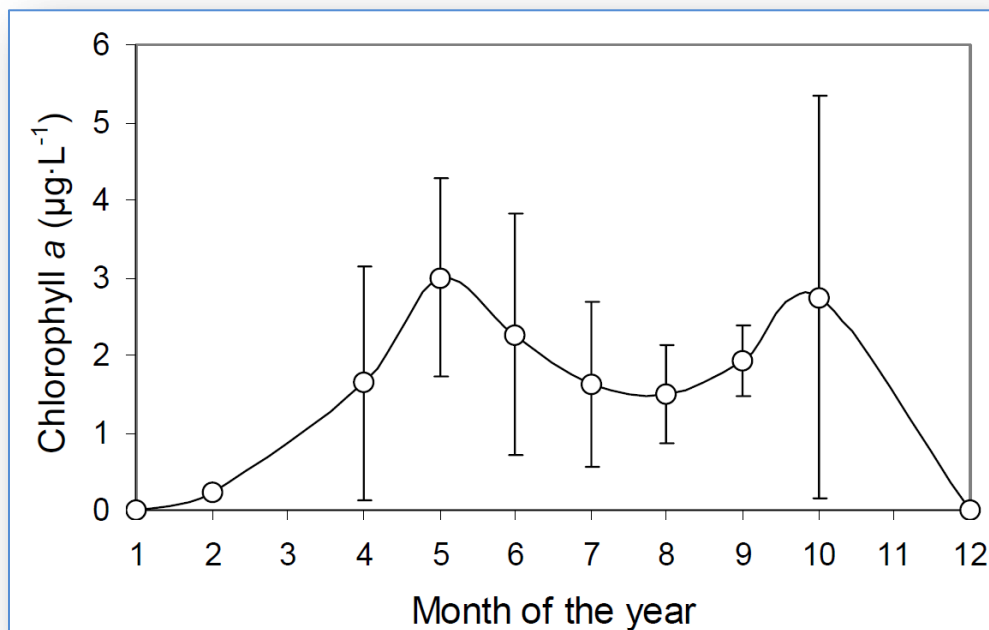


Figure 1. Monthly means and standard deviations for chlorophyll a concentrations ($\mu\text{g}\cdot\text{L}^{-1}$) based on shallow water (<10 m) data from five data sets (Dilke *et al.* 1979, Perry *et al.* 1981, Denman *et al.* 1985, Forbes and Waters 1993, Ware and Thompson unpublished data cited by McQueen and Ware (2006)).

- 14 In areas where field-based information regarding the spatial and temporal variability of phytoplankton is virtually nonexistent, such as the northern Hecate Strait, ocean colour imagery derived from satellite data can be used to develop a basic understanding of the seasonal and interannual variability in phytoplankton population properties such as chlorophyll. Data from several satellite imaging systems have been used for this purpose: (1) SeaWiFS [sea-viewing wide field-of-view sensor]; (2) CZCS [coastal zone colour scanner]; and (3) AVHRR [advanced very high resolution radiometer] (Robinson *et al.* 2004).

- 15 The satellite-derived monthly mean chlorophyll concentrations from 1998 to 2005 for the PNCIMA area are shown in Figure 2 (Lucas *et al.*, 2006). These satellite data also show a strong spring phytoplankton bloom and a weaker fall bloom, and suggest that the interannual variability of chlorophyll concentrations is small in the North Coast and Hecate Strait ecozone. However, it should be noted that satellite-derived chlorophyll estimates are not regarded as reliable replacements for *in situ* measurements in coastal regions where land-derived particulates and coloured dissolved organic matter (CDOM) are prevalent, as both of these water-borne substances can interfere with the light-absorption spectrum of chlorophyll *a* (Cummins and Haigh 2010).

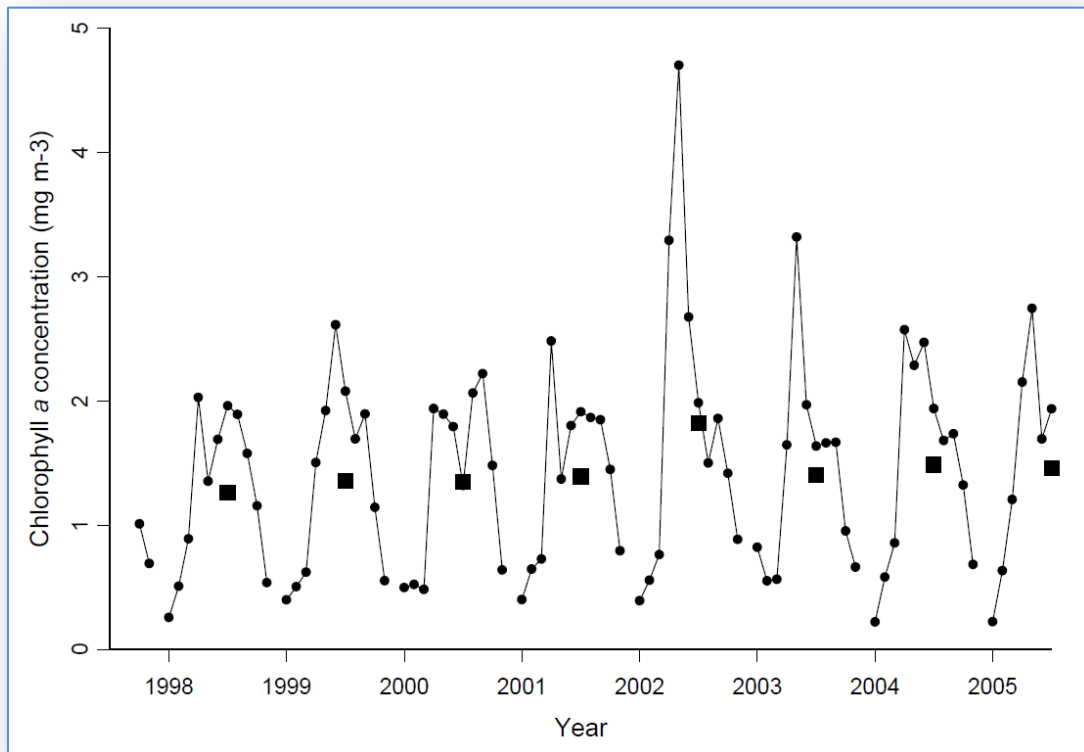


Figure 2. Monthly mean chlorophyll *a* biomass (mg m^{-3}) for the PNCIMA region as measured by the SeaWiFS satellite sensor at 9 km spatial resolution. Note that no data are available for December of any year. Large squares represent the annual average chlorophyll *a* biomass calculated from monthly averages from January to November of each year (Lucas *et al.* 2006).

- 16 Data from a 5-year time series (September 1997 to October 2003) of chlorophyll concentration measured at an approximately 1.1 km resolution by the SeaWiFS color satellite (Peña and Crawford 2004) are shown in Figure 3. The spatially-averaged seasonal cycle shows peak chlorophyll concentration during a spring bloom in May (average 5 mg m^{-3}), as well as relatively high concentrations ($\sim 3 \text{ mg m}^{-3}$) which persist from June through to early fall. This contrasts with many other high latitude ocean regions, in which the spring peak is followed by relatively low biomass and productivity throughout the summer (Mackas *et al.* 2007).

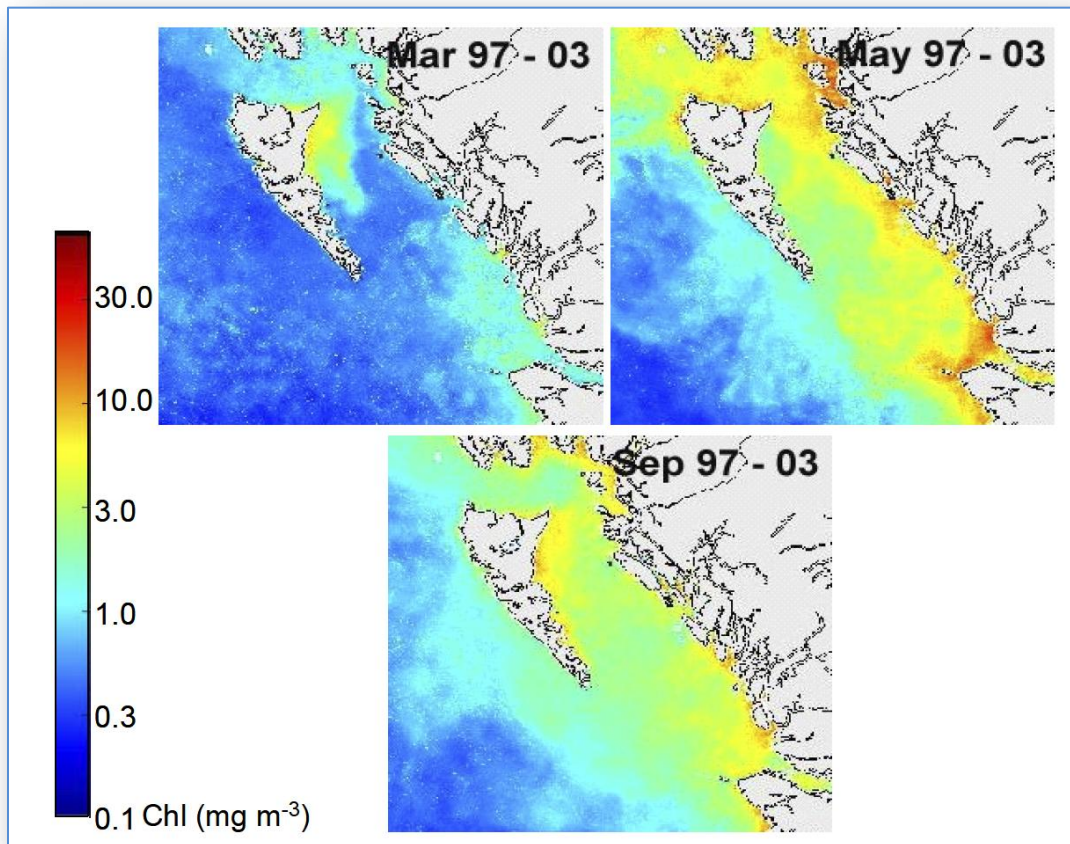


Figure 3. Aggregated monthly averaged satellite chlorophyll data from 1997 to 2003 for March, May and September. Data reveal bloom hotspots but also the fact that the shelf is quite productive ($>1 \text{ mg m}^{-3}$) from March through to September and even into October (Peña and Crawford 2004).

- 17 Robinson *et al.* (2004) examined twenty years of satellite observations to determine spatial and temporal patterns in phytoplankton blooms in the seas adjacent to the Gwaii Haanas National Park Reserve in the northern Hecate Strait region. Seas within and adjacent to the proposed Gwaii Haanas National Marine Conservation Area (GHNMCA) boundaries can be divided into three general regions based on dominant oceanographic processes. During the May to September summer period, seas along the west coast of the GHNMCA (“Gowgaia”) are primarily influenced by upwelling of cool, nutrient-rich waters along the continental slope and narrow continental shelf ($< 5 \text{ km}$ wide). Seas at the southern end of the GHNMCA (“Kunghit”) are influenced by regions of major tidal mixing (M2 currents at Cape St. James reach speeds of $60 \text{ cm}\cdot\text{s}^{-1}$). The seas to the east of the GHNMCA (“Hecate”) are shallow ($< 100 \text{ m}$) and influenced by oceanographic events occurring in Hecate Strait and Queen Charlotte Sound. Data from the CZCS for the period 1979–1985 provide the longest available time-series of satellite-derived chlorophyll estimates for the GHNMCA area. Unlike studies using data for the entire PNCIMA region, the analysis of the ocean colour data for this more northern study revealed large potential interannual variations in satellite-derived chlorophyll for the three regions in the GHNMCA, and indicated that the Hecate region typically had the highest estimated chlorophyll. Seasonally, all three regions showed a bimodal pattern in chlorophyll concentrations, with a spring bloom occurring from March to May and a second summer bloom occurring from July to August (see

Figure 4). In the Hecate and Kunghit regions, the spring bloom occurred in April, whereas in the Gowgaia region, it occurred in March. The summer bloom occurred in the first two regions in July, and in Gowgaia in August. Both the spring and summer blooms appear to occur a little earlier in these three regions than the average timing for the entire PNCIMA area. Also, unlike the average data for the PNCIMA region, the summer bloom is often more intense than the spring bloom. At present, few field samples exist to verify the phytoplankton species or seasonal trends in chlorophyll identified by satellite sensors (Robinson *et al.* 2004).

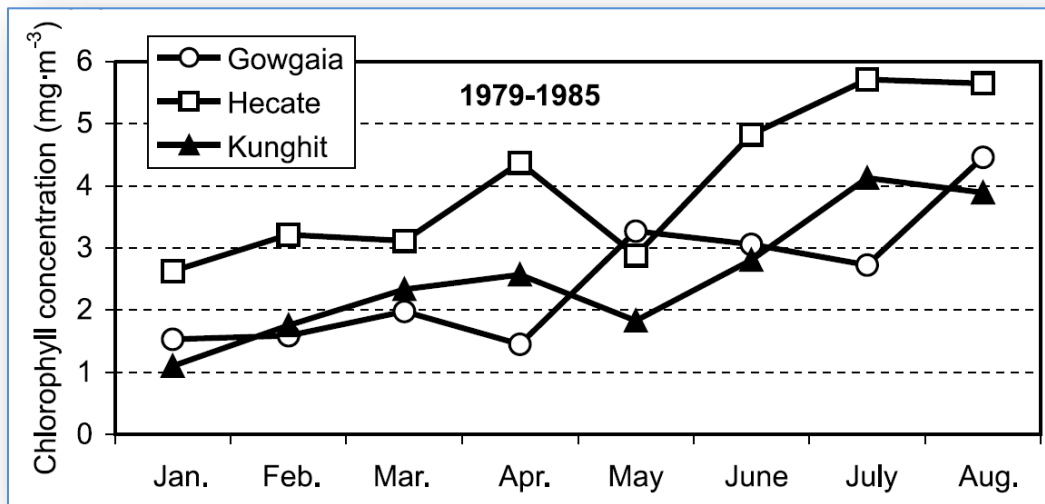


Figure 4. Monthly CZCS-derived estimates of chlorophyll for the three major oceanographic regions surrounding the GHNMC (Robinson *et al.* 2004).

18

Figure 5 shows the monthly average chlorophyll and normalized water-leaving radiance at 555 nm for Hecate Strait from the NASA SeaWiFS global (level 3) monthly product. Overall, these data indicate a bimodal seasonal pattern in chlorophyll for the Hecate Strait region; however, they provide a good illustration of the level of interannual variability of bloom timing between the years. During the strong El Niño year 1998, the data show a very minor spring bloom and a late-summer bloom. In both 1999 and 2000, a major spring bloom occurred in May and June, and a second major fall bloom occurred in September. During 2001, the bimodal pattern in chlorophyll observed in the 1999 and 2000 SeaWiFS monthly averages was not apparent (Robinson *et al.* 2004).

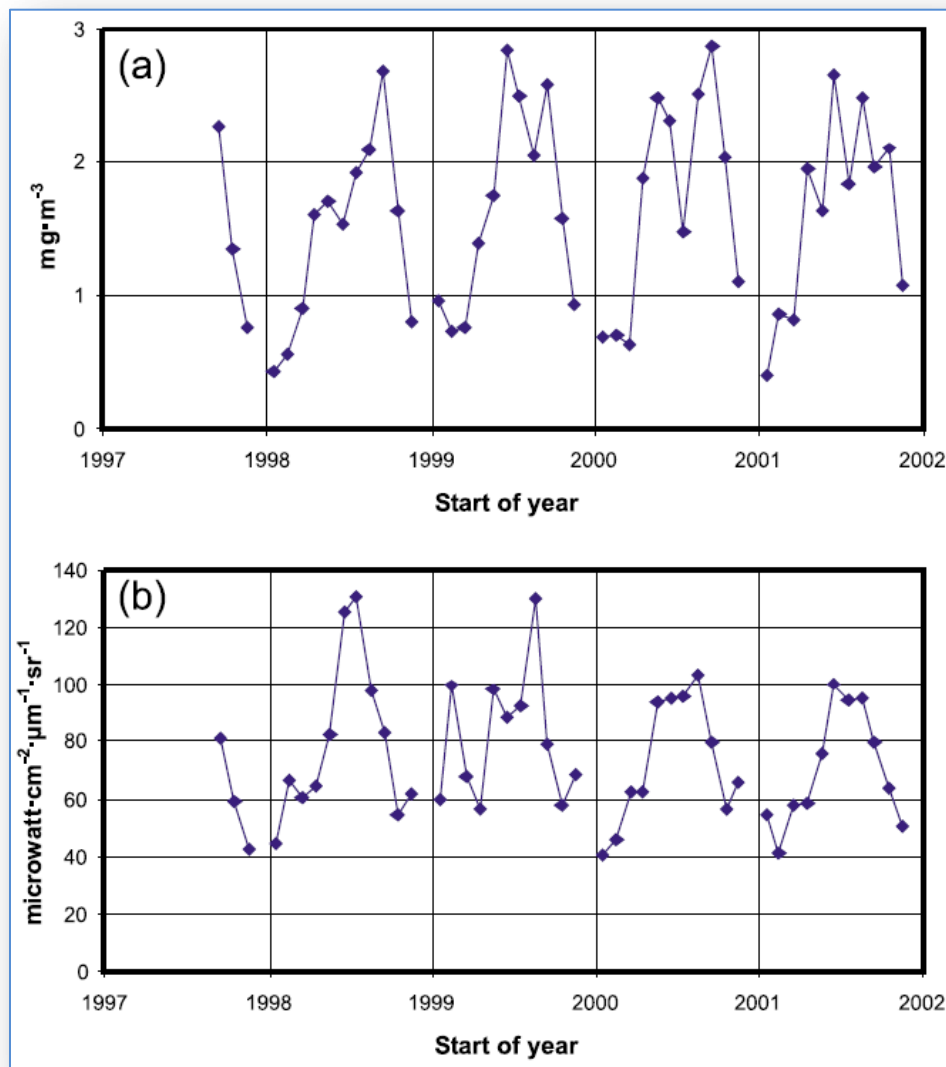


Figure 5. Monthly average chlorophyll (a) and $nLw\ 555\ \text{nm}$ (b) for Hecate Strait derived from the SeaWiFS level 3 imagery from the fall of 1997 to the end of 2001 (Robinson *et al.* 2004).

19 Robinson *et al.* (2004) also examined data from AVHRR imagery for the GHNMCA to determine the temporal distribution of phytoplankton blooms in this region. AVHRR imagery locates large, bright (highly reflective) surface patches, which indicate areas of high concentrations of suspended matter (which can include both living plankton and nonliving inorganic particles). In the GHNMCA region, these patches were most common during the period July through August, when they are most likely indicative of the summer bloom (see Figure 6).

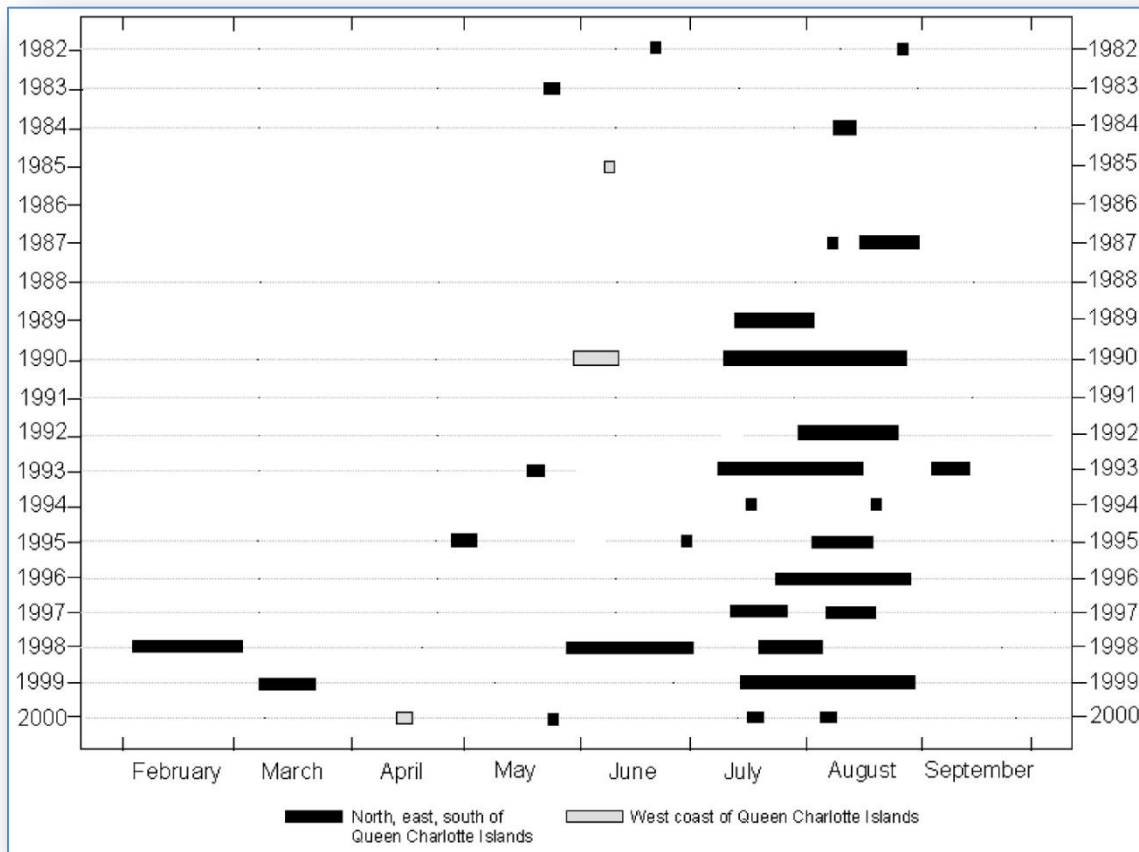


Figure 6. Timing and duration of brightness events detected off the Queen Charlotte Islands derived from AVHRR imagery for the period 1982–2000 (Robinson *et al.* 2004).

20 Faggetter (2001) carried out phytoplankton sampling at a number of sites in northern Hecate Strait during the years 2000 to 2001 (see Figure 7). These samples were collected as a part of the Northcoast Plankton Identification and Monitoring Program at sites where potential existed for the development of shellfish aquaculture. As a result, most of the sites were located in relatively shallow water fairly close to shore. Thus, this data set provides some information on the nearshore phytoplankton bloom dynamics. Of the 10 sites at which sampling occurred, only 5 sites had sufficiently complete enough records to carry out analysis of phytoplankton trends - Birnie Island, Metlakatla Bay, Prince Rupert, Humpback Bay, and Freeman Pass.



Figure 7. Locations for the northcoast plankton study of 2000-2001 (Faggetter 2001).

- 21 At the two locations for which early season data were available, a small, but measurable early spring bloom occurred around the end of April. This was followed by a long duration spring/summer bloom at all locations except Birnie Island which started at the beginning of June and endured to the beginning of August, with several spikes of increased bloom intensity throughout the duration. In October, all sites experienced a small fall bloom. Humpback Bay, the only site with late season data, also showed a small bloom in December. These results are similar to those seen for the GHNMCA, except that the summer bloom started earlier and was much longer in duration. They also support the observations of Peña and Crawford (2004) who noted that chlorophyll concentration peaked during a spring bloom in May, but persisted at a relatively high level from June through to early fall. Thus, it appears that many parts of Hecate Strait are quite productive throughout the summer.

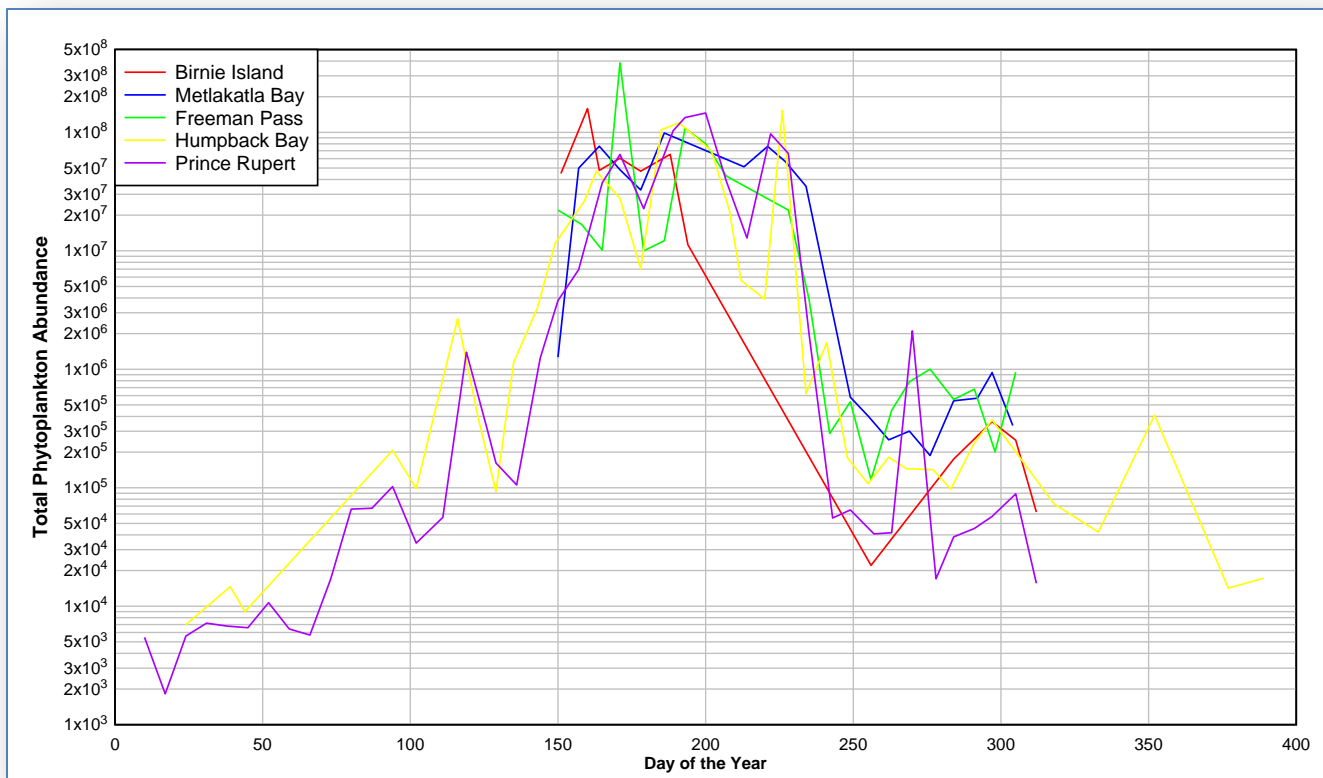


Figure 8. Total plankton abundance during 2000-2001 at five locations in northern Hecate Strait (Faggetter 2001).

2.1.3 Spatial Distribution

- 22 Overall, the PNCIMA region appears to have moderately high phytoplankton biomass over most of the continental shelf from spring through fall, with very high levels at the entrance to some inlets and fjords. Generally, high phytoplankton abundance is often associated with areas of high freshwater input where there is strong tidal mixing. However, in the PNCIMA region, there tends to be a lack of strong tidal mixing where rivers discharge, resulting in poor mixing of the nutrient-rich freshwater into the underlying seawater. Although some regions, such as the Chatham Sound and Fitz Hugh-Smith Sound outflows, support plankton production, they do not have sustained, strong productivity. Thus, phytoplankton biomass is highest at the southeast end of Dixon Entrance, where the freshwater input of the Skeena and Nass Rivers is highest, and in the entrance to Queen Charlotte Sound in the south where the high-nutrient inflow from Queen Charlotte Strait mixes with fresher runoff from Fitz Hugh and Smith Sounds (Lucas *et al.* 2006).
- 23 Figure 9 shows the number of months between spring and early fall from 1997 to 2003 for which chlorophyll levels at each location exceeded 3 mg m^{-3} . Several areas around the perimeter of the Queen Charlotte Basin sustained high phytoplankton biomass throughout much of the spring, summer and fall (particularly Dogfish Banks, Chatham Sound, and off of Fitz Hugh and Smith Sounds). These areas have large and sustained nutrient supply, either from freshwater river runoff and deep-water entrainment, from strong tidal mixing in shallow areas, or from wind-driven upwelling in the summer. Note that some of the 'chlorophyll' in all these regions may be contributed by color from suspended sediments. However, chlorophyll concentrations are usually low near Cape St. James, which is the region with strongest vertical mixing by tidal currents. This is due to the combined effects of strong horizontal advection, strong vertical mixing, and a lack of

vertical stratification (all of which lead to poor retention of biomass, thus preventing blooms from developing) (Mackas *et al.* 2007).

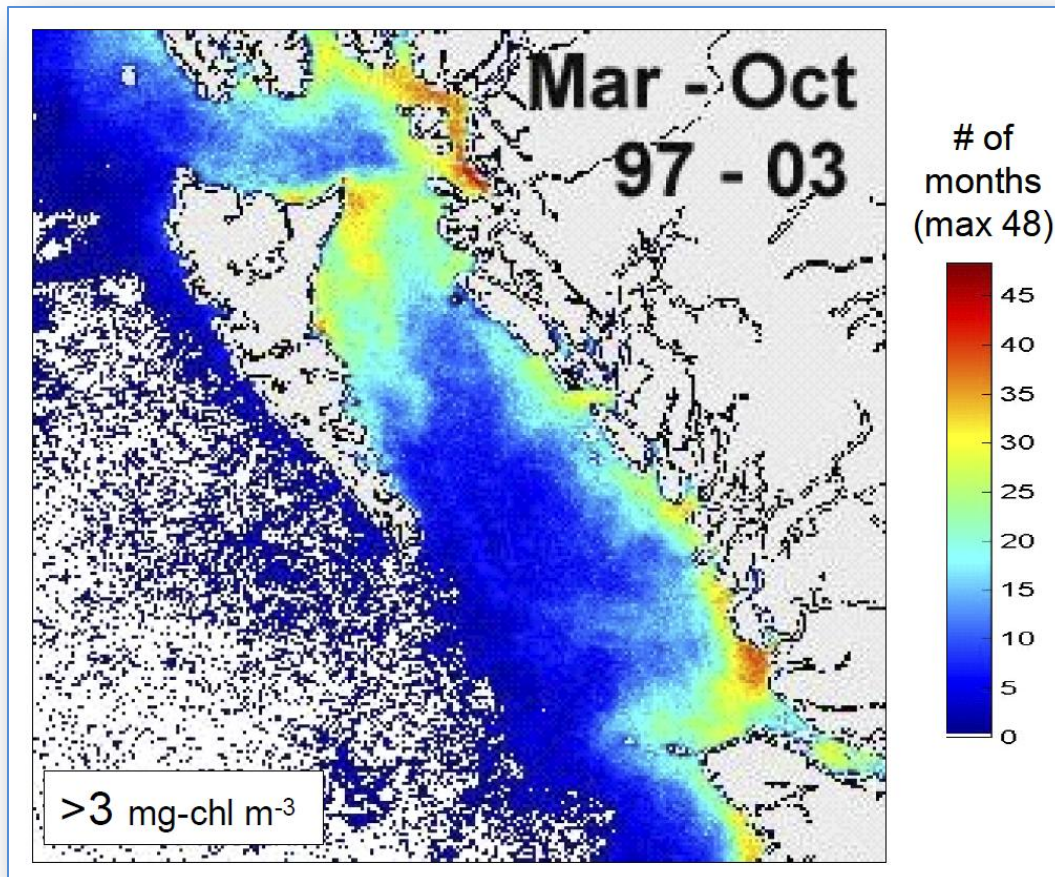


Figure 9. The number of months a given pixel contained chlorophyll levels over 3 mg m⁻³ from March to October using SeaWiFS color satellite data from 1997 to 2003 (Peña and Crawford 2004).

- 24 The analysis of AVHRR imagery carried out by Robinson *et al.* (2004) for the GHNMCA showed that the large bright surface patches (presumed to be phytoplankton blooms) originated from three main sources: Dogfish Bank to the north, Queen Charlotte Sound to the south, and within the GHNMCA (see Figure 10). This corresponds well with the SeaWiFS observations of Mackas *et al.* (2007).

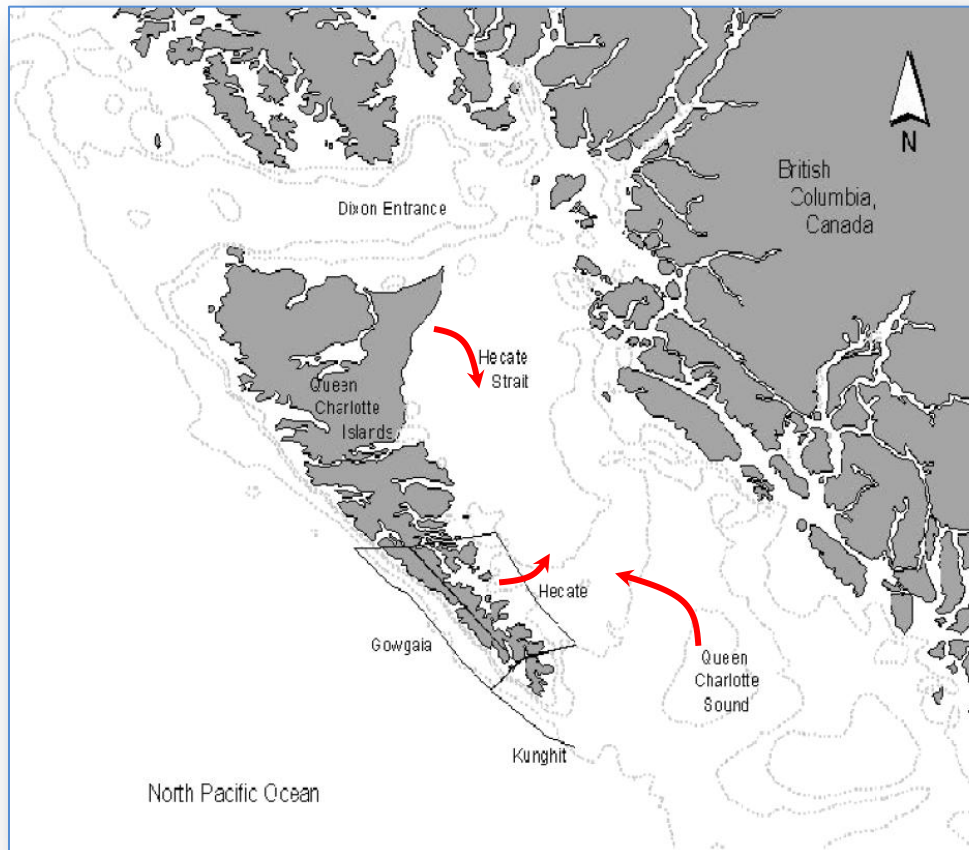


Figure 10. Sources of suspended matter to the GHNMCA.

- 25 Not much data exists for the Hecate Strait area with respect to phytoplankton distribution with depth in the water column. Using data from Denman *et al.* (1985), McQueen and Ware (2006) generated a plot of combined data from Queen Charlotte Sound and Hecate Strait (see Figure 11) which shows the existence of a mixed-depth zone. Above a depth of 20 m, chlorophyll *a* concentrations averaged about $2 \mu\text{g}\cdot\text{L}^{-1}$, between 20-30 m concentrations increased significantly, and below 30-40 m concentrations declined. The mixed depth is considered the region from 0-30 m, and is the depth over which the water can be thoroughly mixed by the wind. A chlorophyll maximum (e.g., the region between 30-40 m) is a common oceanographic feature in many marine water bodies, and is usually located at the bottom of the euphotic zone (upper layer of the ocean where there is sufficient sunlight for photosynthesis to occur) and is associated with the nitricline (region of maximum change in nitrate concentration). The formation and maintenance of the chlorophyll maximum generally results from a combination of factors, such as (1) reduction in the sinking rate of phytoplankton due to increases in nutrient concentration; (2) density changes in the water column; (3) vertical mixing; (4) differential grazing of phytoplankton above the

chlorophyll maximum by herbivores; (5) active growth of phytoplankton at or near the depth of the chlorophyll maximum; (6) an increase in the amount of chlorophyll per cell as a result of adaptation to low light intensity; (7) photodegradation of chlorophyll in cells above the chlorophyll maximum; (8) horizontal layering of water masses; and/or (9) active aggregation of motile phytoplankton in response to light and/or nutrient concentrations (Parsons *et al.* 1977).

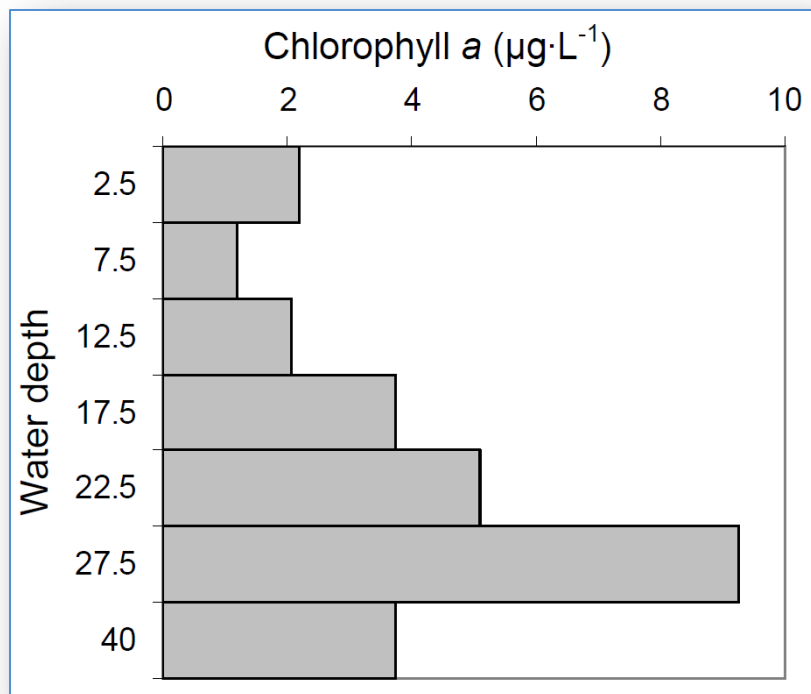


Figure 11. Depth-stratified chlorophyll a concentrations (µg·L⁻¹) from Denman *et al.* (1985) grouped into 5-m depth intervals.

2.1.4 Species Composition

- 26 The phytoplankton community composition varies seasonally in PNCIMA. The spring bloom is composed largely of small, fast-growing diatoms such as *Skeletonema costatum*, *Leptocylindrus danicus*, *Chaetoceros* spp. and *Rhizosolenia* spp. As these species deplete surface nutrients, larger diatoms such as *Thalassiosira* spp., *Thalassionema* spp., and *Eucampia zoodacus* gain in abundance, as do dinoflagellates such as *Prorocentrum micans*, *Dinophysis* spp. and *Ceratium* spp. (Cummins and Haigh 2010). In the summer, a variety of flagellates numerically dominate (e.g., *Ceratium* spp. and *Imantonia rotunda*), but diatoms (e.g., *Leyanella arenaria*) continue to dominate the biomass (Forbes and Waters 1993; Perry 1984). In fall and winter, the diatom contribution drops below 50%. Small flagellates then dominate the relatively low winter phytoplankton productivity and biomass (Mackas *et al.* 2007).

27 Species composition data for the northern reaches of Hecate Strait are very sparse. Unpublished data from Faggetter (2001) (see Table 2 in the Appendix) gives a brief picture of the plankton community composition for several locations in northern Hecate Strait for the years 2000 to 2001 (see Figure 12).

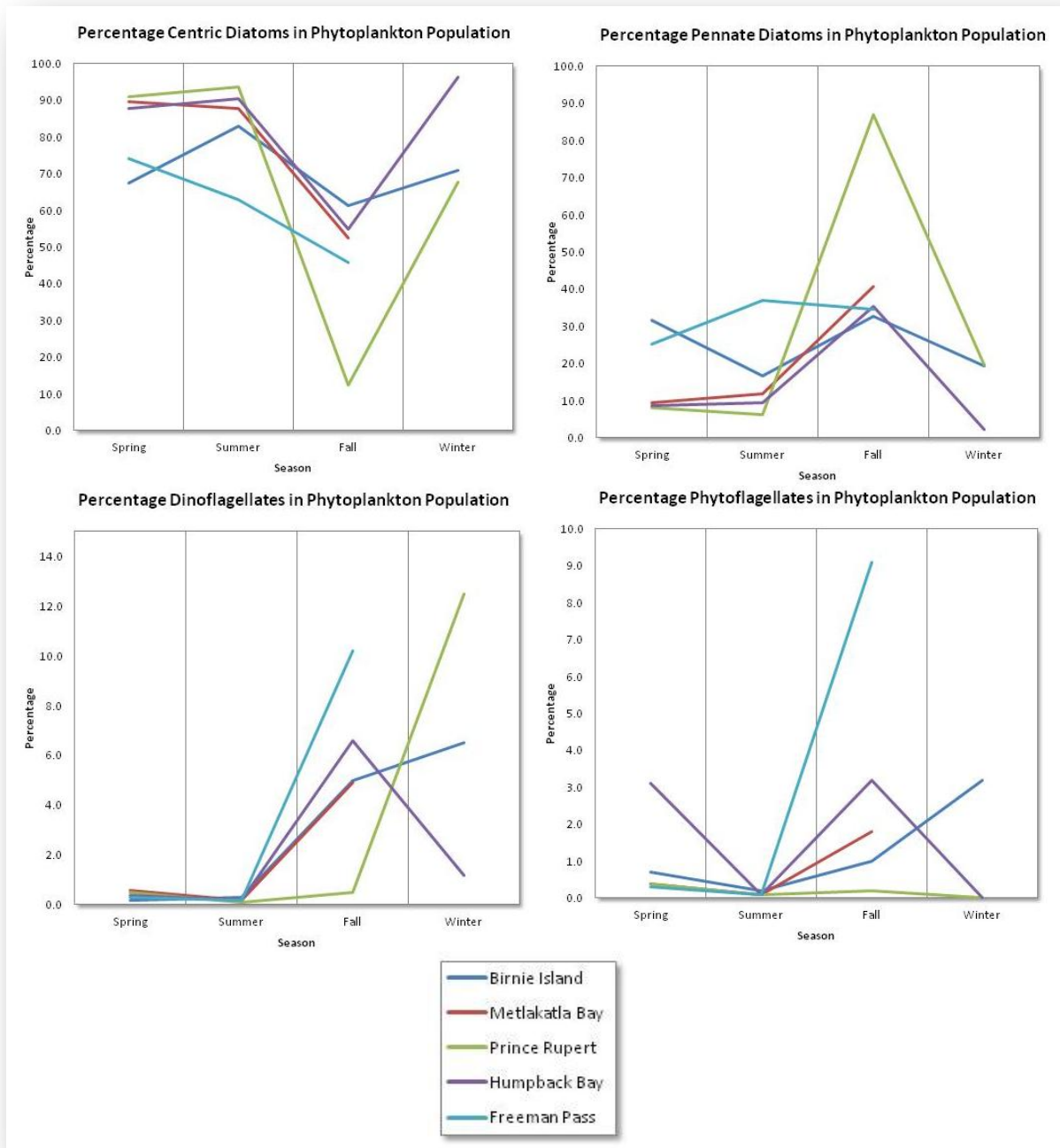


Figure 12. Percentage composition of ecological phytoplankton groups at 5 locations in northern Hecate Strait during 2000-2001 (Faggetter 2001).

28 From this data, we can make the following general observations regarding the phytoplankton species composition at these locations: (1) diatoms dominated the population throughout the year, with centric diatoms making up greater than 50% of the total phytoplankton during most of the year; (2) centric diatoms were least abundant during the fall; (3) at most locations, pennate diatoms were most abundant during the fall; (4) dinoflagellates and phytoflagellates seldom exceeded 10% of the total phytoplankton population, and were most abundant during the fall and winter. Table 1 provides a summary of the general phytoplankton progression during the seasons at the five northern Hecate Strait sites. Some species, such as *Skeletonema costatum*, *Nitzschia* sp., *Pseudo-nitzschia* sp., *Thalassionema nitzschooides*, *Protoperidinium crassipes*, and *Distephanus speculum*, were found in the plankton throughout the year. Other species were distinctive to a season. For example, *Thalassiosira* spp. were dominant during the spring, whereas *Coscinodiscus* spp. were mainly dominant during the fall and winter. *Asterionella japonica* was a summer/fall species. Overall, these results do not closely match those reported for the general PNCIMA region by Cummins and Haigh (2010), Forbes and Waters (1993), Perry (1984) and Mackas *et al.* (2007). This may be due to the fact that the northern Hecate Strait data are from shallow, nearshore, highly productive waters, and are not necessarily representative of the PNCIMA area as a whole.

Table 1. Dominant phytoplankton species occurring at five locations in northern Hecate Strait. Highlighted species are those which were dominant at more than one site (Faggetter 2001).

Ecological Group	Season			
	Spring	Summer	Fall	Winter
Centric Diatoms	<i>Thalassiosira decipiens</i> , <i>Thalassiosira nordenskioldii</i> , <i>Skeletonema costatum</i> , <i>Schroderella delicatula</i> , <i>Chaetoceros debilis</i> , <i>Chaetoceros constrictus</i> , <i>Chaetoceros radicans</i> <i>Coscinodiscus perforates</i>	<i>Chaetoceros debilis</i> , <i>Chaetoceros constrictus</i> , <i>Chaetoceros compressus</i> , <i>Skeletonema costatum</i>	<i>Chaetoceros decipiens</i> , <i>Chaetoceros convolutes</i> , <i>Chaetoceros danicus</i> , <i>Skeletonema costatum</i> <i>Coscinodiscus perforates</i> , <i>Coscinodiscus jonesianus</i> , <i>Ditylum brightwellii</i>	<i>Chaetoceros decipiens</i> , <i>Chaetoceros convolutes</i> , <i>Chaetoceros socialis</i> , <i>Skeletonema costatum</i> <i>Coscinodiscus perforates</i> , <i>Coscinodiscus jonesianus</i> , <i>Coscinodiscus excentricus</i> , <i>Actinoptychus undulatus</i>
Pennate Diatoms	<i>Nitzschia</i> sp., <i>Pseudo-nitzschia</i> sp., <i>Thalassionema nitzschooides</i> , <i>Grammatophora marina</i> , <i>Licmophora abbreviate</i> <i>Cocconeis</i> sp.	<i>Nitzschia</i> sp., <i>Pseudo-nitzschia</i> sp., <i>Thalassionema nitzschooides</i> , <i>Asterionella japonica</i>	<i>Nitzschia</i> sp., <i>Pseudo-nitzschia</i> sp., <i>Thalassionema nitzschooides</i> , <i>Asterionella japonica</i> , <i>Licmophora abbreviate</i> , <i>Cocconeis</i> sp.	<i>Nitzschia</i> sp., <i>Pseudo-nitzschia</i> sp., <i>Thalassionema nitzschooides</i> , <i>Grammatophora marina</i> , <i>Nitzschia longissima</i> , <i>Gyrosigma spencerii</i> , <i>Pleurosigma normanii</i>
Dinoflagellates	<i>Protoperidinium crassipes</i> , <i>Dinophysis infundibulus</i> , <i>Alexandrium tamarensis</i> , <i>Gymnodinium lacustre</i> , <i>Ceratium gracile</i> , <i>Ceratium lineatum</i> , <i>Prorocentrum micans</i>	<i>Protoperidinium crassipes</i> , <i>Protoperidinium pedunculatum</i> , <i>Protoperidinium oblongum</i> <i>Dinophysis infundibulus</i> , <i>Alexandrium</i> sp., <i>Ceratium lineatum</i> , <i>Ceratium tripos</i> , <i>Prorocentrum micans</i> , <i>Prorocentrum gracile</i>	<i>Protoperidinium crassipes</i> , <i>Alexandrium catenatum</i> , <i>Ceratium lineatum</i> , <i>Ceratium fusus</i> , <i>Prorocentrum</i> sp., <i>Noctiluca scintillans</i> (not a photosynthetic species)	<i>Protoperidinium crassipes</i> , <i>Protoperidinium conicoidea</i> , <i>Ceratium lineatum</i> , <i>Ceratium tripos</i> , <i>Prorocentrum micans</i> , <i>Prorocentrum minimum</i>
Phytoflagellates	<i>Distephanus speculum</i> , <i>Euglena</i> sp., <i>Brachiomonas</i> sp.	<i>Distephanus speculum</i> , <i>Euglena</i> sp., <i>Brachiomonas</i> sp., <i>Ebria tripartite</i>	<i>Distephanus speculum</i> , <i>Euglena gracilis</i> , <i>Brachiomonas</i> sp., <i>Ebria tripartite</i> , <i>Micromonas</i> sp., <i>Halosphaera viridis</i>	<i>Distephanus speculum</i>

2.2 Zooplankton

2.2.1 Holoplanktonic Species

- 29 Recent DFO zooplankton sampling (1996-present) in the PNCIMA region has been concentrated in two repeated survey areas located respectively around the Scott Islands, and in lines across south-central Hecate Strait (see Figure 13) (Mackas *et al.* 2007). The time series coverage extends from 1998 to present for southern Hecate Strait (with some scattered earlier sampling between 1983 and 1997) (Mackas *et al.* 2010).

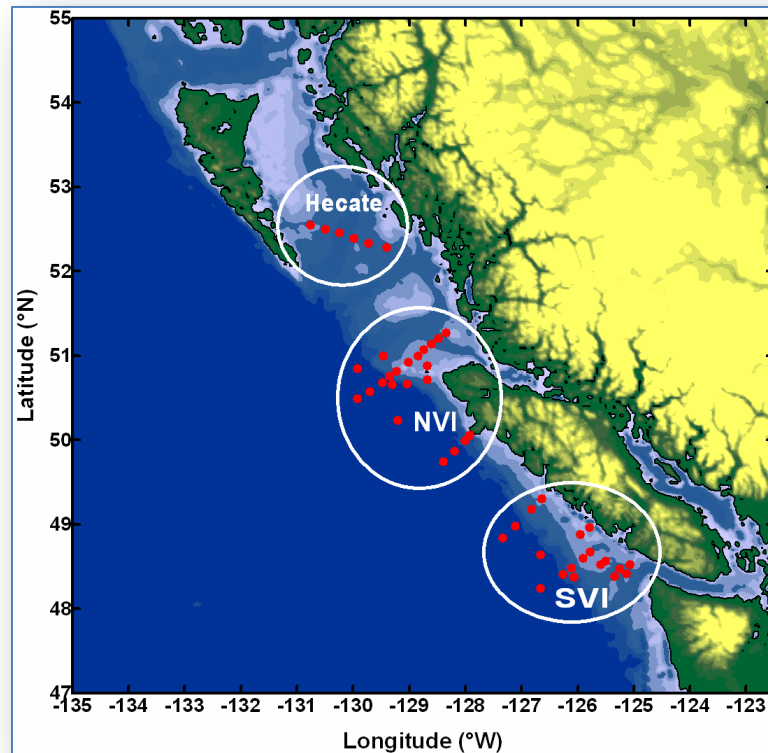


Figure 13. Zooplankton time series sampling locations (red dots) off the BC continental margin. Data are averaged within major statistical areas indicated by ovals; the SVI and NVI regions are further classified into shelf and offshore subregions. The PNCIMA (Pacific North Coast Integrated Management Area) includes both NVI and Hecate Strait areas (Mackas *et al.* 2010).

- 30 The “average” temporal distribution of zooplankton is similar to that of the phytoplankton on which they feed. Minimum annual zooplankton densities, like those of phytoplankton, occur in winter (see Figure 14). In spring, many species of zooplankton spawn, and total numbers follow the upward trend in the phytoplankton population with a short time lag (Mackas *et al.* 2007). The spatial distribution of zooplankton is determined by a combination of nutrient enrichment, which stimulates phytoplankton blooms, localized concentrating effects (e.g., along bathymetric edges), and the retention of critical life stages (Bakun 1996). In regions such as Chatham Sound and eastern Dixon Entrance, there is likely to be relatively little outflow of plankton as a result of the estuarine recirculation in Chatham Sound and the Rose Spit Eddy in eastern Dixon Entrance (Lucas *et al.* 2006). This increases the retention of critical life stages in these regions. The seasonal cycle of zooplankton is subject to significant within-region and within-season variability

(up to 3-5 times larger than the amplitude of the “average” seasonal cycle). This is caused in part by spatial patchiness and in part by interannual variability (Mackas *et al.* 2007).

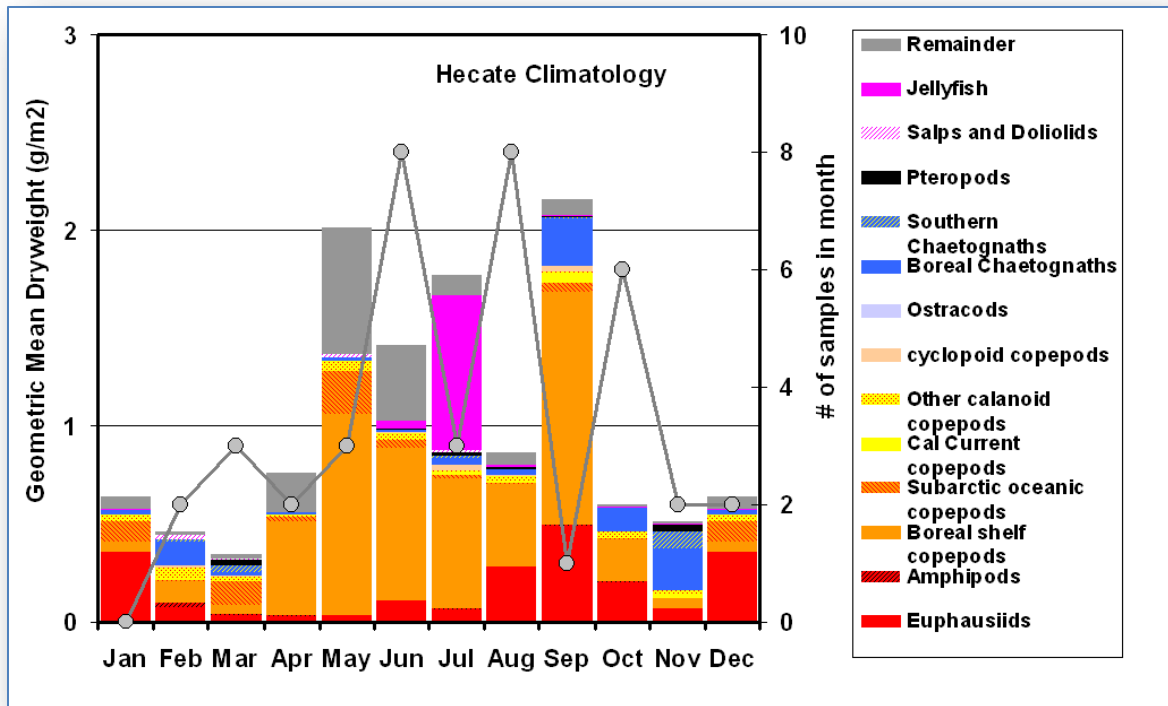


Figure 14. Average seasonal cycle in the Hecate Strait sub-region. Bar graphs show cumulative geometric mean dryweight biomass. Line graph shows the number of samples in each month during the baseline period. Monthly estimates based on few samples typically include data from only one or two years and are less likely to be representative of the true multi-year average (Mackas *et al.* 2010).

- 31 Patchiness of zooplankton off the central and northern BC coast can be very intense, but does not appear to be closely tied to the location of phytoplankton blooms. Since most of the PNCIMA region has high phytoplankton biomass from spring through fall, food availability for herbivorous zooplankton appears to be adequate for much of the year. Thus, the factors controlling patch location and intensity are more likely to be current patterns, bathymetry, and zooplankton diel (daily) vertical migration (Mackas *et al.* 2007).
- 32 Small to medium-sized copepods tend to be the most common zooplankton (Perry 1984; LeBrasseur and Fulton 1967). Following a rapid population increase in the spring, copepods numerically dominate the zooplankton population, with densities reaching thousands of copepods per cubic meter (Mackas *et al.* 2007). Zooplankton species with similar zoogeographic ranges and ecological niches usually have very similar temporal distributions and annual variations. Therefore, temporal variability is often summarized by averaging data for multiple species within species groups. For the Hecate Strait region, there are four main copepod groups (Mackas *et al.* 2010; Mackas and Galbraith 2002):
- 1) neritic (very nearshore) copepods - taxa in this group normally complete their life cycle, and reach their maximum abundance, either within inner-coast estuaries and straits or along the innermost part of the outer-coast continental shelf. Examples include the copepods *Acartia hudsonica* (= *A. clausi*) and *Pseudocalanus moultoni*.

- 2) boreal shelf, or northern, copepods - a composite of the copepods *Calanus marshallae*, *Pseudocalanus mimus*, and *Acartia longiremis*; (distribution ranges from southern Oregon to the Bering Sea).
- 3) subarctic oceanic copepods - a composite of *Neocalanus plumchrus*, *N. cristatus*, and *Eucalanus bungii*; (inhabiting deeper areas of the subarctic Pacific and Bering Sea from North America to Asia).
- 4) southern copepods - a composite of species with ranges centered about 1000 kilometers south of the Hecate Strait region (in the California Current and/or further offshore in the North Pacific Central Gyre), including *Paracalanus parvus* and *Mesocalanus tenuicornis*.

The copepod genera *Pseudocalanus*, *Calanus*, *Neocalanus*, *Acartia*, and *Oithona* are all locally abundant during springtime. The life cycles of the oceanic *Neocalanus* spp. include a prolonged dormant period spent at depths from 300 m to greater than 1000 m. Thus their spatial distribution in the PNCIMA region is confined to the deeper locations, and they are only found in the surface layer during a relatively few months in spring and early summer. However, during this period their biomass can be very large, and they are important prey items for fish, whales and seabirds. From summer into autumn, the *Neocalanus* migrate downward from the surface layer, and the remaining copepods are dominated by *Calanus*, *Pseudocalanus*, *Oithona* and *Metridia* (Mackas *et al.* 2007).

- 33 Data from the study of five sites in the northern Hecate Strait area during 2000-2001 (Faggetter 2001) showed that four copepod species were present throughout the year - *Acartia hudsonica*, *Paracalanus parvus*, *Oithona* sp., and *Tigriopus californicus*. The presence of *Tigriopus californicus*, an intertidal copepod, and *Acartia hudsonica* are evidence of the shallow water, nearshore nature of these sites. *Paracalanus parvus* was most abundant from early June through to early September (in line with the observations of Mackas *et al.* (2010), who recorded southern, or California Current copepods, in September; see Figure 14). *Oithona* sp. was most abundant from mid-September to the end of October, which concurs with the observation of Mackas *et al.* (2007).
- 34 Monitoring of the relative abundance of the different copepod species groups can identify changes in community composition. Southern copepods (eg. *Paracalanus parvus*, *Ctenocalanus vanus*, *Mesocalanus tenuicornis*) and boreal copepods (eg. *Calanus marshallae*, *Pseudocalanus minimus*, *Acartia longiremis*) tend to vary inversely to one another, each group thriving when conditions are suitable to them. Cool years favor endemic boreal taxa, whereas warm years favor colonization by southern taxa (Mackas *et al.* 2010). Recently, the southern species have (despite oscillations) shown a long-term upward trend, suggesting that climate change could produce a shift in dominant species (Cummins and Haigh 2010). Increases in the abundance of boreal copepods is associated with good regional survival and growth of juvenile salmon, sablefish, and planktivorous seabirds (Mackas *et al.* 2007; Mackas *et al.* 2010)
- 35 Euphausiids, another of the crustacean zooplankton, are a key prey for some fish, birds, and whales (Lucas *et al.* 2006). Compared to copepods, euphausiids are larger in body size and have longer individual life spans. Although they are not as numerous as the copepods, euphausiid biomass can be fairly high in late fall and early winter (Mackas *et al.* 2004). Euphausiids begin to increase in both relative and total biomass in late summer and autumn as the spring euphausiid cohort matures (Mackas *et al.* 2010). Euphausiid biomass reaches a maximum in autumn at most locations (Mackas *et al.* 2004). Control of aggregation location and intensity in euphausiids appears to result from the interactions between currents, bathymetry, and swimming and vertical migration behavior (Mackas *et al.* 2007). High euphausiid biomass is often found over steep sea floor slopes (Simard and Mackas 1989; Mackas *et al.* 1997; Simard and Lavoie 1999; Trevorrow 2004). In PNCIMA, these locations include the continental slope, and also the margins of the deep troughs leading from the outer coast into Queen Charlotte Sound (see Figure 15). Both are also zones of high fish catch; it is unlikely that this overlap in distribution is coincidental (Mackas *et al.* 2007).

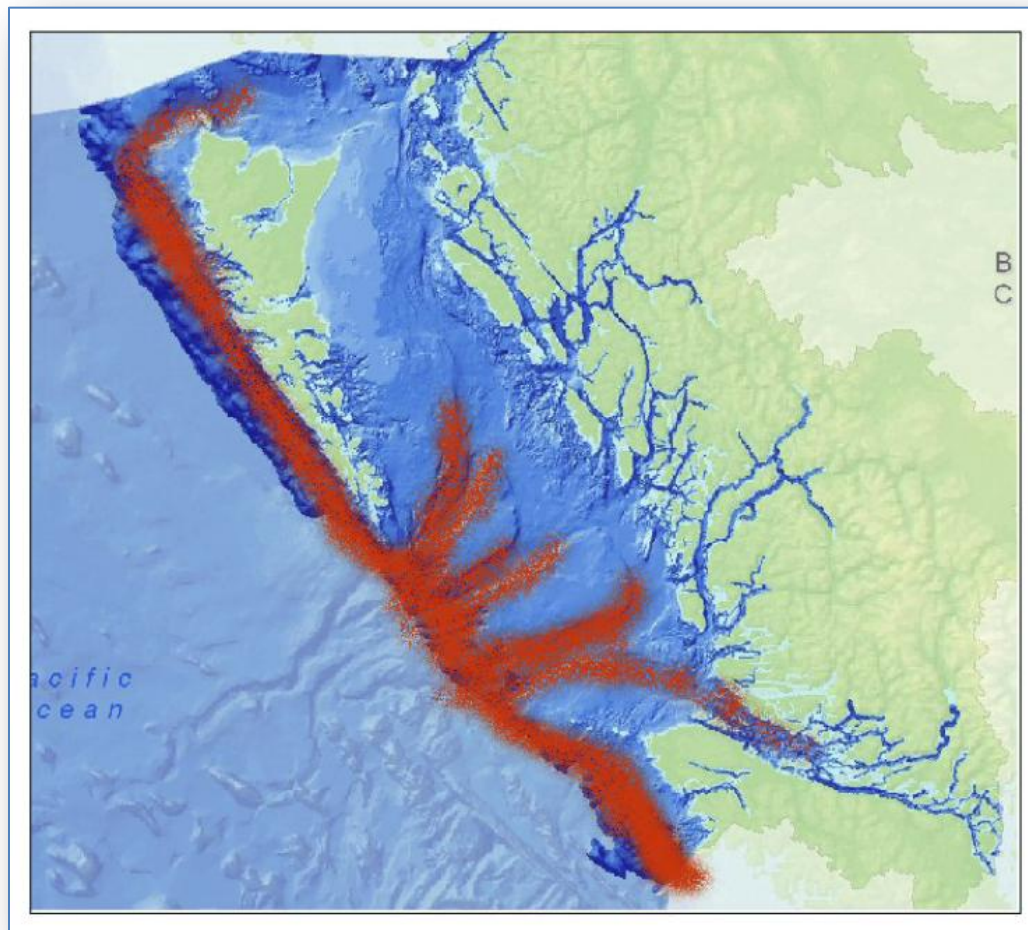


Figure 15. Known and predicted zones of euphausiid aggregation in open water parts of PNCIMA (additional smaller scale aggregations occur in many inlets). Map is based on net tow and acoustic sampling of the BC coast (Simard and Mackas 1989; Fulton et al. 1982; Mackas et al. 1997; 2006).

- 36 The dominant carnivorous zooplankton in the Hecate Strait region are chaetognaths, which are most abundant during fall and winter, and jellyfish, which reach their maximum abundance at mid-summer (see Figure 14). Other important non-crustacean herbivorous zooplankton include shelled pteropods, salps and doliolids. These groups are occasionally abundant in Hecate Strait, but on average make up less of the total biomass than they do off the outer coast of Vancouver Island (Mackas *et al.* 2010). Data from the study of five sites in the northern Hecate Strait area during 2000-2001 (Faggetter 2001) also showed that several ciliate species could be very abundant numerically during June and July, particularly *Tintinnopsis* sp., *Parafavella gigantea*, *Ptychocylis acuta*, *Helicostomella subulata*, and *Dictyocysta reticulata*.
- 37 Compared to the continental margin off Vancouver Island (both south and north), Hecate Strait has lower total zooplankton biomass (by 1.5 to 3 times), smaller amounts of deep-water oceanic species (pteropods, subarctic oceanic copepods, salps), and larger amounts of meroplanktonic larvae (Mackas *et al.* 2007).

2.2.2 Meroplanktonic Species

2.2.2.1 Invertebrate Species

- 38 Many of the larval invertebrate meroplankton are most abundant in the springtime following a spring spawning event (Mackas *et al.* 2004); however, spawning for some species also occurs in the summer and early fall. Described below are some of the important commercial invertebrate species which have meroplanktonic larvae.

2.2.2.1.1 Geoduck (*Panopea abrupta*)

- 39 Male and female geoduck clams spawn annually beginning in late April and peaking in late June. Mass fertilization occurs in water column. Fertilized eggs develop rapidly into ciliated, motile larvae. During the next 7 months, the larvae drift in the plankton, dispersed by water currents, and pass through several developmental stages (trochophore, veliger and umbone). The larval phase ends when larvae settle, change form, and attach themselves to a suitable substrate by byssal threads, a process referred to as spatting. Upon final settling, the juvenile geoduck, or spat, creates a permanent burrow where it usually remains for life (Williams 1989).

2.2.2.1.2 Littleneck Clam (*Protothaca staminea*) and Butter Clam (*Saxidomus giganteus*)

- 40 Male and female clams spawn from May to September in the Strait of Georgia, and begin somewhat later on the north coast. Mass fertilization occurs in water column. Fertilized eggs develop into ciliated, motile larvae within 12 h of fertilization. The larval phase includes several stages (trochophore, veliger and umbone), and lasts for 3-4 weeks, during which time the larvae drift in the plankton and are dispersed by water currents. The larval phase ends when larvae settle from the plankton and attach themselves to gravel or broken shell by byssal threads. At approximately 5 mm size, the spat creates a permanent burrow where it remains for life (Williams 1989).

2.2.2.1.3 Manila Clam (*Tapes philippinarum*)

- 41 Male and female manila clams spawn during August in central coast. Mass fertilization occurs in water column. Fertilized eggs develop into ciliated, motile larvae within 12 h of fertilization. The larval phase includes several stages (trochophore, veliger and umbone), and lasts for 3-4 weeks, during which time the larvae drift in the plankton and are dispersed by water currents. The larval phase ends when larvae settle from the plankton and attach themselves to gravel or broken shell by byssal threads. At approximately 5 mm size, the spat creates a permanent burrow where it remains for life. Since manila clams require surface water temperatures in excess of 14°C to permit gametogenesis, spawning and larval development, they are only found along the central and south coast (Williams 1989).

2.2.2.1.4 Razor Clam (*Siliqua patula*)

- 42 Male and female razor clams spawn in July and early August in Queen Charlotte Islands. Mass fertilization occurs in water column. Fertilized eggs develop into ciliated, motile larvae within 12 h of fertilization. The larval phase includes several stages (trochophore, veliger and umbone), and lasts for about 3-4 weeks, during which time the larvae drift in the plankton and are dispersed by water currents. The larval phase ends when larvae settle from the plankton and attach themselves to sand or broken shell by byssal threads. At about 5 mm size, the spat burrows into sand; however no permanent burrow is constructed due to instability of sand. Recruitment of juvenile clams has occurred at low levels in Queen Charlotte beaches since 1971 (Williams 1989).

2.2.2.1.5 Opal Squid (*Loligo opalescens*)

- 43 Mature male and female squids move to shallow, sheltered waters to form pre-spawning aggregations. Mating occurs year round, but the major spawning period is between February and August. The female deposits her eggs in egg cases on mud or sand bottoms of sheltered locations. After 3 months of egg development, hatching occurs at night, and larvae are about 5 mm total length. Juvenile squid feed on tiny crustaceans in the plankton, and are dispersed by water currents (Williams 1989).

2.2.2.1.6 Prawn (*Pandalus platyceros*)

- 44 Prawn are protandrous hermaphrodites, spending the early part of life cycle as males and the later part as females. Breeding occurs in the fall, and is usually complete by the end of October. Females lay eggs which remain attached to their abdominal appendages until hatching occurs in March and April, usually at water depths between 70-90 m. Free-swimming larvae, or nauplii, spend 2-3 months in plankton. Late and post-larvae remain in shallow water (less than 54 m) until winter months. Prawn reside in shallow water bays and inlets during their first year feeding on amphipods and mysids which are supported by the detritus from summer plankton and larger algae production (Williams 1989).

2.2.2.1.7 Shrimp (*Pandalus* spp.)

- 45 Shrimp are also protandrous hermaphrodites. Some individuals may develop directly into females. Breeding occurs in the fall (November). Females lay eggs which remain attached to their abdominal appendages until hatching in March and April, usually at water depths between 18-54 m. The nauplii spend 2-3 months in the plankton, but utilize progressively deeper depths as they develop. Eventually they settle to bottom, and by late June metamorphosis is complete. Like prawn, shrimp remain in shallow water bays and inlets during their first year feeding on amphipods and mysids (Williams 1989).

2.2.2.1.8 Dungeness crab (*Cancer magister*)

- 46 Mature female crabs generally molt between May-August, and mating occurs immediately after the female has molted and before the new exoskeleton hardens. In October or November, eggs are fully developed, at which time the eggs are extruded and fertilized. The bright orange clutch of eggs remain attached to the female's abdomen. Throughout the winter, she remains inactive, buried in bottom sediments protecting and aerating her eggs. The eggs hatch in the spring, and planktonic larvae are released into the water. The larval phase, lasting about 3 to 4 months, consists of five zoeal and one megalopa stages. From May to September, megalopae settle and metamorphose into the first post-larval instar. Recruitment of juveniles is probably from this general offshore larval population, at least regionally, and appears to be independent of local adult stock abundance. Juvenile crabs remain in the lower intertidal or shallow subtidal waters, and may overwinter in shallow water (DFO 2000a; Williams 1989). In the northern Hecate Strait region, zoeal crab larvae have been observed during September (Faggetter 2001).

2.2.2.1.9 Red Sea Urchin (*Strongylocentrotus franciscanus*) and Green Sea Urchin (*Strongylocentrotus droebachiensis*)

- 47 Male and female red sea urchins generally spawn from June to September, peaking in July, but the spawning periods vary from area to area. For green sea urchins, the spawning period generally occurs from February to March. Mass fertilization occurs in water column. Fertilized eggs develop into free-swimming larvae which drift and feed in plankton. After 6-8 weeks, the larvae settle and develop into juvenile sea urchins (DFO 2003; Williams 1989). In the northern Hecate Strait region, echinoderm eggs have been observed in the plankton from May through to July, and echinopluteus (sea urchin) larvae have been present in October (Faggetter 2001).

2.2.2.1.10 California Sea Cucumber (*Parastichopus californicus*)

- 48 Male and female California sea cucumbers spawn in shallow water (less than 16 m) during June to August, and assume a "cobra-like" posture while releasing gametes. Fertilization occurs in water column. Larvae drift as plankton for about 7-13 weeks, then settle and develop into juvenile sea cucumbers (Williams 1989).

2.2.2.2 Vertebrate Species

- 49 For most species of larval fish (ichthyoplankton), abundance is greatest in winter and spring. This timing can be quite significant because wind-driven displacement of surface water can be large in the winter, resulting in dispersal of surface plankton and decreased retention of larvae. Poor larval retention within coastal waters may significantly limit the abundance of adult fish in subsequent years. The recruitment of Pacific Cod stocks has been correlated with this wash-out phenomenon, showing improved stock size following milder winters (Tyler and Crawford 1991). In addition to this, one or two large Haida Eddies form off Cape St. James in most winters and move offshore in spring and summer, where they decay over the next few years. These eddies tend to be larger during winters that have stronger poleward (southeast) winds. Since they transfer large amounts of shelf/slope waters, including the plankton community members contained therein, they also contribute to decreased larval retention and poor recruitment (Crawford *et al.* 2003; Mackas and Galbraith 2002; DFO 2002).
- 50 There appears to be a spatially dependent trophic (food chain) linkage from phytoplankton to fish in the PNCIMA region. Thus, areas of high phytoplankton productivity support high biomasses of groundfish and pelagic fish. For example, the northeast sector of Hecate Strait supports high fish

biomass. This region is adjacent to deep, well-mixed channels by which the Skeena River water enters Hecate Strait, so mixing of fresh, nutrient-rich Skeena water into Hecate Strait might be a factor in producing both high phytoplankton productivity and high fish biomass. Another example is the region around Dixon Entrance where the three troughs that transect Queen Charlotte Sound and Hecate Strait produce convergent water flows which most likely result in increased phytoplankton and zooplankton abundance, and subsequent fish production. Further support for this trophic linkage is seen in the results from the Hecate Strait Assemblage bottom trawl survey, which suggests phytoplankton productivity and the biomass of several groundfish stocks are simultaneously increasing (Lucas *et al.* 2006). Described below are some of the important commercial fish species which have meroplanktonic larvae.

2.2.2.2.1 Rockfish (*Sebastes* spp.)

51 Although rockfish are sometimes reported as being ovoviviparous (bearing live young without maternal nutrition), many studies have confirmed that they are a primitive viviparous group and supply nutrients to developing embryos (Boehlert and Yoklavich 1984; Boehlert *et al.* 1991; Wourms 1991; Hopkins *et al.* 1995; MacFarlane and Bowers 1995; Beckmann *et al.* 1998). Most species mate in the fall, but sperm may be stored and fertilization may not take place until several weeks later (Wyllie Echeverria 1987; Love *et al.* 1990). The female retains the embryos for 4–5 weeks until hatching (Boehlert and Yoklavich 1984), and parturition usually occurs in spring or summer for northerly populations (O'Connell 1987; Yoklavich *et al.* 1996). Generally, the free-swimming planktonic larvae are found in the upper mixed zone of the ocean for a variable period of time before metamorphosing into juveniles (DFO 2000b; Larson *et al.* 1994). Larvae are about 5 mm at birth, and are carried inshore to protected bays where they rear during summer and fall (Williams 1989). Different species release their larvae at different depths. For example, copper rockfish (*Sebastes caurinus*) released their larvae in rocky or reef habitats at water depths of less than 20 m, yellowtail rockfish (*Sebastes flavidus*) release their larvae in deeper, offshore waters, and quillback rockfish (*Sebastes maliger*) release their larvae in rocky or reef habitat at water depths of less than 40-50 m. The larvae of different species ultimately migrate towards different habitat types as they metamorphose into juveniles. Copper rockfish juveniles use beds of eelgrass, yellowtail rockfish juveniles tend to hide in rock crevices, and quillback rockfish juveniles occur in boulder areas just above kelp (e.g. *Agarum* and *Laminaria*) beds, or may associate in colonies of cloud sponges (Williams 1989). Some important commercial rockfish in the PNCIMA region include:

- Bocaccio (*Sebastes paucispinis*)
- China or Yellowstripe Rockfish (*Sebastes nebulosus*)
- Pacific Ocean Perch (*Sebastes alutus*)
- Quillback Rockfish (*Sebastes maliger*)
- Redbanded Rockfish (*Sebastes babcocki*)
- Redstripe Rockfish (*Sebastes proriger*)
- Rougheye Rockfish (*Sebastes aleutianus*)
- Sharpchin Rockfish (*Sebastes zacentrus*)
- Shortspine Thornyhead (*Sebastolobus alascanus*)
- Silvergray Rockfish (*Sebastes brevispinis*)
- Widow Rockfish (*Sebastes entomelas*)
- Yellowmouth Rockfish (*Sebastes reedi*)
- Yellowtail Rockfish (*Sebastes flavidus*)

2.2.2.2.2 Sablefish (*Anoplopoma fimbria*)

- 52 Sablefish spawning occurs from January to March along the continental shelf. Larval sablefish stay in surface waters over the shelf and slope (MOE 2011a).

2.2.2.2.3 Lingcod (*Ophiodon elongates*)

- 53 Lingcod males appear on the shallow water, rocky bottom spawning grounds from October through to November. The females arrive in January, and spawn in January and February. The adhesive egg masses are laid in rock crevices where there are strong currents. Males guard egg masses until they hatch in late March. The larvae are dispersed by currents, and remain in upper 3 m of the water column for 2 to 3 months, where they feed on plankton. The larvae may form schools. In late May and early June, they move inshore to eelgrass and kelp beds, and begin their demersal life in mid to late June (Williams 1989). In the northern Hecate Strait region, hexagrammidae (e.g., lingcod) larvae have been observed in the plankton in May (Faggetter 2001).

2.2.2.2.4 Pacific Cod (*Gadus macrocephalus*)

- 54 Pacific cod spawning generally occurs from February to March in waters from 40 to 120 m in depth. Pacific cod are oviparous, and eggs are fertilized externally. Eggs are approximately 1 mm in size and remain near the bottom. Hatching occurs in 8 to 28 days, depending on water temperature and salinity (Hart 1973). Larvae are approximately 3-4 mm in length at the time of hatching, and are born with a yolk sack that is absorbed within 10 days (Palsson 1990). Larvae and juveniles are pelagic, and there is some evidence that both larvae and juveniles are transported to nursery habitats by currents (Garrison and Miller 1982).

2.2.2.2.5 Pacific Hake (*Merluccius productus*)

- 55 The Pacific hake is semi-pelagic, roaming from ocean floor to mid-water within the coastal region of the California ocean current system. There are two stocks that inhabit the coastal waters off BC: an offshore and a Strait of Georgia stock. The offshore stock is larger and highly migratory and ranges from southern California to Queen Charlotte Sound, while the smaller non-migratory stock is limited to the Strait of Georgia. Females mature at 3-4 years of age, and spawning occurs between January and June. Eggs float in the water column and hatch in about 3 days (MOE 2011b).

2.2.2.2.6 English Sole (*Pleuronectes vetulus*)

- 56 The English sole spawns from October to April in deep water (over 200 m). Eggs are buoyant, and remain pelagic until hatching in about 6 days. Larvae are approximately 2-3 mm in size, and swim to the surface where they drift in plankton feeding on their yolk sacs for 6-10 days. Currents carry larvae into shallow water, where metamorphosis occurs and they take up a permanent benthic existence (Williams 1989).

2.2.2.2.7 Pacific Halibut (*Hippoglossus stenolepis*)

- 57 Pacific halibut spawn in deep water (275-412 m) from December to February. Eggs and larvae are pelagic for 4 to 5 months, occurring anywhere between 40 and 935 m depth in the water column, but mainly concentrated between 100 and 200 m. Newly hatched larvae generally occur below 425 m depth at the outside the edge of the continental shelf, are 8 to 15 mm long, and feed from their yolk sac until they have reached 18 mm in length. As they grow, the juveniles rise to shallower water, and after 3 to 5 months, occur at depths less than 100 m. Eggs and larvae drift westward with current into the Bering Sea area (Williams 1989).

2.2.2.2.8 Salmon (*Oncorhynchus* spp.)

- 58 The oceanic portion of PNCIMA is a submarine continuation of a region known as the Queen Charlotte Basin (QCB) which can be considered a semi-enclosed sea. The central portion of the basin is Hecate Strait (Hyatt *et al.* 2007). Salmon make use of a variety of diverse marine habitats in the QCB which are created by the complex seasonal interactions between bathymetry, wind, freshwater runoff, and tidal currents (Thomson 1981). From a perspective of salmon utilization, the QCB may be viewed as consisting of (Hyatt *et al.* 2007):
- 1) transitional, estuarine staging, and rearing areas for the juvenile and adult stages of all species (e.g., coastal inlets and major estuaries of the Nass and Skeena Rivers)
 - 2) upwelling areas of productive underwater shoals and banks that are especially important as rearing areas for aggregations of sub-adult coho and chinook salmon (Dogfish, North Island, Goose, and Cook banks)
 - 3) continental-shelf, surface-water eddies that may entrain juvenile salmon and plankton for periods of days to weeks (e.g., the clockwise rotating Rose Spit Eddy and the counter-clockwise flowing Queen Charlotte Sound Eddy, Crawford *et al.* 1995)
 - 4) advection zones along the continental shelf where surface waters may move rapidly seaward as filaments or plumes with replacement from depth by upwelling nutrient rich waters.

Historic surveys of the distribution and abundance of juvenile salmon suggest differential use of these areas across seasons (Hartt and Dell 1986). Thus, in early spring and summer, juveniles of all species are found aggregated in nearshore inlets and estuaries serving as their points of sea entry (e.g., Skeena, Nass, Bella Coola, etc.). However, by October, juvenile salmon of all species are found somewhat further offshore concentrated in pelagic, surface waters (< 50 m) located over the continental shelf (Welch 2001). All Pacific salmon species, whether rearing in or migrating through the QCB, tend to aggregate in the nearshore waters of the continental shelf. The virtual absence of juvenile salmon in the offshore waters of PNCIMA serves to emphasize the importance of nearshore areas to salmon populations originating from watersheds within and external to the QCB (Hyatt *et al.* 2007).

- 59 Although the detailed migratory routes and timing variations of individual stocks and species are known in only the most general terms, it is clear that key ecologically or biologically significant areas (EBSAs) for salmon exist in the PNCIMA region. Thus, the waters of Dixon Entrance are a key zone that hosts annual migrations of large populations of juvenile and adult salmon originating from large river systems such as the Nass and Skeena. In addition, coastal areas near to the Bella Coola and Atnarko rivers or to the Smith and Rivers inlets north of Johnstone Strait may also be important potential EBSAs. Similarly, Johnstone Strait and Dixon Entrance are obvious areas of high sensitivity because salmon migratory behaviours, ocean currents, and coastal landforms combine to concentrate juvenile and adult salmon originating from southern watersheds as they pass through PNCIMA waters on their northward migrations in spring and

southern migrations in summer through fall respectively. For salmon species such as coho and chinook that are more likely to reside for prolonged periods in the PNCIMA region, areas of high biological production near banks and shoals attract aggregations of rearing juveniles, and may also be regarded as especially sensitive to disturbance (Hyatt *et al.* 2007). For example, the shoal-region centered on Juan Perez Sound on the southeast side of Moresby Island is a “hot spot” for biological production for many species in the southern QCB (Royal Society of Canada 2004), and thus it is not unexpected that several species of juvenile salmon also concentrate in this area.

- 60 In general, juvenile salmon growth is reduced when southern copepods dominate the plankton community (see Figure 16; Peterson and Schwing 2003, Mackas *et al.* 2007), possibly because southern copepods are less energetically favourable for growth (i.e. low lipids) (Cummins and Haigh 2010).

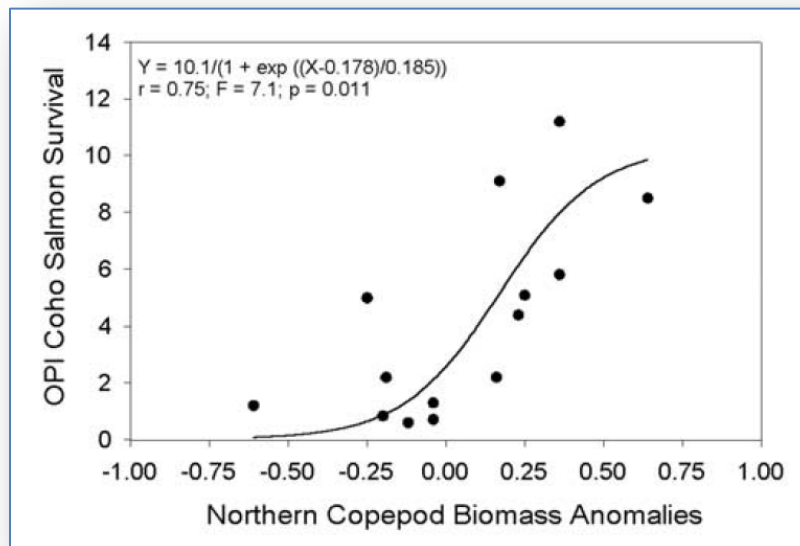


Figure 16. Relationship between coho salmon survival and biomass anomalies (changes relative to the average baseline) for three cold water (northern) copepod species *Pseudocalanus mimus*, *Acartia longiremis*, and *Calanus marshallae* (Peterson and Schwing 2003).

2.2.2.2.8.1 Pink Salmon (*Oncorhynchus gorbuscha*)

- 61 Pink salmon eggs hatch from late-December to late February, and alevins remain in gravel until they emerge from the redds as fry in March and April, at which time they migrate immediately to the sea. The fry occupy the nearshore waters of estuaries and coastal inlets for several weeks to months, during which time feeding and growth depend on zooplankton and epibenthic organisms derived from estuarine and detritus-based food-webs. Following their estuarine and/or coastal inlet transition, pink salmon rapidly migrate northwest through PNCIMA waters to the Gulf of Alaska (GOA) (Hyatt *et al.* 2007; Williams 1989).

2.2.2.2.8.2 Chum Salmon (*Oncorhynchus keta*)

- 62 Pink salmon alevins remain in gravel after hatching until yolk has been absorbed. The fry emerge from the gravel in March and April, and migrate immediately to coastal estuaries where their diets are frequently dominated by amphipods and benthic copepods. The fry school prior to reaching salt water, and rear in nursery areas along shoreline, typically in eelgrass beds, tidal marsh channels and protected bays. As they grow, they move to deeper water or into the outer estuary. During July and August, they move offshore (Hyatt *et al.* 2007; Williams 1989).

2.2.2.2.8.3 Sockeye Salmon (*Oncorhynchus nerka*)

- 63 Sockeye salmon eggs hatch in winter, and the fry emerge from redds in March to May, depending on whether they are interior or outer coast populations. The fry migrate to a nursery lake, where they spend 1-3 years rearing before initiating their seaward migration as smolts. After rearing in fresh water, sockeye migrate seaward during the interval from early April (southern PNCIMA) to late May (northern PNCIMA). During the early portion of marine life, juvenile sockeye generally move northwestward at rates of 6-7 km per day. They consume zooplankton (copepods, euphausiids), small larval fish, and occasionally amphipods during early marine life (Hyatt *et al.* 2007; Williams 1989).
- 64 Gottesfeld *et al.* (2008) investigated the migration and feeding patterns of sockeye salmon juveniles in Chatham Sound during 2007. They observed that at the end of May, high numbers of sockeye smolts were found near the mouth of the Skeena River, and that the first sockeye smolts had reached Ogden Channel. In the first week of June, the smolts became abundant in the eastern Ogden Channel. From the middle of June onward, sockeye were only found in the seaward half of Ogden Channel, and to the south and west along the routes to outside waters such as Beaver Passage. As the Skeena origin sockeye thinned out at the end of their juvenile residence, larger sockeye from coastal lakes to the south appeared. These fish were presumed to have travelled north along the coast on their way to the Gulf of Alaska. Thus, sockeye smolts tended to move northward upon reaching the marine environment. As a result, few of the Nass River sockeye were found in southern Chatham Sound, although some sockeye from further south were present. Early in the season, a few sockeye appeared to have moved up Grenville Channel from Area 6 and the central coast. Later in the season, southerly-derived sockeye are found in the western part of Ogden Channel, which they may have entered from Petrel and Principe Channels.
- 65 A comparison of stomach contents with zooplankton samples collected in areas adjacent to the fish collection sites demonstrated a high degree of selectivity in the diet of juvenile sockeye. For example, the contents of stomachs from juvenile sockeye at one site contained 84% cladocerans, 11% cumaceans, and 3% barnacle cyprids, while the most abundant zooplankton taxa in the plankton sample from that site were calanoid copepods, oikopleuran larvaceans, and copepod nauplii. At another site, where the relative density of calanoid copepods was nearly eight times that of oikopleuran larvaceans in the water column, oikopleurans comprised 81% of all stomach contents of the juvenile sockeye. In general, calanoid copepods, which were by far the most abundant taxon in all zooplankton samples, were significantly underrepresented in most of the stomachs that were examined. At only one site, where diet selectivity was apparently less than in other areas, were calanoid copepods the most common dietary component (Gottesfeld *et al.* 2008).

2.2.2.2.8.4 Coho Salmon (*Oncorhynchus kisutch*)

- 66 Coho fry emerge from redds in March and April, at which time they disperse downstream and into side-channel and off channel habitats to rear. After spending 1-3 years rearing in stream and side-channel habitats or littoral zones of lakes, the smolts migrate to the estuary, where they feed principally on fish and a wide range of marine invertebrates. In smaller systems, fry may rear in estuary until late September or November and overwinter in nearshore areas. Generally smolts do not utilize inner estuaries for extended periods of time, but may rear in the outer estuary until June, or off tidal flats until fall. In late summer or fall, most juveniles migrate to the open ocean to feed. Coho salmon commonly exhibit less extensive marine migrations than pink, chum, or sockeye salmon and spend more time in inshore coastal waters closer to their watersheds of origin (Hyatt *et al.* 2007; Williams 1989).

2.2.2.2.8.5 Chinook Salmon (*Oncorhynchus tshawytscha*)

- 67 Chinook alevins remain in gravel until yolk sac is absorbed, and the fry emerge from gravel in March to May. Stream-type chinook salmon rear as juveniles for up to 2 years in fresh water before migrating to sea. In the PNCIMA region, most stream-type chinook originate from large, interior river basins (e.g., Skeena River, Nass River). By contrast, ocean-type chinook salmon migrate to sea within a few weeks to months of fry emergence and then spend 4-5 years rearing in marine waters where they may either undertake extensive migrations or alternately remain close to their watersheds of origin. Chinook populations originating from the smaller river systems scattered along the coast of PNCIMA are generally ocean-type. Chinook salmon fry are highly piscivorous at larger sizes during their period of marine rearing (Hyatt *et al.* 2007; Williams 1989).

2.2.2.2.9 Eulachon (*Thaleichthys pacificus*)

- 68 Mature eulachon ascend larger rivers in large numbers during April and May to spawn in freshwater. Eggs are laid over coarse sand or gravel and adhere to sand grains. In 2-3 weeks, the eggs hatch, and 4-7 mm larvae are carried to the rivers mouths by currents. The larvae are dispersed by currents, and may rear in estuaries (Williams 1989).

2.2.2.2.10 Herring (*Clupea harengus pallasii*)

- 69 Mature herring leave their offshore feeding grounds during October to December, and migrate to inshore spawning areas. Maturation is completed inshore in deep channels and bays near the spawning areas. Spawning peaks in late March to mid-April on the north coast and the Queen Charlotte Islands. Spawn is deposited on intertidal and subtidal vegetation, and eggs are fertilized externally. The adults return to offshore feeding grounds after spawning. Herring eggs hatch simultaneously in about 10-21 days, depending on the water temperature. The newly hatched larvae drift in plankton and live on their yolk sac for about 6 days before beginning to feed on plankton (Williams 1989).

3 Effects of Oil on Plankton

70 Acute, short-term toxic effects of fresh oil on organisms tend to be caused by low molecular weight fractions that weather relatively quickly. Chronic sublethal toxic effects are due mostly to high molecular weight (polynuclear aromatic hydrocarbon - PAH) fractions, which have a relatively minor role in acute effects, but persist to cause long-term effects (Spies *et al.* 1996). It has been suggested that most analyses underestimate the potential of oil to cause harm by not taking into account the importance of sublethal effects (Howarth 1991). Clark and Finley (1982) stated that in cold waters, “...sublethal physiological and behavioural effects on organisms are likely to be of more lasting ecological significance than immediate lethal effects.” (as cited by Sloan (1999)).

3.1 Phytoplankton

71 The acute and chronic (sublethal) effects of oil on phytoplankton in nature remain poorly understood (Howarth 1991). Toxicity appears to be closely related to the amount of dissolved nonvolatile components of the oil (Ostgaard 1994). Diatoms, the most dominant phytoplanktonic algal group in the Hecate Strait region, are well studied in the laboratory. In a review of laboratory studies, Capuzzo (1987) concluded that at high concentrations, oil could be lethal or reduce photosynthesis and growth in phytoplankton; however, at low concentrations, it could stimulate phytoplankton growth. In a study on the effects of crude oil on the growth and metabolism of the diatom, *Thalassiosira* sp., Parab *et al.* (2008) showed that signs of acute toxicity occurred at higher concentrations of crude oil (0.5%) while stimulatory effects were observed at lower concentrations (0.01 and 0.1%). In this study, it appeared that the biosynthesis of protein and nucleic acids may have been targeted by the toxic action of the oil.

72 Single-species laboratory studies are not very representative of the natural phytoplankton assemblage at a particular location. Laboratory studies using samples from natural phytoplankton populations can provide some understanding about community succession. A study carried out by Huang *et al.* (2011) using natural phytoplankton collected seasonally from the Yueqing Bay and exposed to crude oil fractions showed the following results:

- 1) High concentrations of crude oil reduced phytoplankton growth and decreased chlorophyll *a* content and cell density, whereas low concentrations of crude oil increased phytoplankton growth.
- 2) The biodiversity, evenness, and species richness of phytoplankton were all significantly influenced by crude oil in all seasons.
- 3) The dominant species changes were different under different crude oil concentrations in different seasons. Thus, it appeared that different species had different tolerances to oil pollution, thus leading to abnormal succession.

3.2 Zooplankton

73 It is generally believed that zooplankton are unlikely to suffer long term impacts from spilled oil due to the rapid dilution and dispersion of oil in the water column (Suchanek 1993). Johansson *et al.* (1980) found that zooplankton densities declined significantly near a spill, but biomass reestablished within five days. Overall, effects of oil on zooplankton are greater at the water surface than at depth and greater in enclosed inshore waters than in open seas (Sloan 1999).

- 74 Due to the hydrophobic nature of many PAHs and other moderately hydrophobic oil constituents, they are able to freely cross the plasma membranes of cells, and thus perturb cell function. As a defense against exposure to such compounds, some marine organisms possess mechanisms to bind these compounds at the plasma membrane and transport them out of cells (Epel 1998). One such mechanism involves the use of a protein referred to as the multixenobiotic resistance transport protein (MXR). Organisms that express less of the MXR transporter protein will likely be more susceptible to oil-derived hydrocarbons. Mollusk and echiuroid worm embryos, both of which express the MXR transporter protein, are ten times more tolerant to degraded oil than echinoderm and fish embryos/larvae. Concentrations of degraded oil as low as 0.2 ppm can impact echinoderm embryo development (Cherr and Griffin 2001).
- 75 Field research suggests that the zooplankton community structure may be susceptible to low oil concentrations (Davies *et al.* 1980; Teal and Howarth 1984; Reid 1987). Sublethal effects may include impacts on feeding, behavior, reproduction, and development in zooplankton (Spies 1987). Seuront (2011) studied the behavior of the widespread calanoid copepod *Temora longicornis* in the presence of water-soluble fractions of hydrocarbons. The mating behavior and the mating success of copepods rely on chemoreception to locate and track a sexual partner. This study showed that hydrocarbon contamination of seawater decreases the ability of male copepods to detect and track a female, and thus most likely have an overall impact on population fitness and dynamics. Another study, performed by Jensen and Carroll (2010), looked at copepods of the genus *Calanus*, which are keystone species in the transfer of energy from the lower to higher trophic levels of the Arctic/sub-Arctic food web. Their findings indicated that *Calanus glacialis* adult females may withstand some exposure to crude oil components, but the survival of their offspring, in terms of hatching success, is negatively affected. Reduced feeding efficiency was observed in *Calanus finmarchicus* exposed to high concentrations of crude oil components, which indicates that adults are sensitive to exposure to crude oil.
- 76 Many zooplankton species contain high levels of natural oils in their eggs or overwintering cysts as energy stores, so it is possible that they could accumulate toxic petroleum compounds in these lipid stores (Reid 1987). Zooplankton may be important in transporting oil into sediments. For example, copepods will ingest oil droplets, which they apparently do not metabolize (Teal and Howarth 1984), and release them in their fecal pellets which settle to the bottom (Capuzzo 1987). Alternatively, the ingested oil could be transferred to copepod predators (Sloan 1999).

3.3 Ichthyoplankton

- 77 The early planktonic larvae of fish are more vulnerable to oil due either to their greater sensitivity, or to their greater proximity to the water surface, or both. In general, eggs and larvae are more sensitive than juvenile stages, which, in turn, are more sensitive than adults. Oil can affect developing fish by retarding growth, causing premature hatching, and causing developmental or genetic changes (Carls and Rice 1990). Many marine fish species have floating eggs or larvae which inhabit near-surface waters; putting them in close proximity to slicks at vulnerable times in their lives. Moreover, if the oil is treated with dispersant, this will likely increase the toxic effects on the young fish and eggs (Baker 1991). On the other hand, while floating eggs and larvae are vulnerable, many are produced and they tend to disperse widely, which decreases their likelihood of contact with oil (Sloan 1999).

3.4 Plankton Ecosystem

- 78 It is very difficult to replicate the complexities of the natural environment in laboratory studies. One way of trying to look at the “holistic” response of an ecosystem to a stressor, such as oil pollution, is to carry out a mesocosm experiment. A mesocosm is an experimental system that simulates real-life conditions as closely as possible, whilst allowing the manipulation of environmental factors. In practice, mesocosms are experimental water enclosures, designed to provide a limited body of water with close to natural conditions, in which environmental factors can be realistically manipulated to see how the entire ecosystem responds to a particular stressor. Howarth (1989) concluded that mesocosm experiments yielded the “*best information of the ecological effects of oil*”, particularly for low-level chronic contamination in plankton communities.
- 79 Hjorth *et al.* (2008) carried out a mesocosm experiment in which they examined the coupled effects of PAH (a component of oil) toxicity with nutrient stress on a plankton community which included bacteria, phytoplankton, and zooplankton. Regardless of nutrient stress, all mesocosms exposed to PAH were affected directly, showing a 20% decrease in chlorophyll *a* on the first day of the experiment. Primary production also dropped by 50% in the mesocosms exposed to PAH. Indirectly, bacterial activity increased as a result of nutrient release from algal death. With time, the plankton system became dominated by zooplankton, which was also the trophic group that experienced the longest lasting effects from PAH exposure. The occurrence of late effects in the zooplankton community was seen in all treatments, but the magnitude of the effects was dependent on the degree of nutrient stress. Thus, short-term effects were most evident on the phytoplankton community, whereas long-term effects appeared in the zooplankton community.
- 80 In an environment such as Hecate Strait, there are many additional factors which must be considered when determining the impact that an oil spill may have, for example:
- 1) Time of the year - the phytoplankton population will be more vulnerable to an oil spill during the spring bloom, when abundance is highest, than during the middle of the winter.
 - 2) Local spatial and temporal variations - even if the overall seasonal cycle for the PNCIMA region is known, there will be significant variations from year to year and location to location within PNCIMA.
 - 3) Extreme seasonal events - oil spills occurring during a storm event will experience different degrees of mixing and dissipation than spills during calm weather. This will also affect the degree of impact on the plankton.
 - 4) Climate fluctuations and long term climate changes (Pacific Decadal Oscillation, El Niño-Southern Oscillation, global warming, ocean acidification) - these factors may add additional stressors to the phytoplankton population, creating unexpected results.
- 81 Abbriano *et al.* (2011) have reviewed the planktonic response to the Deepwater Horizon oil spill. They observed that specialists within the diverse bacterial communities exhibited rapid boom-and-bust cycles, and showed signs of returning to background levels as early as 60 days after the blowout. While individual phytoplankton species experienced relative mortality or enhanced growth, depending on their sensitivity to the oil, the direct negative effects of oil were probably largely offset by a decrease in predation. Dispersion and degradation of oil in the surface seawater, high rates of reproduction of marine planktonic organisms, and circulation and mixing in the ocean may also have contributed to rapid recovery of phytoplankton populations within weeks to months. Zooplankton, due to their rapid reproduction and ability to avoid direct contact with oil, may have been minimally affected. Therefore, while delayed impacts of bioaccumulation in the higher trophic levels may still prove significant, the planktonic community - marine bacteria, phytoplankton, zooplankton, and fish larvae - have appeared to be quite resilient to the direct impacts of the oil. Note, however, that Abbriano *et al.* (2011) have pointed out that the Gulf of

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Mexico plankton community has “... *pre-existing acclimation to the presence of hydrocarbons...*”. Hecate Strait is a relatively pristine environment by comparison. Also, this review has not looked at the impacts of oil on the meroplanktonic larvae of species with multiyear life cycles. So, while the overall plankton community appears to recover quite quickly after an oil spill, there may still be long term issues, particularly with sensitive species.

4 Conclusions

82 While a number of laboratory and mesocosm studies have been carried out to examine the effects of oil on plankton, the overall impact on the entire plankton community in its natural environment, both in the short term and over a number of years, is relatively poorly understood. There are many environmental variables which change both spatially and temporally, making each spill event a unique impact on the ecosystem where it occurred. While studies from the Deepwater Horizon spill have shown that the plankton community appears to have recovered relatively quickly, we are still waiting to learn about the impacts to sensitive species and long term effects. This lack of understanding regarding the long term effects of changes in species composition and impacts on organisms with multiyear life cycles, combined with our limited knowledge of the PNCIMA region, particularly the northern reaches of Hecate Strait, mean that the use of the precautionary principle is essential in assessing the degree of risk that an oil spill represents for this region.

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6 Appendix

Table 2. Phytoplankton data from five locations in northern Hecate Strait showing the most numerically abundant species, ranked in order, for each ecological group. Relative percent contribution of each ecological group to total phytoplankton numerical abundance is given in brackets (Faggetter 2001).

Location	Dominant Phytoplankton Species			
	Spring (March - May)	Summer (June - August)	Fall (September - November)	Winter (January - February)
Birnie Island	Centric diatoms (67.4%) - <i>Chaetoceros debilis</i> , <i>Chaetoceros constrictus</i> , <i>Thalassiosira decipiens</i>	Centric diatoms (82.9%) - <i>Chaetoceros debilis</i> , <i>Skeletonema costatum</i> , <i>Chaetoceros constrictus</i>	Centric diatoms (61.2%) - <i>Chaetoceros decipiens</i> , <i>Chaetoceros danicus</i> , <i>Coscinodiscus jonesianus</i>	Centric diatoms (71.0%) - <i>Chaetoceros decipiens</i> , <i>Coscinodiscus jonesianus</i> , <i>Chaetoceros convolutus</i>
	Pennate diatoms (31.7%) - <i>Nitzschia</i> sp., <i>Pseudonitzschia</i> sp., <i>Thalassionema nitzschioides</i>	Pennate diatoms (16.7%) - <i>Nitzschia</i> sp., <i>Pseudonitzschia</i> sp., <i>Thalassionema nitzschioides</i>	Pennate diatoms (32.8%) - <i>Thalassionema nitzschioides</i> , <i>Licmophora abbreviata</i> , <i>Pseudonitzschia</i> sp.	Pennate diatoms (19.4%) - <i>Thalassionema nitzschioides</i> , <i>Nitzschia</i> sp., <i>Pseudonitzschia</i> sp.
	Dinoflagellates (0.2%) - <i>Ceratium gracile</i> , <i>Dinophysis infundibulus</i> , <i>Protoperidinium crassipes</i>	Dinoflagellates (0.3%) - <i>Ceratium tripos</i> , <i>Protoperidinium crassipes</i> , <i>Protoperidinium pedunculatum</i>	Dinoflagellates (5.0%) - <i>Ceratium lineatum</i> , <i>Alexandrium catenatum</i> , <i>Protoperidinium crassipes</i>	Dinoflagellates (6.5%) - <i>Ceratium lineatum</i>
	Phytoflagellates (0.7%) - <i>Distephanus speculum</i>	Phytoflagellates (0.2%) - <i>Distephanus speculum</i> , <i>Euglena</i> sp.	Phytoflagellates (1.0%) - <i>Distephanus speculum</i>	Phytoflagellates (3.2%) - <i>Distephanus speculum</i>
Metlakatla Bay	Centric diatoms (89.6%) - <i>Chaetoceros debilis</i> , <i>Coscinodiscus perforates</i> , <i>Chaetoceros constrictus</i>	Centric diatoms (87.9%) - <i>Skeletonema costatum</i> , <i>Chaetoceros debilis</i> , <i>Chaetoceros constrictus</i>	Centric diatoms (52.5%) - <i>Coscinodiscus perforates</i> , <i>Chaetoceros decipiens</i> , <i>Ditylum brightwellii</i>	N/A
	Pennate diatoms (9.4%) - <i>Nitzschia</i> sp., <i>Cocconeis</i> sp., <i>Grammatophora marina</i>	Pennate diatoms (11.8%) - <i>Nitzschia</i> sp., <i>Pseudonitzschia</i> sp., <i>Asterionella japonica</i>	Pennate diatoms (40.8%) - <i>Thalassionema nitzschioides</i> , <i>Pseudonitzschia</i> sp., <i>Asterionella japonica</i>	N/A.
	Dinoflagellates (0.6%) - <i>Protoperidinium crassipes</i> , <i>Dinophysis infundibulus</i> , <i>Ceratium lineatum</i>	Dinoflagellates (0.2%) - <i>Protoperidinium crassipes</i> , <i>Ceratium lineatum</i> , <i>Dinophysis infundibulus</i>	Dinoflagellates (4.9%) - <i>Prorocentrum</i> sp., <i>Ceratium lineatum</i> , <i>Protoperidinium crassipes</i>	N/A
	Phytoflagellates (0.4%) - <i>Distephanus speculum</i> , <i>Euglena</i> sp.	Phytoflagellates (0.1%) - <i>Distephanus speculum</i> , <i>Euglena</i> sp., <i>Ebria tripartita</i>	Phytoflagellates (1.8%) - <i>Distephanus speculum</i> , <i>Brachiomonas</i> sp., <i>Ebria tripartita</i>	N/A

Table 1. Continued.

Location	Dominant Phytoplankton Species			
	Spring (March - May)	Summer (June - August)	Fall (September - November)	Winter (January - February)
Prince Rupert	Centric diatoms (90.9%) - <i>Coscinodiscus perforates</i> , <i>Chaetoceros debilis</i> , <i>Skeletonema costatum</i>	Centric diatoms (93.6%) - <i>Skeletonema costatum</i> , <i>Chaetoceros debilis</i> , <i>Chaetoceros compressus</i>	Centric diatoms (12.5%) - <i>Coscinodiscus perforates</i> , <i>Chaetoceros decipiens</i> , <i>Chaetoceros convolutus</i>	Centric diatoms (67.8%) - <i>Coscinodiscus perforates</i> , <i>Skeletonema costatum</i> , <i>Actinopterychus undulatus</i>
	Pennate diatoms (8.2%) - <i>Nitzschia</i> sp., <i>Licmophora abbreviate</i> , <i>Grammatophora marina</i>	Pennate diatoms (6.3%) - <i>Nitzschia</i> sp., <i>Asterionella japonica</i> , <i>Pseudonitzschia</i> sp.	Pennate diatoms (86.9%) - <i>Nitzschia</i> sp., <i>Thalassionema nitzschioides</i> , <i>Pseudonitzschia</i> sp.	Pennate diatoms (19.6%) - <i>Nitzschia</i> sp., <i>Nitzschia longissima</i> , <i>Grammatophora marina</i>
	Dinoflagellates (0.5%) - <i>Alexandrium tamarensis</i> , <i>Gymnodinium lacustre</i> , <i>Protoperidinium crassipes</i>	Dinoflagellates (0.1%) - <i>Ceratium lineatum</i> , <i>Protoperidinium crassipes</i> , <i>Alexandrium</i> sp.	Dinoflagellates (0.5%) - <i>Prorocentrum</i> sp., <i>Noctiluca scintillans</i> , <i>Protoperidinium crassipes</i>	Dinoflagellates (12.5%) - <i>Prorocentrum micans</i> , <i>Protoperidinium crassipes</i> , <i>Ceratium tripos</i>
	Phytoflagellates (0.4%) - <i>Distephanus speculum</i> , <i>Brachiomonas</i> sp., <i>Euglena gracilis</i>	Phytoflagellates (< 0.1%) - <i>Distephanus speculum</i>	Phytoflagellates (0.2%) - <i>Distephanus speculum</i> , <i>Euglena gracilis</i>	Phytoflagellates (0%) - None observed
Humpback Bay	Centric diatoms (87.7%) - <i>Chaetoceros radicans</i> , <i>Coscinodiscus perforates</i> , <i>Skeletonema costatum</i>	Centric diatoms (90.4%) - <i>Skeletonema costatum</i> , <i>Chaetoceros debilis</i> , <i>Chaetoceros compressus</i>	Centric diatoms (55.0%) - <i>Chaetoceros decipiens</i> , <i>Coscinodiscus perforates</i> , <i>Ditylum brightwellii</i>	Centric diatoms (96.4%) - <i>Chaetoceros socialis</i> , <i>Coscinodiscus excentricus</i> , <i>Coscinodiscus perforatus</i>
	Pennate diatoms (8.8%) - <i>Nitzschia</i> sp., <i>Grammatophora marina</i> , <i>Thalassionema nitzschioides</i>	Pennate diatoms (9.4%) - <i>Nitzschia</i> sp., <i>Pseudonitzschia</i> sp., <i>Asterionella japonica</i>	Pennate diatoms (35.2%) - <i>Thalassionema nitzschioides</i> , <i>Pseudonitzschia</i> sp., <i>Cocconeis</i> sp.	Pennate diatoms (2.4%) - <i>Nitzschia</i> sp., <i>Gyrosigma spencerii</i> , <i>Pleurosigma normanii</i>
	Dinoflagellates (0.4%) - <i>Prorocentrum micans</i> , <i>Alexandrium tamarensis</i> , <i>Gymnodinium lacustre</i>	Dinoflagellates (0.2%) - <i>Prorocentrum gracile</i> , <i>Prorocentrum micans</i> , <i>Alexandrium</i> sp.	Dinoflagellates (6.6%) - <i>Ceratium lineatum</i> , <i>Ceratium fusus</i> , <i>Protoperidinium crassipes</i>	Dinoflagellates (1.2%) - <i>Prorocentrum minimum</i> , <i>Protoperidinium conicoidea</i> , <i>Protoperidinium crassipes</i>
	Phytoflagellates (3.1%) - <i>Brachiomonas</i> sp., <i>Euglena</i> sp., <i>Distephanus speculum</i>	Phytoflagellates (0.1%) - <i>Distephanus speculum</i> , <i>Brachiomonas</i> sp.	Phytoflagellates (3.2%) - <i>Micromonas</i> sp., <i>Distephanus speculum</i> , <i>Brachiomonas</i> sp.	Phytoflagellates (0%) - None observed
Freeman Pass	Centric diatoms (74.1%) - <i>Chaetoceros debilis</i> , <i>Thalassiosira nordenskioldii</i> , <i>Schroederella delicatula</i>	Centric diatoms (62.8%) - <i>Chaetoceros compressus</i> , <i>Chaetoceros debilis</i> , <i>Chaetoceros constrictus</i>	Centric diatoms (45.9%) - <i>Coscinodiscus perforates</i> , <i>Chaetoceros decipiens</i> , <i>Skeletonema costatum</i>	N/A
	Pennate diatoms (25.3%) - <i>Nitzschia</i> sp., <i>Thalassionema nitzschioides</i> , <i>Grammatophora marina</i>	Pennate diatoms (36.9%) - <i>Nitzschia</i> sp., <i>Pseudonitzschia</i> sp., <i>Asterionella japonica</i>	Pennate diatoms (34.7%) - <i>Nitzschia</i> sp., <i>Thalassionema nitzschioides</i> , <i>Licmophora abbreviata</i>	N/A
	Dinoflagellates (0.3%) - <i>Protoperidinium crassipes</i> , <i>Dinophysis infundibulus</i> , <i>Alexandrium tamarensis</i>	Dinoflagellates (0.2%) - <i>Ceratium lineatum</i> , <i>Protoperidinium crassipes</i> , <i>Protoperidinium oblongum</i>	Dinoflagellates (10.2%) - <i>Ceratium lineatum</i> , <i>Protoperidinium crassipes</i> , <i>Ceratium fusus</i>	N/A
	Phytoflagellates (0.3%) - <i>Distephanus speculum</i>	Phytoflagellates (0.1%) - <i>Distephanus speculum</i> , <i>Ebria tripartite</i> , <i>Euglena</i> sp.	Phytoflagellates (9.1%) - <i>Distephanus speculum</i> , <i>Ebria tripartite</i> , <i>Halosphaera viridis</i>	N/A

7 Disclaimer

The findings presented in this report are based on data available as of December, 2011. Ocean Ecology has exercised reasonable skill, care, and diligence to collect and interpret the data, but makes no guarantees or warranties as to the accuracy or completeness of this data.

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Prepared By:



Barb Faggetter, Ph.D
Oceanographer, R.P.Bio.

Reviewed By:



Kennard Hall, Captain
Partner, Ocean Ecology