Applying Remote Sensing Data to Fisheries Management in BC

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2016

Canadian Technical Report of Fisheries and Aquatic Sciences 3156

Fisheries and Oceans Canada | Pêches et Océans Canada

Canada

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Rapport technique canadien des sciences halieutiques et aquatiques

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Cat. No. Fs97-6/3156-PDF ISBN 978-0-660-04564-1 ISSN 1488-5379 (pdf)
Cat. No. Fs97-6/3156E ISBN 978-0-660-04563-4 ISSN 0706-6457 (paper)

Correct citation for this publication:
Hannah, C.G. and McKinnell, S. (Eds.). 2016. Applying remote sensing data to fisheries management in BC. Can. Tech. Rep. Fish. Aquat. Sci. 3156: vi + 32p.

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ABSTRACT

Projects were developed by Fisheries and Oceans Canada to explore how remotely-sensed data from Earth-orbiting satellites might serve fisheries. Four projects focused on highly migratory fishes with broad distributions: Pacific salmon (*Oncorhynchus* spp.), Pacific hake (*Merluccius productus*), and albacore tuna (*Thunnus alalunga*). A fifth dealt with the development of ocean indices. Some results were useful immediately but others require additional study. Notably, Canada is a member of the North Pacific Anadromous Fish Commission whose Enforcement Committee coordinates surveillance activities that detect and deter illegal fishing, primarily for salmon, in the North Pacific. Using years when salmon research fishing coincided with satellite and hydrographic observations, the relationship between salmon abundance, temperature and hydrography was examined. Habitat maps were produced and reported to the NPAFC in 2014 and 2015. The Canadian albacore tuna fishery occurs along the continental shelf break during summer. Daily records of catch in 2013 were compared with sea surface temperature (SST) and chlorophyll *a* fronts derived from high resolution satellite data. There was little explanatory or predictive power in these data. Nevertheless, the results are a first step in the development of a habitat model for albacore tuna. Pacific hake migrate seasonally from California to British Columbia and the fraction of the stock in Canadian waters varies from year to year. Spring SST anomalies near northern California appeared to indicate the extent to which Pacific hake migrate north into Canadian waters as did summer chlorophyll *a* anomalies off the northwestern coast of Vancouver Island. Future research will be required to determine if these can be used as leading indicators of the resource available to Canadian fishermen. Satellite-based altimetry and ocean colour data were critical for the development of scientific advise by DFO scientists about the effects of discharging a large quantity of iron sulfate and other iron-rich materials into international waters of the Northeast Pacific Ocean in 2012. Satellite data allowed the subsequent plankton bloom to be detected and monitored.

Salmon productivity were assembled, documented, reviewed and published. Smolt survivals for sockeye salmon populations were updated, reviewed and presented at the 2015 State of Pacific Ocean workshop. Satellite-derived chlorophyll and SST data were assembled to develop indicators of phytoplankton phenology and biomass and their relationship to marine survival of salmon. While distinct spatial and temporal patterns of chlorophyll *a* are evident, there are large amounts of missing data (average of 50% and up to 80% in winter) posed difficulties for the analysis and interpretation. These data were compared to salmon productivity indices of 17 Conservation Units of Fraser sockeye salmon and to the smolt survivals of Chilko Lake (Fraser system) sockeye salmon. Ongoing research will examine decorrelation scales of these environmental data and their interconnection with indices like the Bakun upwelling index. Further work relating satellite derived chlorophyll and temperature data to salmon productivity and survival data sets is warranted. Future analyses may resolve whether chlorophyll data can improve salmon abundance forecasting.

RÉSUMÉ

Cinq projets ont été développés dans la région du Pacifique par le ministère des Pêches et des Océans pour explorer comment les données scientifiques de télédétection obtenues par les satellites en orbite terrestre pourraient être appliquées utilement aux besoins de la recherche de la pêche, la gestion et l'exécution. Quatre des projets portaient sur les espèces de poissons hautement migratrice dont la distribution est à l'échelle de l'hémisphère: le saumon du Pacifique (*Oncorhynchus* spp.), le merlu du Pacifique (*Merluccius productus*) et le thon germon (*Thunnus alalunga*). Un cinquième portait sur le développement des indices océaniques. Ce ne sont pas tous les projets qui ont généré des résultats qui étaient immédiatement utiles pour la gestion mais certains l'ont fait, et certains exigent une étude supplémentaire. Le Canada est un membre de la Commission des Poissons Anadromes du Pacifique Nord dont le comité exécutif coordonne les activités de surveillance aérienne dans le Pacifique Nord qui visent à détecter et décourager la pêche illégale, principalement pour le saumon, sur les hautes mers. Il était possible de comprendre la relation entre l'abondance du saumon, de la température et de la structure de l'océan en examinant les données de pêche au saumon historique qui coïncidaient avec les observations satellitaires et les données hydrographiques historiques. Des cartes de l'habitat du saumon ont été produites et les résultats ont été communiqués à la Commission au cours de ses réunions annuelles en 2014 et 2015. La pêche canadienne de thon germon se produit le long de la bordure du plateau pendant l'été. Des registres journaliers de prises en 2013 ont été comparés aux fronts de la température de surface de la mer (SST) et de chlorophylle dérivés à partir de données satellitaires à haute résolution, mais il y avait peu de pouvoir explicatif ou prédictif dans ces données. Néanmoins, les résultats sont une première étape dans le développement d'un modèle de l'habitat pour le thon germon. Le merlu du Pacifique effectue des migrations saisonnières de la Californie à la Colombie-Britannique. La fraction du stock dans les eaux canadiennes varie d'une année à l’autre. Les anomalies printanières de SST près du nord de la Californie ainsi que les anomalies estivales de chlorophylle au large de la côte nord-ouest de l'île de Vancouver semblent indiquer la mesure dans laquelle le merlu du Pacifique migre vers le nord dans les eaux canadiennes. Des recherches futures seront nécessaires pour déterminer si ceux-ci peuvent être utilisés comme des indicateurs avancés de la ressource disponible pour les pêcheurs canadiens. Les données satellitaires d’altimétrie et de la couleur de l'océan ont été essentielles pour le développement de conseils scientifiques par les scientifiques du MPO sur les effets d'une grande quantité de sulfate de fer et d'autres matériaux riches en fer qui ont été déversés intentionnellement par un navire canadien affrété par la Haida Salmon Restoration Corporation (HSRC) dans les eaux internationales de l'océan Pacifique Nord en 2012. Les données ont permis la détection et le suivi du plancton qui est survenu suite à ce déversement. Les séries chronologiques et de la productivité des saumons rouges, roses, et kétas ont été assemblées, documentées, examinées et publiées. Les séries chronologiques des taux de survie de saumoneaux pour les populations de saumon rouge ont été mises à jour, révisées et présentées à l'atelier sur l’état de l’océan Pacifique 2015. Les données satellitaires de la chlorophylle et de température de la surface de la mer ont été assemblées et filtrées. Des indicateurs de la phénologie et de la biomasse du phytoplancton, qui peuvent potentiellement refléter des conditions d'alimentation et de la survie en mer du saumon, ont également été développés. Bien que des modèles spatiales et temporelles distincts de la chlorophylle sont évidents, il y a de grandes quantités de données manquantes (~ moyenne de 50% et jusqu'à 80% en hiver) qui ont posé des difficultés pour l'analyse et l'interprétation. La chlorophylle et SST ont été comparés, par le biais des cartes de corrélation avec des indices de la productivité du saumon rouge du Fraser provenant de 17 unités de conservation et des taux de survie des saumoneaux rouges du lac Chilko dans le système de la rivière Fraser. Les recherches en cours examinent les échelles spatiales et temporelles de décorrélation avec des données environnementales, la connexion entre ces variables, et à d'autres indices comme l'indice de courants ascendants de Bakun. D'autres travaux supplémentaires mettant en relation les données de chlorophylle et de température à la productivité du saumon et aux ensembles de données de survie est désirable. Les analyses futures permettront peut-être de déterminer si les données de chlorophylle peuvent améliorer les prévisions de l'abondance du saumon.

1.0. INTRODUCTION

Assessment and management of British Columbia fisheries is a key priority for the Department of Fisheries and Oceans (DFO) and the Government of Canada. Harvestable surpluses of fish and shellfish species, when they occur, provide jobs and wealth to Canadians. Variations in resource abundance affect fishers' catches and incomes but the causes of these variations are not yet well determined. Some of the variability is due to the reproductive dynamics of populations while some is due to the variability of the environment. The links between environmental variability and resource abundance is a topic of considerable interest in fisheries research and significant improvements in understanding are emerging slowly. DFO's Wild Pacific Salmon Policy, for example, identifies a need for improved understanding of the causes and effects of variations in oceanic and freshwater environments and their role in the changing productivity of salmon stocks. Likewise, the distribution of highly migratory species, and the production of coastal groundfish and shellfish stocks is affected by environmental variations that ultimately influence how these fisheries are managed. Helping Canadians adapt to climate change is also a high priority (DFO's Aquatic Climate Change Adaptation Services Program). Understanding how environmental variability and change affects fish populations is a key part of providing robust scientific advice so that sound management decisions can be made and proper policies can be developed.

Recent research indicates that satellite observations have the potential to provide indicators that relate directly to important processes that control fish populations in British Columbia waters. The goal of this project is to develop robust indices that can be integrated into the science advice for fisheries management in British Columbia. The focus is on several salmon stocks, hake, and albacore tuna.

Satellite data are not used routinely in developing scientific advice on commercial fish stocks. To achieve this requires that we are able provide robust scientific links between such indices and key parameters of specific populations (e.g. marine survival or adult return rates of a specific salmon stock; northward migration measures for hake). The use of satellite data to guide the deployment of aerial surveillance assets to protect salmon fisheries resources from high seas poaching would also be highly innovative. Both activities would be major accomplishments for DFO and its international partners.

The projects goals at the outset included contributing to:

- Making a contribution to international governance of North Pacific albacore tuna by improving our understanding of oceanographic-climatic drivers on spatial distribution, recruitment, and stock productivity and to use this understanding to implement spatial dynamics and environmental drivers in stock assessment modeling;
- Spatial and temporal management regulations of mixed-stock salmon fisheries with the aim of reducing fishing pressure on weak stocks;

- Improved understanding of the partitioning of freshwater versus marine contributions to sockeye salmon recruitment variations within major coastal eco-regions leading to improved forecasts of recruitment for key fish stocks;
- Improved international governance of Pacific salmon through our understanding of relative role of density-dependent effects from populations from neighbouring countries compared with oceanographic drivers.

Several outcomes were anticipated at the outset:
- Satellite-based indices integrated into the science advice for at least 3 British Columbia fish stocks;
- Satellite-based indices included in integrated fish management plans for at least 3 BC fish stocks;
- Ocean salmon habitat maps for use by DFO Conservation Branch for operational planning.

In consideration of the diversity of approaches needed for different fish stocks, the work was divided among 5 major projects:
1. Ocean indices for the North Pacific (Project 2000)
2. Albacore tuna (Project 3000)
3. Pacific hake (Project 4000)
4. Oceanic salmon habitat maps (Project 5000)
5. Salmon management (Project 6000)

The work was made possible by a grant from the Government Related Initiatives Program (GRIP) of the Canadian Space Agency. GRIP fosters the use of Canada's space resources by the Government of Canada to develop government's use of space-based land, ocean, and atmospheric observations.

2.0. PROJECT SUMMARIES AND OUTCOMES

2.1. OCEAN INDICES FOR THE NORTH PACIFIC (PROJECT 2000)

2.1.1. Project description

Oceans are dynamic. They are affected by physical, biological, and chemical forces that vary on multiple spatial and temporal dimensions and and multiple scales. Given all of this complexity, it is critical to be able to capture the dominant signals in a relatively simple fashion. Indices are a common means of reducing the complexity. The more useful ones exhibit a property known as resonance, in that they reflect changes in time and/or space beyond the location where they were derived. In the North Pacific Ocean, for example, the month to month variation of the Pacific Decadal Oscillation index (Mantua et al. 1997) is calculated only from sea surface temperature. It accounts for 20% of the variation in sea surface temperature (SST) throughout the entire ocean, but it is evident in tree ring growth, zooplankton species composition, etc. Fisheries resources are often affected by factors operating at smaller scales of variation (e.g.

coastal upwelling zones or marginal seas) where the dominant factors affecting fish abundance are found locally. Developing indices that correspond to the time and space scales of the resources is an important aspect of fisheries research, particularly when the cause of variation in fish abundance is not fully understood.

The goal of this component was to develop indices that represent spatial and temporal variability of the NE Pacific based on sea surface height (SSH), SST, and ocean colour (for open ocean and selected coastal areas), to test theories of the spatial and temporal evolution of the PDO and the North Pacific Gyre Oscillation (NPGO), and to develop linkages with other fisheries activities.

2.1.2. Project investigators

William R. Crawford, Angelica Peña, Josef Cherniawsky, Charles Hannah

2.1.3. What operational question was addressed?

A) Are eddy indices derived from satellite telemetry (e.g. Crawford et al. 2002) useful for understanding fish stock variability in the NE Pacific?

B) Can the majority of SST variation along the shelf from California to Alaska be described by 1 or 2 time series or is much of the variability predominately local?

C) Are the large scale indices like the Pacific Decadal Oscillation (PDO) and North Pacific Gyre Oscillation (NPGO) useful for explaining any biological time series?

2.1.4. What was the result?

A) Eddy Indices

The Crawford Eddy Index (CEI) of eddy activity in the NE Pacific was revised (including some technical revisions) and extended to include the period from 1993 to 2014. It was used by J.B. LeCompte (Pacific Biological Station, unpublished) as one environmental index among many to help interpret the time series of recruitment Pacific Ocean Perch (*Sebastes alutus*) in Queen Charlotte Sound and Hecate Strait. The results were encouraging but the technique using Bayesian statistics is still under development.

B) SST and Chlorophyll Variability

A dataset of satellite derived SST and chlorophyll *a* for the NE Pacific for the period 1988 to 2010 was created. The SST data was taken from the gap free analysis of GRHSST (Group for High Resolution Sea Surface Temperature; http://www.ghrsst.org). The chlorophyll *a* was taken from the NASA MEaSUREs 2012 project dataset (ftp.oceancolor.ucsb.edu/pub/org/oceancolor/MEaSUREs/). The MEaSUREs group is devoted to 'the development of unified and coherent ocean color time series through the merging of data from multiple sensors' (http://measures.oceancolor.ucsb.edu/measures/Main_Page). They are using the Garver-Siegel-Maritorena (GSM) model for this task. Information about the GSM model can be found at: http://wiki.icess.ucsb.edu/measures/GSM. The MEaSUREs data set used SeaWIFS data for the period September 1997 to June 2002 and combined data from SeaWIFS, MODIS and MERIS for the period July 2002 to December 2010.

To allow the SST and chlorophyll *a* concentration to be sampled at the same spatial resolution, both were processed onto a common time base (8 day averages) and at two spatial grids (0.25° latitude/longitude and 1° latitude/longitude). These two data sets were used by Project 6000 for various analyses.

Analysis of SST along the continental slope from California to Alaska suggested that at time scales of a month or more, the entire shelf region is dominated by coherent in-phase increases and decreases in surface temperature – the first mode of an EOF analysis contains 56% of the energy. This first mode includes, but is not dominated by the major El Niño events. The spatial structure of the mode is consistent with the spatial patterns of the PDO but the modal time series is only weakly correlated with the PDO. The second mode (16%) is a north-south temperature tilt (warm in north and cool in the south and vice versa). The results show that in general when the water is warm off BC coast it is also warm in California and Alaska. This supports the idea that it should be possible to find a small number of SST indices that are useful for understanding fish stock variability in the NE Pacific.

Whitney (2015) used surface chlorophyll data to show that anomalous winds in the winter of 2013/2014 reduced nutrient transport from the subarctic North Pacific towards subtropics. The anomaly reduced the surface chlorophyll in the transition zone, located between the subarctic and subtropical zones, to the lowest levels observed since the SeaWIFS sensor started in 1997. It is expected that the impacts of the anomalous winds may affect fish and top predator communities in the next few years.

C) Climate Indices

Indices of Pacific basin-wide climate and ocean variability abound. They include the Aleutian Low Pressure Index (ALPI), North Pacific Index (NPI), Pacific Decadal Oscillation Index (PDO), North Pacific Gyre Oscillation (NPGO), Oceanic Niño Index, ONI and Southern Oscillation Index (SOI). A significant effort is underway to make sense of these climate indices (e.g. Di Lorenzo et al. 2013) but no contribution was made to the effort. Nevertheless, a presentation was prepared to summarize a coherent storyline that is being developed by Di Lorenzo and colleagues. Material for the presentation was drawn from two presentations:

- Emanuele Di Lorenzo, Nathan Mantua and Mathew Newman. Forecasting North Pacific climate and ecosystem changes: Advances and challenges PICES 2014. (www.pices.int/publications/presentations/PICES-2014/2014-S1/S1-1430-DiLorenzo.pdf)
- Emanuel Di Lorenzo. Changes in character of North Pacific variability and ecosystem implications, PICES 2013 (www.pices.int/publications/presentations/PICES-2013/2013-S2/S2-0905-DiLorenzo.pdf)

Again, the results are encouraging but the results are not ready for transition to operations.

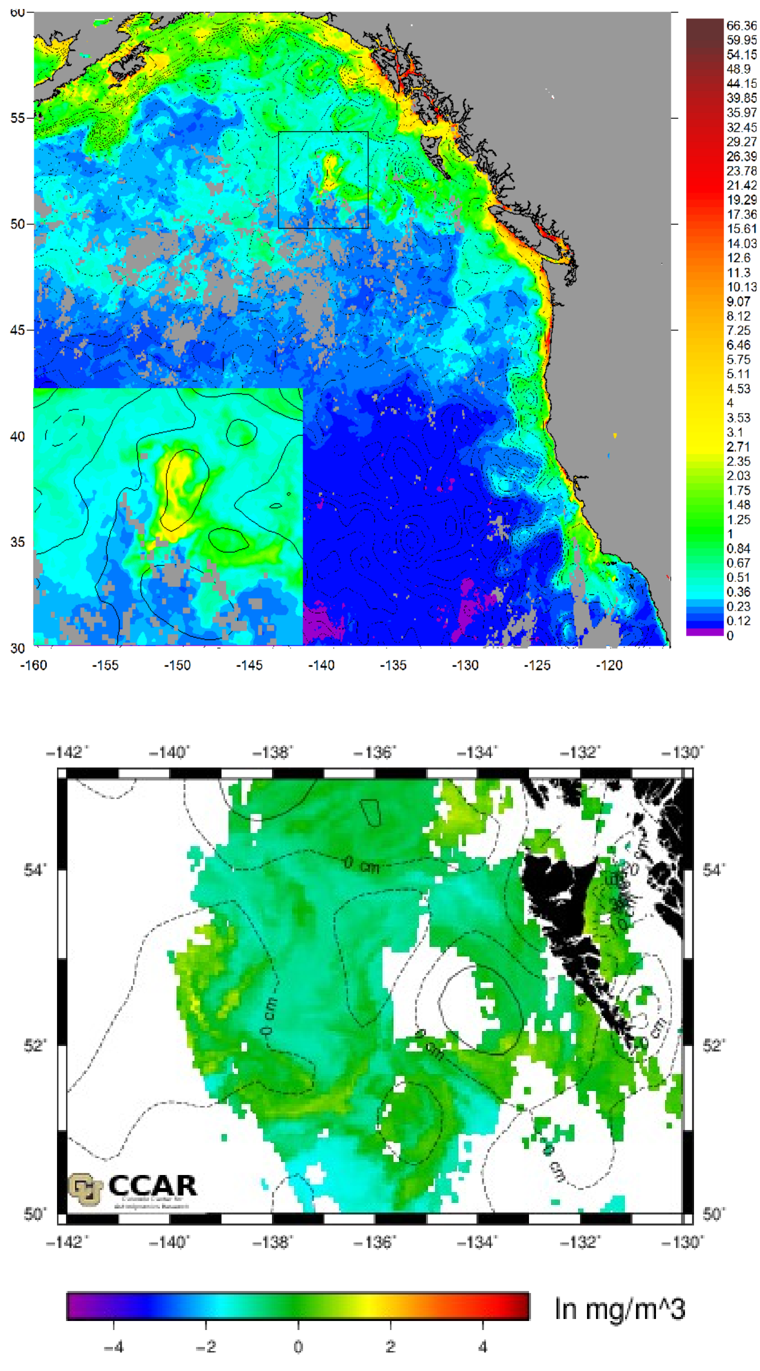

Figure 1: Image of ocean surface chlorophyll concentration in August in the Northeast Pacific [above] and the Gulf of Alaska west of Haida Gwaii on 30 August 2012 at 2.5 km resolution and sea surface height contours for the same day. Source: http://eddy.colorado.edu/ccar/ssh/nrt_global_grid_viewer

D) Other Activities

Sea level (from satellite altimetry) was examined with the expectation of being able to extract useful signals of currents along the shelf edge, associated with warm events from the south. This effort was not successful.

2.1.5. Are the results ready to transition to operations?

None of the results presented here are ready for transition to operations, but several are worth pursuing.

2.1.6. Is the result worth pursuing further? Why?

The scientific directions pursued in this project will continue to be pursued – understanding the linkages between environmental variability and the fluctuations in fish populations is central to the DFO mandate. Here we highlight some important activities are relevant to the project's goals but that occurred outside of this project:

2.1.6.1. The Blob: During this project the largest recorded pool of surface warm water developed in the North Pacific, apparently independently of tropical events such as El Niño (Freeland and Whitney 2014). The evolution of this warm pool and tracking its impacts on the marine ecosystem will be an ongoing activity of DFO Science in Pacific Region. Satellite data such as SST and ocean colour are an important part of this monitoring.

2.1.6.2. Monitoring effects of iron discharge in the ocean: In much of the NE Pacific, iron is a micronutrient that is least available for phytoplankton growth and its relative scarcity limits biological productivity in the region (Martin and Fitzwater 1988). Where limiting nutrients have been identified in freshwater ecosystems they have been applied artificially in the hope of improving juvenile salmon survival (Hyatt et al. 2004). In 2012, the Haida Salmon Restoration Corporation (HSRC) chartered a vessel and discharged many tonnes of iron sulfate and other iron compounds to the surface waters of the North Pacific Ocean, just west of Canada's EEZ to add iron to the NE Pacific beyond Canada's territorial waters (Figure 1). Satellite data allowed Canadian oceanographers to provide advice to the Government of Canada on the potential environmental impacts of iron supplementation and to provide advice relevant to legal action against organizations conducting large-scale iron fertilization of the ocean. The scientific aspects this work are reported in Batten and Gower (2014) and the State of the Ocean report for 2012 (Irvine and Crawford 2013). This was an important application of satellite data to the operations of Fisheries and Oceans Canada. Ready access to satellite data allowed Canadian scientists an opportunity to provide better advice to the Government of Canada.

2.1.6.3. Run Timing and Diversion Rate Models for Fraser River Sockeye: Two of the most important operational uncertainties in DFO in the Pacific Region are the annual dates of arrival of the various Fraser River sockeye salmon stocks and the fractions of the run that migrate via the east and west coasts of Vancouver

Island (the diversion rate). Fish that follow the western route to the Fraser River are also caught by fishermen in Washington State so there are challenges for sharing the resource. Key variables that are used to forecast these unknowns annually include ocean currents and SST in the Gulf of Alaska. Forecasts based on an ocean circulation model have predictive skill so a Canadian Science Advisory Secretariat (CSAS) review meeting was held in October 2015 '*to assess the performance of newly developed run timing and diversion rate models, including those that utilize near real-time oceanographic data*.' Top performing models included current velocity and SST (DFO 2016) and many of these models rely on data that are currently publicly available but served by foreign agencies (e.g. NOAA). DFO will use the advice from the CSAS meeting to decide how to use these results in formulating advice to the industry and partners (http://www.dfo-mpo.gc.ca/csas-sccs/Publications/SAR-AS/2016/2016_008-eng.html).

To maintain operational capacity into the future this forecast system should be integrated into the coupled environmental prediction system being developed by jointly by Environment Canada, DFO, and DND. This would provide a key operational output for the system that would be meaningful for DFO.

<u>2.1.6.4. Operational Seasonal Forecasts</u>: Environment Canada is looking for operational applications for its seasonal forecasts. Two natural applications are: 1) the salmon return timing project discussed above and 2) SALOSIS: the high seas surveillance and enforcement planning project (Project 5000).

2.2. ALBACORE TUNA (PROJECT 3000)

2.2.1. Project description

The albacore tuna (*Thunnus alalunga*) is an highly migratory species with global distribution. After hatching in the subtropical North Pacific Ocean, juveniles migrate northward and eastward on seasonal foraging excursions near the North American continental shelf. From July through October, Canadian and U.S. fishermen use the hook and line method (trolling) to catch the ~5 kg fish that inhabit surface waters. The fishing boats are small, the distances are great, and the fish distribution is patchy, so any oceanic information that will increase the encounter rates between fish and fishermen will potentially improve fishing success. On very small scales, juvenile albacore tuna are described as associated with oceanic frontal structures (eg. Laurs et al. 1984), perhaps at convergence zones or upwelling fronts that may concentrate their prey. If these fronts can be identified by satellite remote sensing, they may lead tuna fishermen to their prey.

2.2.2. Project investigators

John Holmes, Skip McKinnell, and Evelyn Chen

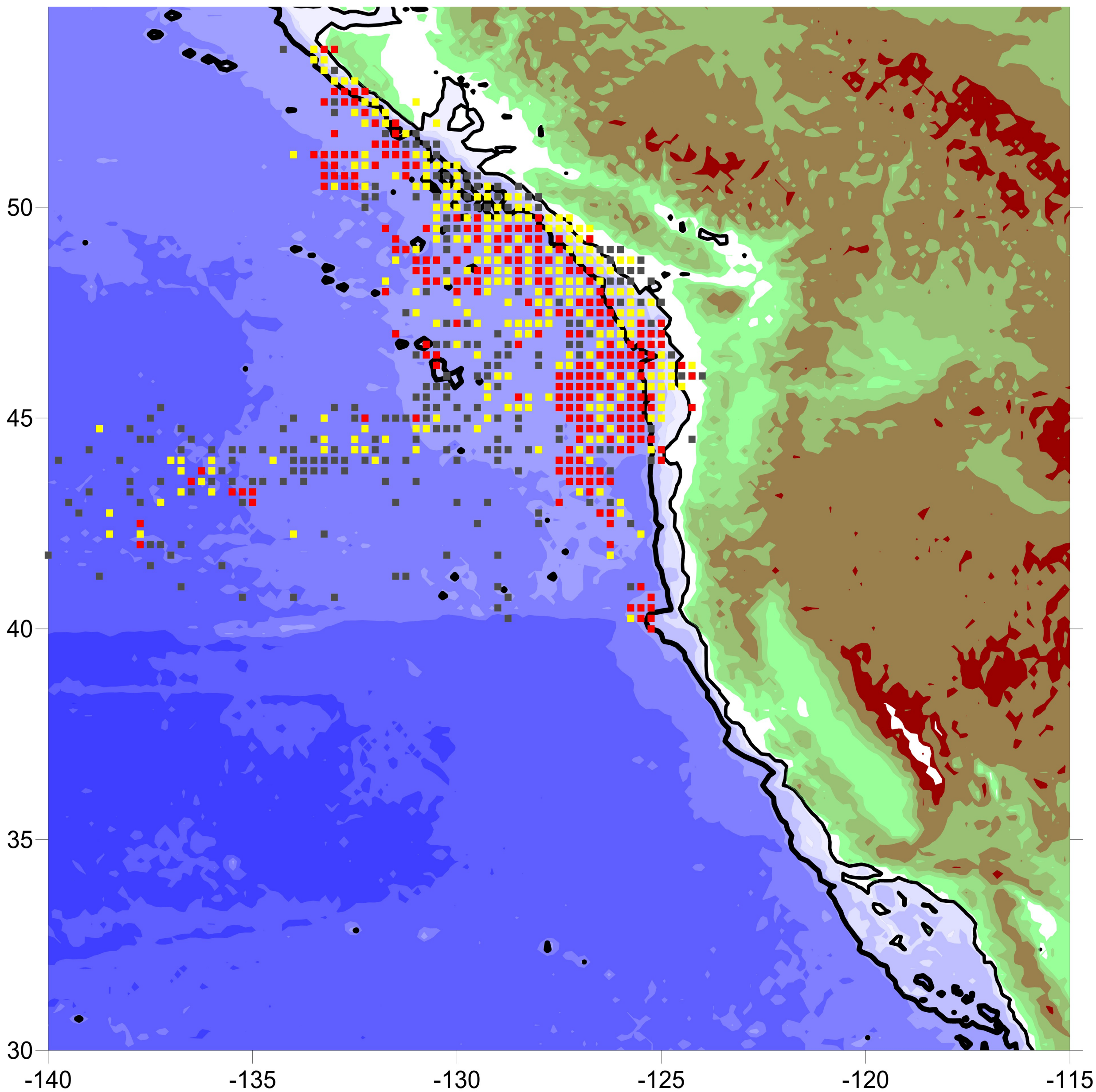

Figure 2: Spatial distribution of the Canadian albacore troll fishery in 2013 categorized by catch-per-unit-effort (CPUE). Data are summarized into 0.25 x 0.25° spatial strata for all months. Strata in which fewer than three vessels reported effort are not shown. Bathymetry is shown in shades of blue (dark=deep) with the 2000 m (thick line) and 200 m (thin line) highlighted. Colours indicate the lower 1/3 (gray), middle 1/3 (yellow) and upper 1/3 (red) of the observed CPUE.

2.2.3. What operational question was addressed?

Are SST fronts derived from satellite SST data and chlorophyll fronts derived from satellite chlorophyll data useful indicators of Catch per Unit Effort (CPUE) by the Canadian tuna fleet?

2.2.4. What was the result?

The Canadian albacore tuna fishery uses troll gear with jigs and operates annually from mid-June through to the end of October. Fishers are required to maintain and submit logbooks of daily fishing activities including the date, start time and position, stop time and position, the number of albacore retained and released, the number of other species retained and released, estimated weight of retained and released albacore and other species, and the number of jigs used for fishing. At the end of a trip, the off-load weight measured by the buyer or processor (which forms the basis for payment) is recorded in the logbook. Logbooks are returned to DFO by mid-November and it is the data in the logbooks that were used in this analysis.

Catch (number of fish) and effort (jig-hours) data for the 2013 season were summarized into ¼° x ¼° latitude/longitude x 8-day temporal strata corresponding with the reporting of the chlorophyll data. CPUE (number of fish/jig-hour) was estimated for each stratum. Daily SST data were obtained from U.S. NOAA website (ftp://eclipse.ncdc.noaa.gov/pub/OI-daily-v2/NetCDF/) and 8-day average values were calculated (McKinnell 2014). Eight-day average chlorophyll concentrations near the ocean surface derived from ocean colour sensors were obtained from a U.S. NOAA website (https://coastwatch.pfeg.noaa.gov/erddap/griddap/).

Both the SST and chlorophyll data were filtered to enhance the identification of mesoscale oceanographic structures (SST and chlorophyll fronts or gradients) using a modification of the approach described by Belkin and O'Reilly (2009) and implemented by McKinnell (2014a). The method implemented by McKinnell applied a modified median filter on 5 pixel by 5 pixel cells. Only those cells with valid data in all 25 pixels were filtered so the spatial domain was reduced by 0.5° around the periphery and near regions with missing (chlorophyll) data. On each iteration, fewer pixels were adjusted and the process was halted when there was a 95% reduction from the number of pixels adjusted on the first iteration. A Sobel filter was then applied to the domain to enhance the fronts within the domain. The filters for the chlorophyll data were restricted to cloud-free grid cells where there was enough pixels within a region to apply the filter.

The SST, chlorophyll and albacore CPUE data were summarized into temporal bins centered on four dates during the 2013 fishing season (July 15- day 197, August 15- day 227, September 15- day 258, October- day 288) for the analysis reported here (McKinnell 2014b).

In 2013, the Canadian fishery generally operated on the seaward side of the shelf-break (Figure 2). Most fishing occurred within a relatively narrow range of longitudes whose lower and upper quartiles (126.6°W, 128.4°W) differed by less than 2°. Limited fishing occurred in transition zone waters (between the sub-arctic gyre to the north and the sub-tropical gyre to the south) outside of the exclusive economic zones (EEZ) of Canada and the United States. There was a total of 6407 daily fishing records (99.5% of the 2013 records) located east of 140°W. The frequency distribution of latitudes fished in 2013 was strongly bimodal with modes off at the mouth of the Columbia River and off Nootka Sound on the west coast of Vancouver Island. A K-means cluster analysis of latitudes fished placed the boundary between southern and northern fishing regions at 48.6°N. Both the southern and northern locations were fished throughout the season, although fishing terminated earlier in the south (Figure 3) owing to provisions in the Canada-United States Pacific Albacore Tuna Treaty which limits Canadian activities in US waters to a September 15 termination date.

Quartiles were used to indicate LOW CPUE (lower 25% of records) or HIGH CPUE (upper 25 %).The lower and upper quartiles of CPUE, at fishing locations east of 140°W, had limits of 0.329 and 0.933 fish per jig-hour, respectively. HIGH CPUE (upper quartile) was not evident when fishing began in early June nor at the end of the fishery in October, except for the very last 8 day period (Figure 4). The HIGH CPUE quartile occurred consistently from day 197 to 258 (mid-July to mid-September). The LOW CPUE quartile was encountered throughout the fishing season indicating that poor fishing could be encountered at any time. Both the HIGH CPUE quartile and the LOW CPUE quartile occurred seaward of the shelf break over bottom depths exceeding 2000 m, i.e., the toe of the continental slope and the abyssal plain.

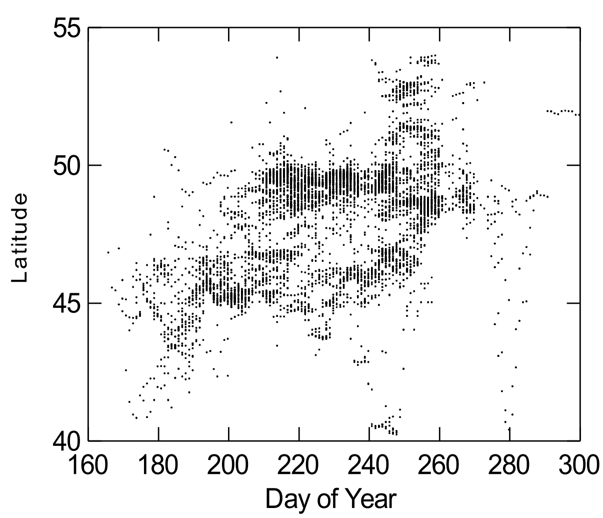

Figure 3: Latitudes fished by the Canadian fishery by day in 2013.

Both HIGH and LOW CPUE fishing occurred at the same median SST in 12 weekly periods (Figure 4) in the northern region. Significant differences in SST between HIGH and LOW CPUE quartiles occurred only in weeks centered on day of year 199 (July 8) and 239 (August 27), with higher CPUE occurring in warmer water. In the southern region, the median SST was significantly higher in HIGH CPUE fishing locations relative to LOW CPUE fishing locations (Figure 4).

Median weekly chlorophyll concentrations tended to be relatively low and less variable at fishing locations (primarily off Oregon) at the beginning of the 2013 fishing season compared with chlorophyll concentrations encountered during the rest of the season (Figure 4). Both the variability and the median chlorophyll concentrations were higher through the summer, but weekly differences between median chlorophyll concentrations at locations of high CPUE and low CPUE were marginally significant, if at all. There was a slight tendency for high CPUE events to be found in regions of lower chlorophyll concentration but this pattern was not consistent throughout the year. Median chlorophyll concentrations in the southern region of the fishery were significantly lower than those found in the northern region through most weeks of the fishery. Four of 23 weekly comparisons (10 in the south and 13 in the north) of chlorophyll concentration at HIGH and LOW CPUE had statistically significant differences in median chlorophyll concentrations. In each case, low chlorophyll concentration was associated with HIGH CPUE (Figure 4).

Macro oceanographic features in the high resolution SST (5 km) and chlorophyll (4 km) data in relation to fishing locations and catches at the beginning of the season (day 184) and near the peak of the fishing season (day 238) are shown in Figure 5 and Figure 6, respectively. These dates where chosen to demonstrate the oceanographic features identified by frontal filters. Fishing occurred from inshore to offshore in early July and offshore fishing locations followed in a relatively narrow band of latitude through waters of intermediate SST (Figure 5). There is little visual evidence in the SST or chlorophyll gradient images that fishing was associated with frontal features (either SST or chlorophyll), but the offshore fishing locations clearly occur in the North Pacific Transition Zone where juvenile albacore tuna are known to be abundant at that time of year (McKinnell and Seki 2016). Fishing activities occurred along the continental slope and seaward of the more intensive SST and chlorophyll gradients near the peak of the season in late August (Figure 6). Oceanographic complexity in the southern fishing region centered off the Columbia River is mostly due to upwelling and the majority of effort appears to occur seaward of the upwelling. Fishing appears to be occurring seaward of the strongest of gradients along the west coast of Vancouver Island, where a combination of upwelling, complex bathymetry, and the Vancouver Island Coastal Current provide physical mechanisms for the observed heterogeneous frontal structures.

An analysis of covariance (ANCOVA) of all albacore tuna log-transformed CPUE records pooled across the entire season with region as a grouping factor, and weekly means of SST, SST fronts, chlorophyll, chlorophyll fronts (the latter 3 log-transformed) as linear covariates, did not detect significant differences in logCPUE between regions after accounting for SST and chlorophyll properties. The only statistically significant variable in the ANCOVA was a positive association of logCPUE with SST ($P<<0.001$, $n=1057$), but this correlation explained little of the variation in CPUE ($R^2 = 4\%$).

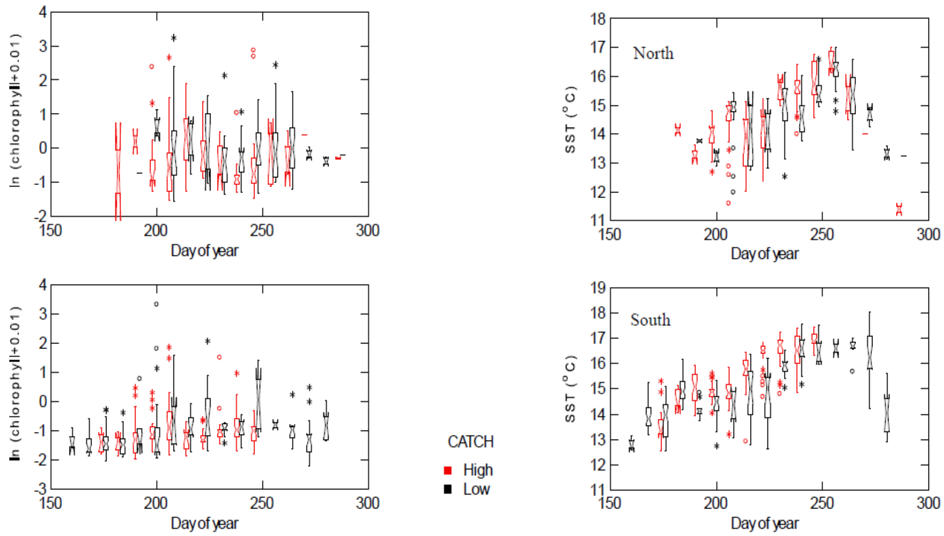

Figure 4: Box and whisker plots of median 8-daily average SST (right panels) and chlorophyll concentrations (ln [mg m^{-3} + 0.01]) (left panels) at HIGH and LOW CPUE for the northern (top panels) and southern (bottom panels) fishing regions.

Mantel's test was used to assess spatial correlations between monthly SST and SST frontal gradients with albacore CPUE during four intervals (centred on days 197, 227, 258, and 288). None of the correlations with frontal gradients were statistically significant ($P > 0.05$), although weak positive correlations between CPUE and SST were observed in July (day 197) and September (day 288) and a strong positive relationship explaining 41% of the variation in CPUE data ($r = 0.64$) was estimated for October (Figure 7). There was no statistically significant relationship in August ($P > 0.05$; Figure 7). The weak positive relationships in July and September and the lack of relationship in August may simply be a result of the correspondence between the annual cycle of ocean surface temperature and the annual cycle of tuna availability (both peaking in the summer throughout most of the domain fished by the Canadian albacore tuna fleet). These results point to the importance of other factors not modeled in this project as determinants of CPUE spatial distribution once albacore tuna have arrived on the fishing grounds. The arrival of albacore on the fishing grounds in the spring and their departure in the fall are dependent on SST within a 14-19°C band (e.g., Alverson 1961, Laurs et al. 1984). The strong correlation between CPUE and SST in October is consistent with this seasonal change in the importance of SST.

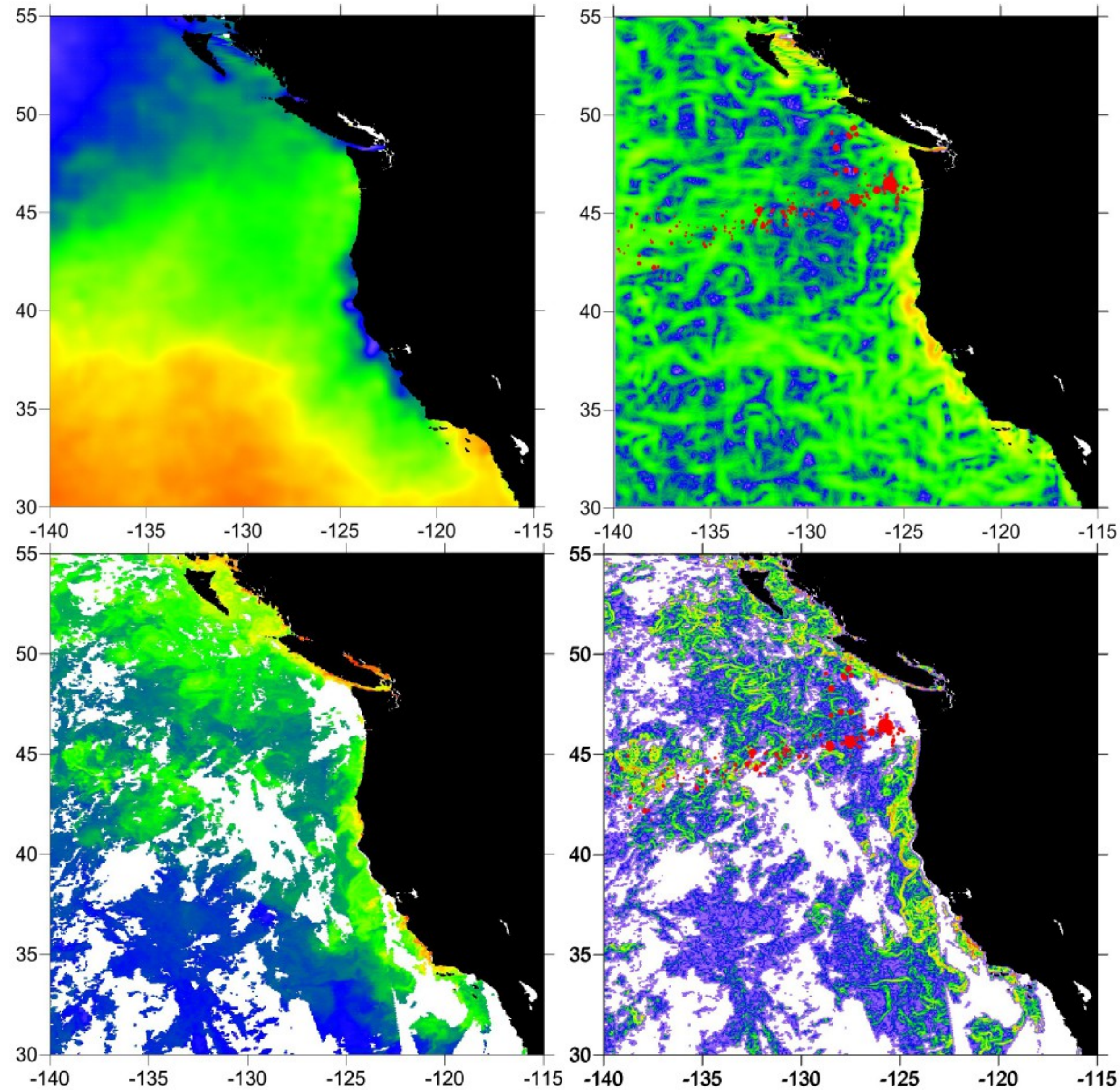

Figure 5: SST (top left) and log-transformed SST gradients (top right) on July 3, 2013. SST ranged from a low of 10.5°C (blue) to a high of 24.5°C (red). Red dots in the SST and chlorophyll gradient plots (right) are scaled to albacore tuna CPUE indicating fishing success on all days during that 8 day period. Chlorophyll concentrations (bottom left) and chlorophyll frontal gradients (bottom right) during an 8 day period centred on July 3, 2013 (day of year 184). Both have log transforms applied to them. White regions indicate missing data or data on the very margins of patches that could not be included in a Sobel filter.

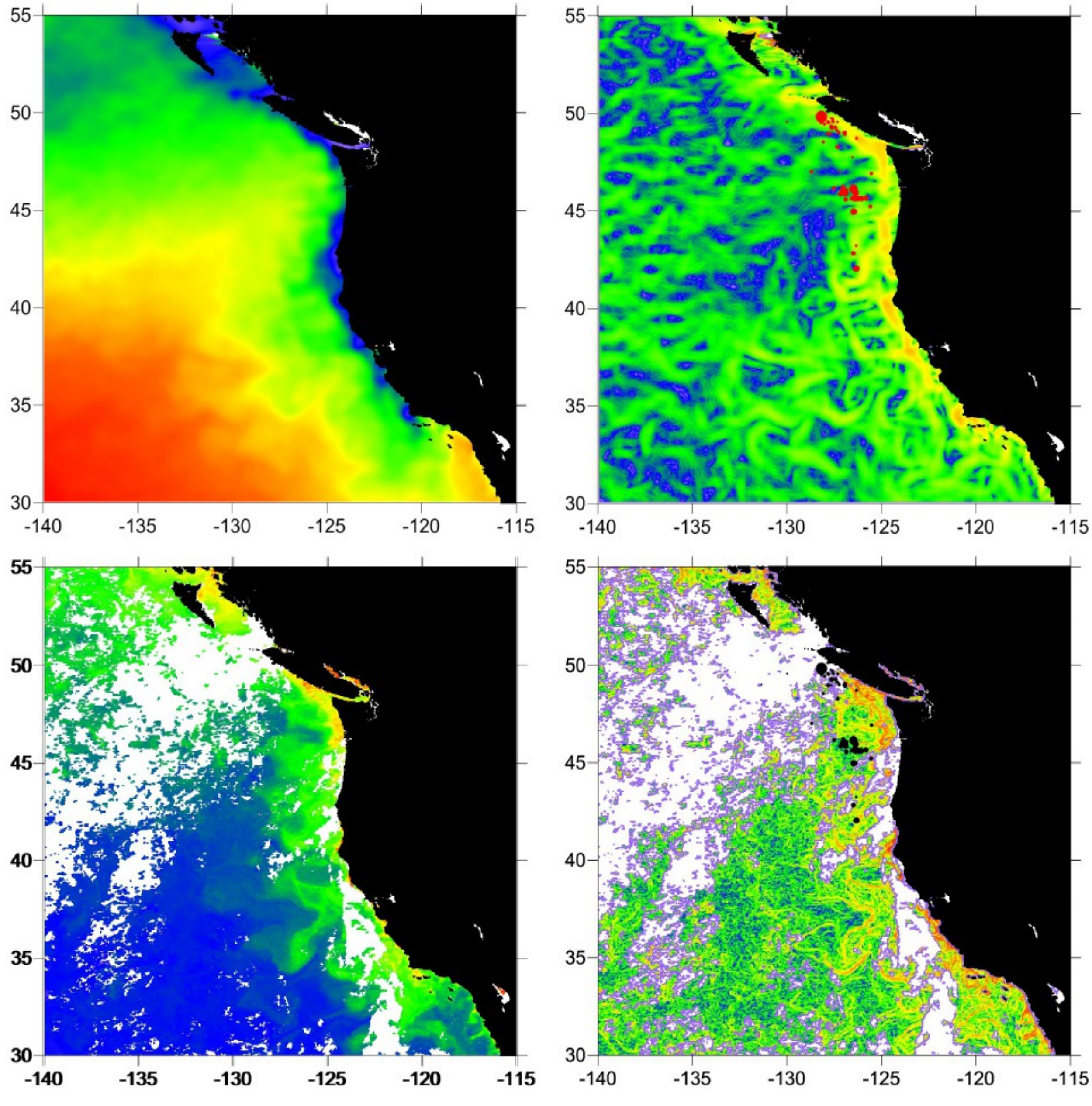

Figure 6: SST (top left) and log-transformed SST gradients (top right) on August 28, 2013 (day of year 240). SST range as in Figure 13. Circular red plot symbols indicate fishing success on albacore tuna (CPUE) on all days during that 8 day period. Chlorophyll concentrations (bottom left) and chlorophyll fronts (bottom right) during an 8 day period centred on August 28, 2013. Both have log transforms applied to them. White regions indicate missing data or data on the margins of patches that could not be included in a Sobel filter. Black dots are the same as red dots in the panel above; the colour was changed for legibility.

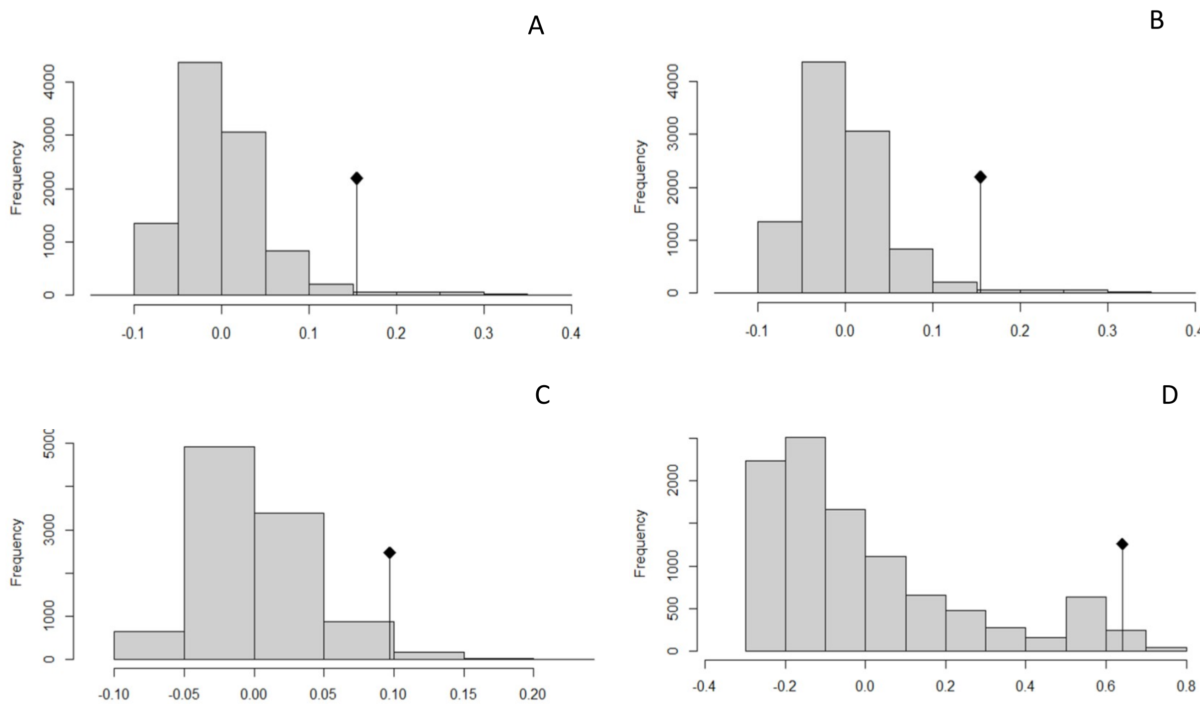

Figure 7: Frequency distributions of the spatial correlations between SST and albacore tuna CPUE in July (A), August (B), September (C), and October (D) of 2013. The black vertical line topped with a diamond symbol is the observed sample correlation while the bars show the distribution of this correlation based on 10,000 permutations of the input matrices. In each month, the observed sample correlation is more extreme than what might be expected from random permutations of the input data.

2.2.5. Is the result ready to transition to operations?

The goal of the project was to investigate whether various North Pacific oceanographic indices had some ability to predict the availability or abundance of juvenile albacore tuna in Canadian waters and develop an operational forecasting tool. At present, the results shown here are not ready for transition to operations because they contain little explanatory or predictive power.

2.2.6. Is the result worth pursuing further? Why?

Yes, the results shown here represent a step in the development of a habitat model for North Pacific albacore and demonstrate that temporal change along with other factors (e.g., proximity to frontal structures, winds, sea surface height) might be important characteristics of juvenile albacore habitat within the normal SST band occupied by these fish. That is, habitat can be broadly characterized based on SST, but the finer-scale details of distribution and abundance within this habitat are based on other physical and possibly biological (e.g., food availability) attributes. For example, juvenile albacore in the California Current system are largely piscivorous and feed on small pelagic fish species such as herring, anchovy, sardine, saury, and young hake and the productivity of some of these species is supported by upwelling. All vessels were pooled for analysis as though the fishing master has no effect on what is caught. Experience likely plays a role in the success of vessels and it would be worthwhile to evaluate whether there are differences in how vessels occupy, or do not, certain oceanographic features and how these decisions influence CPUE. Lastly, examining the proximity of high CPUE to frontal structures within a specific thermal band, especially in the upwelling region along the US west coast would be useful for better defining habitat relationships. The overall goal is to develop a robust habitat model that would permit better tuning of standardize abundance indices used in future stock assessments.

2.3. PACIFIC HAKE (PROJECT 4000)

2.3.1. Project description

The Pacific hake (*Merluccius productus*) is a species of fish that migrates seasonally northward along the North American coast from California to the Gulf of Alaska. It is the object of fisheries in the United States and Canada. The numbers of fish that migrate into Canadian waters, and are available to Canadian fishermen, is variable from year to year according to the general abundance of the stock, its age composition (older fish migrate further north), and environmental factors such as ocean temperature. Warmer years are generally associated with a larger fraction of the stock migrating into Canadian waters than in cooler years. Knowing how the fish will be distributed each year is of interest to the fishermen.

2.3.2. Project investigators

Jessica Nephin and Stéphane Gauthier

2.3.3. What operational question was addressed?

Can temperature and/or chlorophyll *a* concentrations, determined by satellite remote

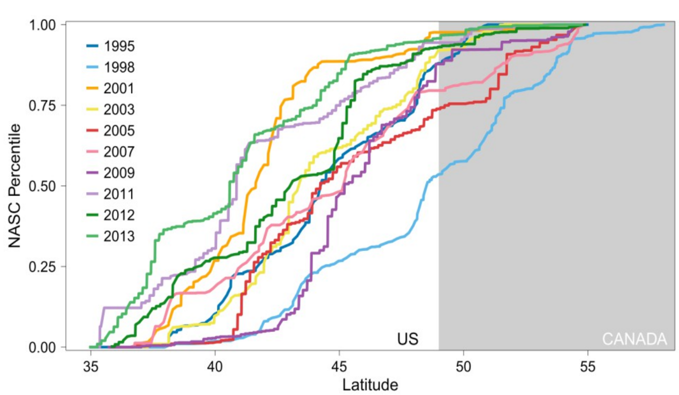

Figure 8: Cumulative percentage distribution of Pacific hake determined as acoustic backscatter from 35° to 58° latitude from acoustic survey years between 1995 and 2013. Shading indicates Canadian territorial waters.

sensing, predict the annual northward extent of Pacific hake migration?

2.3.4. What was the result?

1. On average, 17% of the Pacific hake stock was located within Canadian waters during survey years between 1995 and 2013. Estimates of Pacific hake biomass were obtained using the acoustic scattering signal.The years with the largest fraction of the stock migrating northward into Canadian waters occurred in 1998 (47%) and 2005 (26%) (Figure 8). Although the two years of maximum northward migration coincided with the two years of highest average regional spring sea surface temperature (roughly 1°C higher than the 1995 to 2013 average)(Figure 9), there was no statistically significant relationship between them when all years were considered. However, the correlation between coastal spring sea surface temperature anomalies at 40° latitude (Cape Mendocino, California) and the percentage of hake in Canadian waters was statistically significant (ρ = 0.87, P = 0.003). Thus, spring temperature anomalies near northern California may be an indicator of the extent to which Pacific hake migrate north into Canadian waters.
2. Average spring chlorophyll *a* anomalies were relatively high in 2009 and 2013 along the coast (Figure 10). However, both spring and summer chlorophyll anomalies were highly variable, both spatially and seasonally, making it difficult to detect regional differences among years. Despite this variability there was a statistically significant relationship between summer chlorophyll anomalies off the northwestern coast of Vancouver Island (51°N 129°W) and the percentage of Pacific hake in Canadian waters (ρ = 0.82, P = 0.01, Figure 11). Positive chlorophyll *a* anomalies occurred in that region in 1998, 2005 and 2007, years which tended to have a greater percentage of Pacific hake in Canadian waters.
3. For survey years that occurred between 1995 and 2013 an average of 13% of the stock was located beyond the 1000 m isobath. In 2013, the largest fraction (approx. 33%) of Pacific hake acoustic density was found in waters deeper than 1000 m. There was no indication that surface temperature or chlorophyll *a* concentration were influencing the offshore movement of Pacific hake.

2.3.5. Is the result ready to transition to operations?

Project results will be discussed during the Pacific hake Scientific Review Group (SRG), which meets annually to review the assessment as part of a US-Canada treaty. Indications that Pacific hake move northward in warmer years is a factor already taken into account during the planning of the joint US-Canada Pacific hake acoustic survey.

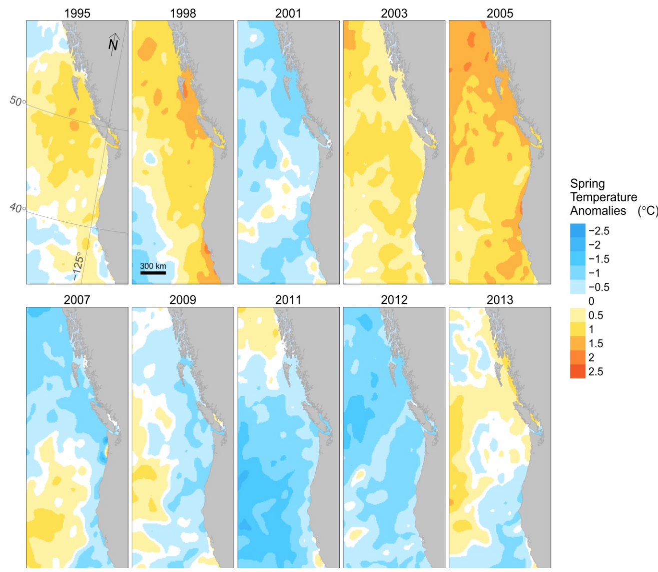

Figure 9: Spatial distribution of April to June average sea surface temperature anomalies (°C, calculated from the 1995 to 2013 mean) during acoustic survey years between 1995 and 2013. Derived from GHRSST data of ¼° resolution.

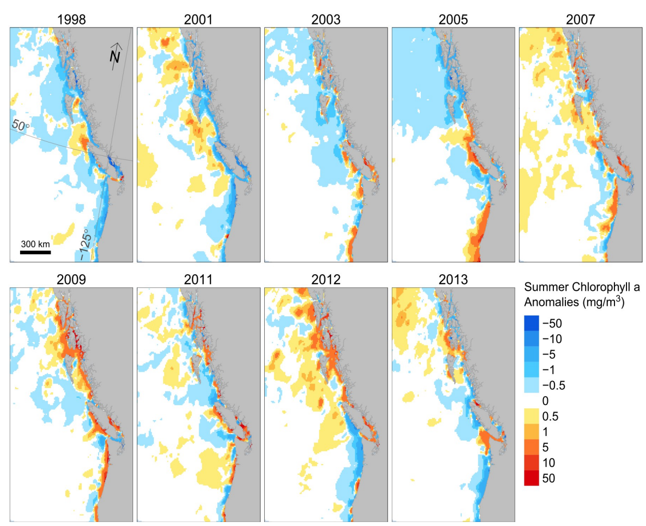

Figure 10: Spatial distribution of average July-September chlorophyll a concentration anomalies (mg m^{-3}) from acoustic survey years between 1998 and 2013. Anomalies calculated from the 1998 to 2013 mean chlorophyll derived from SeaWiFS (1998 - 2002) and MODIS (2003 - 2013) data of ¼° resolution.

2.3.6. Is the result worth pursuing further? Why?

The results strongly suggest that oceanographic conditions influence the extent of the northward migration of Pacific hake into Canadian waters. The satellite derived data likely represent proxies for conditions encountered within the habitat of Pacific hake, which are typically distributed in deeper waters (between 200-400 m). Prey sources and availability for Pacific hake are likely influenced by a number of other factors (currents, upwelling, etc.) and satellite data should be coupled with other sources of information to analyse these trends. In future work, these data should be decomposed as spatially explicit biomass-at-age indices as it is generally understood that larger (older) Pacific hake migrate further north than their smaller (younger) counterparts, and it is therefore expected that year-class strength will confound results on the northward extent of migration.

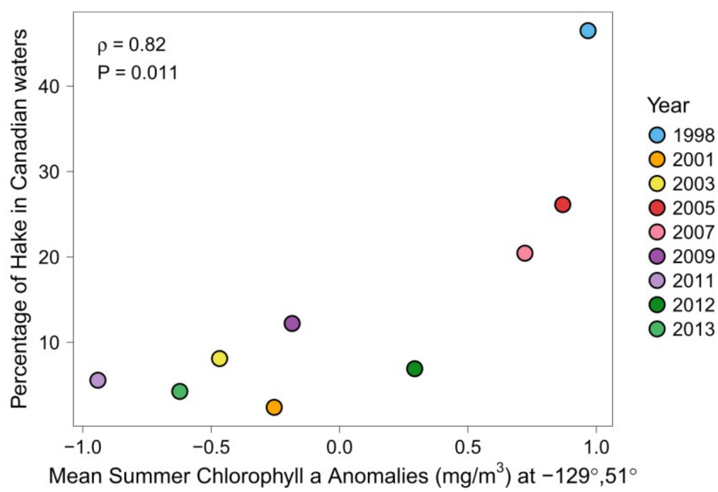

Figure 11: Relationship between spring mean chlorophyll a concentration anomalies (mg m^{-3}) at 129°W longitude and 51° N latitude and the percentage of Pacific hake in Canadian waters (≥ 49°N latitude). ρ represents Spearman's correlation coefficient.

2.4. OCEANIC SALMON HABITAT MAPS (PROJECT 5000)

2.4.1. Project description

The distribution of Pacific salmon includes the entire Subarctic North Pacific from the North Pacific Transition Zone to Bering Strait and even into the Arctic Ocean. They are abundant and valuable and a target for illegal, unreported, and unregulated (IUU) fisheries. Since 1989 when cooperative surveillance of the North Pacific was begun (McKinnell 1989), through 1993 when it became an integral activity of the North Pacific Anadromous Fish Commission (NPAFC), ships and aircraft have been deployed annually to detect and apprehend vessels that are fishing for salmon on the high seas. The NPAFC was established in 1993 with the understanding that there would be no fishing for salmon on the high seas by the Member Nations (Canada, Japan, Korea, Russia, and the United States). Given the magnitude of the surveillance task, the SALOSIS project (**SAL**mon **O**cean **S**urveillance **I**nformation **S**ystem) was established to determine whether salmon habitat could be defined using a combination of satellite remote sensing data and historical knowledge of how salmon are distributed in relation to ocean conditions. The project examined the possibility of developing operational maps of oceanic salmon habitat for use by DFO Conservation and Protection and the Enforcement Committee of the NPAFC in operational planning for monitoring and detecting high seas poaching.

2.4.2. Project investigators

Skip McKinnell, Marc Trudel

2.4.3. What operational question was addressed?

A) How are Pacific salmon distributed in relation to surface and subsurface hydrography?

B) Determining the relative risk of salmon being caught in each NPAFC enforcement region (Figure 12).

C) If the results are useful for Conservation and Protection surveillance planning.

2.4.4. What was the result?

The distribution of Pacific salmon is associated with the major oceanographic features that define the Subarctic North Pacific Ocean and Bering Sea. The region is characterized by a strong seasonal cycle, relatively low salinity in the upper layers, and cooler temperatures with winter sea ice at the northern and western margins. The intent of this study was to examine oceanic properties at and below the surface in the hope of finding an index of where Pacific salmon are found, and where they are not found. Historically, the most readily measured and easily available hydrographic data are sea surface temperatures (SST); a parameter that can also be measured remotely from satellites. Three meridians of longitude (155°E, 175°E, and 145°W) were selected initially for closer inspection because training vessels from Hokkaido University had repeatedly combined gillnet fishing and hydrographic casts along meridional transects between 1988 and 2001 (Figure 13). The southernmost stations along 145°W were not at low enough latitudes to understand where the southern limit occurred. Therefore, study focused on the two meridians in the western North Pacific.

Over the years, gillnet fishing effort along 155°E generally had two peak periods: one in early June and one in late June. Fishing along 175°E occurred in late July. The analysis of Pacific salmon range extremes found that no single oceanographic variable was able to indicate where surveillance was unnecessary. Both latitude and SST (which are highly correlated) were effective in minimizing the latitudinal overlap between gillnet

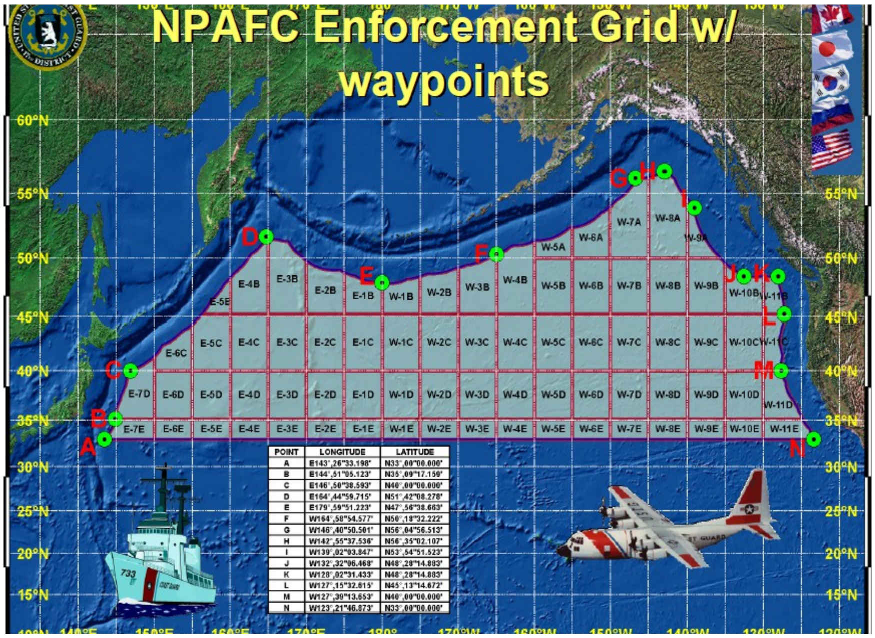

Figure 12: Enforcement zone definitions and waypoint locations used by the NPAFC Enforcement Committee for surveillance activities in the North Pacific.

fishing operations with no catch and those producing catch in the area where (and when) the fish were caught (Figure 14). It does not seem likely that a single criterion can be found that applies to the entire Pacific basin but a full-scale analysis of this was not conducted. Future work should focus on filling data gaps with new sampling, and providing an assessment to develop criteria that provide the maximum benefit of surveillance from the least cost of ship/aircraft operations.

2.4.5. Is the result ready to transition to operations?

Project reports have been submitted to the NPAFC and presented to its Enforcement Committee for the past two years. Interest has been expressed to continue the work. The results, based on the project's retrospective data analysis, are likely to be most useful for surveillance activities in the northwestern North Pacific (~155°E). They are not (yet) generally applicable because the association between salmon and hydrographic parameters varies across the Pacific. In the eastern North Pacific, the distribution of salmon in relation to hydrography is not well known at the southern limits of their distribution.

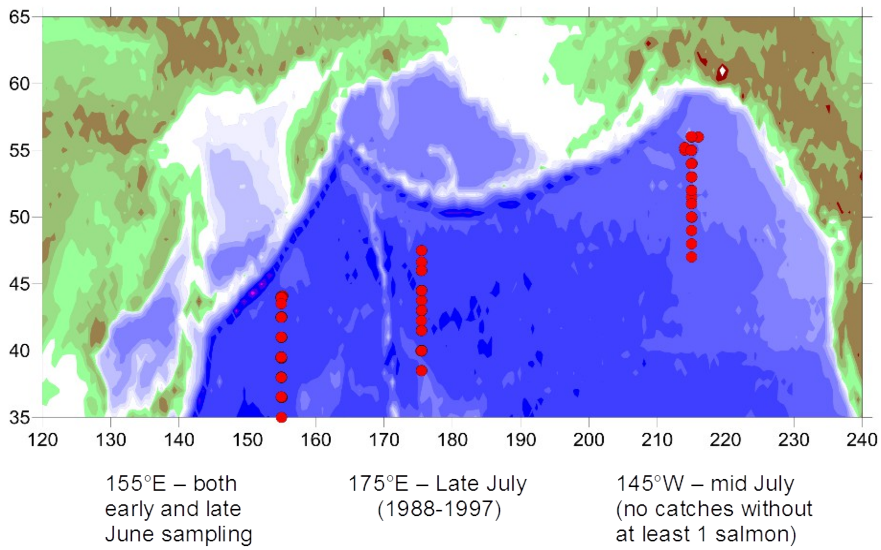

Figure 13: Locations of repeated hydrographic sampling and salmon fishing (Hokkaido University) between 1988 and 2001.

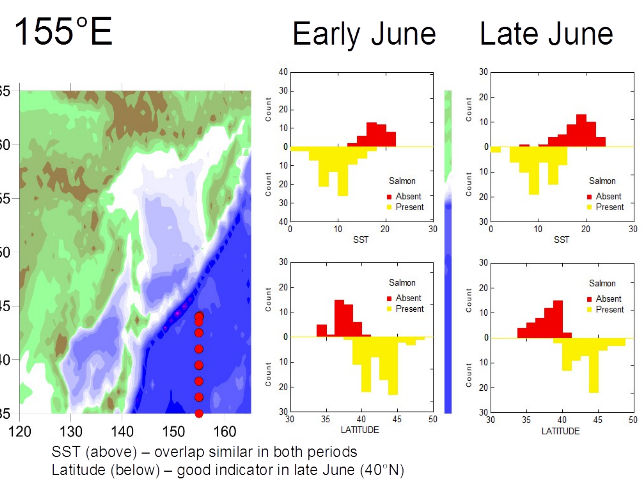

Figure 14: Frequency distributions of SST (upper row) and latitude (lower row) according to whether salmon were caught (yellow) or not caught(orange) in fishing operations at stations along 155°E in early June (left column) and late June (right column).

2.4.6. Is the result worth pursuing further? Why?

An area of future research should consider the relative abundances of salmon at different locations rather than simply seeking out the extremes of their distribution. Range extremes are just that, extremes, rather than everyday occurrences and so are heavily influenced by unusual outliers. If salmon are rarely found at such extremes, the costs to conduct surveillance at the range extremes will be much higher than the benefits derived from it. Optimum strategies would seek to maximize the benefit of surveillance, eg. by conducting surveillance activities in regions where there are high probabilities of catching salmon and higher probabilities of illegal fishing.

Latitude and SST were more useful in determining the likelihood of catching, or not catching, a salmon. Average mixed layer temperature also fared well in the competition. As mixed layer temperature and SST are highly correlated, both should be considered in future analyses, as might ocean colour, or sea surface heights that were not considered here because ocean colour and altimeters were not yet operating during the years of extensive salmon research in the North Pacific. This may be an area to explore further as data from the International Year of the Salmon Program begin to flow.

Much of the North Pacific does not have concomitant hydrographic measurements and salmon fishing that would allow equivalent surveillance criteria throughout the region. It may be possible to extrapolate from one region to another, but it seems relatively clear that a single basin-scale criterion is not possible (Welch et al.,1998). A desirable outcome of an International Year of the Salmon would be to fill some of these data gaps.

A potentially useful addition to the project is the inclusion of seasonal SST forecasts. With a three month lead, for example, an annual SALOSIS analysis would be able to provide forecasts in time for operational planning meetings. Seasonal SST forecasts are being made by some meterological centres (eg. JMA) but are not served by most data centres at present. The DFO/EC/DND CONCEPTS initiative aims to establish an operational global atmosphere-ocean-ice assimilation and modelling system in Canada to produce ocean products that may serve this need.

2.5. SALMON MANAGEMENT (PROJECT 6000)

2.5.1. Project description

The project goals included developing models to predict key life-history characteristics of Canadian Pacific salmon including survival, growth, and migration (routes and timing) and to identify environmental indices derived from satellite remote sensing datasets that have the potential for integration into the DFO Science advisory process to inform salmon marine survival estimates and improve adult returns forecasts. The first steps in this process were the assembly and review of (1) salmon productivity and survival datasets and (2) relevant satellite remote sensing datasets. Initial analyses examined whether changes in the magnitude, distribution, and timing of the spring bloom of marine phytoplankton at specific spatial and temporal scales associated with the location and timing of the early marine phase of juvenile sockeye could be used to explain variability in estimates of marine survival for salmon stocks, including sockeye salmon from Barkley Sound and elsewhere.

2.5.2. Project investigators

James Irvine, Kim Hyatt, Carrie Holt, Lyse Godbout, Howard Stiff

2.5.3. What operational question was addressed?

A) What is the temporal and spatial variability in recruits/spawner (productivity) and smolt survival for Canadian populations of sockeye, pink, and chum salmon?
B) What is the spatial and temporal variability of estimates of sea surface temperature and chlorophyll *a* derived by remote sensing of coastal and open ocean regions of the eastern North Pacific Ocean?
C) Can data on coastal ocean conditions (i.e. surface temperature and chlorophyll *a*) derived from remote sensing be used to predict/understand changes in Pacific salmon productivity (i.e. changes in salmon size, abundance, and survival)?
D) What is the extent of co-variation between marine survival of Barkley Sound sockeye index stocks and satellite-derived indices of sea surface temperature and chlorophyll production from 1998-present and can they improve forecasts of abundance?

2.5.4. What was the result?

Component 1: Sockeye, pink, and chum salmon productivity

The quest for robust relationships between environmental variables and biological parameters of a particular salmon stock is made difficult by the large spatial scales involved in the salmon life cycle, by their transition from fresh water to marine environment and back again, and by the diversity of behaviours exhibited among species. Throughout history, measurement errors in salmon data have tended to be much larger than those associated with physical measurements.

The new database of recruits and spawners (Project 6000) should reduce the errors in the salmon data due to extensive quality control and the identification of outliers in spawner/recruit data caused by anomalies such as landslides which are not related to marine productivity. Time series of recruits/spawner (productivity) for sockeye, pink, and chum salmon were assembled, documented, reviewed and published (Ogden et al. 2015; http://www.dfo-mpo.gc.ca/Library/359366.pdf). Time series of smolt survivals for sockeye salmon populations were updated and reviewed and presented at the 2015 State of Pacific Ocean workshop (Chandler et al. 2015; www.dfo-mpo.gc.ca/Library/358018.pdf).

In addition, an ability to use the ratio of recruits/spawner should improve the likelihood of finding robust relationships as recruits/spawner is thought to be a good index of total survival and thus more closely related to marine productivity and the environmental indices.

Component 2: Chlorophyll and sea surface temperature

Satellite-derived data for chlorophyll and sea-surface temperature were assembled and filtered. Indicators of phytoplankton phenology and biomass within 2° latitude by 5° longitude regions of the NE Pacific that may reflect feeding conditions and potentially marine survival of salmon were developed. Distinct spatial and temporal pattern of chlorophyll *a* with longitude and latitude are evident. Unfortunately, there are large amounts of missing data (~ average 50% and up to 80% in the winter). Algorithms that take into account the spatial and environmental components were successfully developed to fill the missing values of chlorophyll *a*. Additional fine tuning of these algorithms will be performed prior to further testing the linkages between salmon survival and satellite derived products.

Chlorophyll and sea-surface temperature were compared, via correlation maps, to salmon productivity indices derived from 17 Conservation Units of Fraser sockeye salmon, Big Qualicum chum salmon growth patterns, and survivals of Chilko Lake (Fraser system) sockeye salmon smolts. Ongoing research is examining the space and time decorrelation scales of these environmental data, the connection of these to each other and to other indices like the Bakun Upwelling Index.

Component 3: Linkages between salmon productivity and survival indices and satellite derived products

High resolution (weekly x ¼° latitude/longitude) chlorophyll *a* and SST data from satellite imagery for the years 1998-2010 were spatially-filtered to represent the continental shelf from coastal Oregon to Alaska, including the ‘inside’ waters of the Strait of Georgia north to Dixon Entrance. The data were aggregated into five marine domains associated with seven sockeye indicator stocks for which marine survival time-series exist, and temporally-filtered to focus on the four weeks surrounding sockeye salmon smolt ocean entry timing. Within each domain, one annual index of mean SST and three chlorophyll production indices (mean chlorophyll concentration; percent exceedance over the 75^{th} percentile threshold; and spring bloom initiation date) were derived from the filtered satellite data to correlate with annual marine survival.

When classified by cool/warm ocean climate phase, both chlorophyll concentration and exceedance indicators showed a consistent pattern of increased production in cool years relative to warm years across all domains for both PDO and ENSO classifications. For ENSO neutral years, chlorophyll *a* production levels were either intermediate, or more closely approximated production levels in cool ENSO years. In general, the PDO effect was more pronounced for both indicators in all domains. PDO and ENSO effects on spring bloom timing were most pronounced in the ‘California Current’ domains (Columbia and WCVI) – reinforcing PDO/ENSO phases were associated with the widest shifts in the onset of the spring bloom: warm/warm years averaged bloom initiation dates about one month in advance of cool/cool years on the south coast, diminishing to one-to-two weeks in central/north coast areas. Warm/warm years averaged 1.0-1.5°C warmer SST than cool/cool years.

Across British Columbia, stepwise multiple regression models indicated the most significant factors associated with stock-specific marine survival were: SST (Somass, Long, Tatsamenie); spring bloom concentration (Chilko, Tuya); spring bloom timing (Okanagan, Chilko). For all stocks combined, higher survival was associated with cooler temperatures and higher chlorophyll productivity during the ocean entry period.

Evidence suggests that smolt survival for Chilko Lake sockeye salmon varies depending upon the time of smolt entry to the marine environment. A direct link between Chilko sockeye salmon smolt survival and updated coastal condition data has not yet been demonstrated.

2.5.5. Is the result ready to transition to operations?

1. Time series of recruits/spawner and their descriptions are publicly accessible on-line via a government data portal (http://open.canada.ca/data/en/dataset/3d659575-4125-44b4-8d8f-c050d6624758).
2. Some additional data processing is needed before satellite-derived data for chlorophyll and sea-surface temperature data can be released.
3. It may be necessary to use a 4 dimensional coupled model to understand how chlorophyll concentrations in April can, after two months of advection, diffusion, sinking, and consumption by zooplankton, can affect salmon growth and survival.

2.5.6. Is the result worth pursuing further? Why?

Management forecast models that attempt to account for physical oceanic state shifts (e.g., survival-stanza method) tend to out-perform forecast models that exclude ocean climate states, such as the sibling-based or coho-leading indicator forecast methods. Forecast returns using the survival-stanza method have reasonably reflected observed returns for Barkley Sound sockeye stocks (with a few notable departures) since the late 1980s. Further work relating satellite derived chlorophyll and temperature data to additional salmon productivity and survival data sets is warranted (e.g. pink and chum salmon, additional sockeye salmon). Sub-objectives of future analyses may resolve whether chlorophyll data can improve Barkley Sound sockeye salmon forecasting include:

1. refining the spatial and temporal definition of the “Barkley/WCVI” marine domain affecting the stock (e.g., annual smolt ocean entry timing, marine domain residence time, etc.)
2. identifying the key chlorophyll-based index (or indices) as there seems to be little agreement on the most appropriate indicator (e.g., bloom start date, mean concentration, peak concentration, etc) in all situations
3. determine the relationship of “local” chlorophyll indicators to regional factors (SST) and broader oceanic indices (PDO/ENSO combinations, etc.)

The results achieved to date have not provided for a revolutionary change in procedures for forecasting southern sockeye salmon returns. The current practice is based on a two-state, warm-ocean, cold-ocean model that is used to predict shifts from lower to higher marine survival for salmon entering the California Current Upwelling System (i.e.

Columbia River salmon in general, Okanagan and Barkley Sound sockeye specifically). The results suggested that combinations of seasonal variations in SST and chlorophyll concentration (or timing) may be useful in the future as a basis for providing advice that will improve forecasts for a wider range of Canadian sockeye Conservation Units from southern BC to the Alaska-BC transboundary area, but the results are preliminary.

One result that has emerged is that differences in the timing and magnitude of annual chlorophyll “blooms” in different marine production domains (e.g. Georgia Basin versus WCVI) do serve to explain why covariance in survival is relatively weak among sockeye salmon making sea entry within different marine domains (e.g. Barkley Sound versus Strait of Georgia) and stronger among those entering the same marine domain (e.g. Barkley Sound and Columbia River). This modifies conclusions from earlier analyses of (Mueter et al. 2002, 2005) which suggested that covariance would be strongest among nearest neighbour stocks, i.e. this will be true within but not necessarily between marine production domains (e.g. Fraser River and Barkley Sound are closer both with respect to their freshwater locations of origin and their points of marine entry than are Barkley Sound and Columbia River although marine survival covariance between the latter pair is stronger than in the former).

3.0. OVERALL PROJECT SUMMARY

3.1. MAJOR CONCLUSIONS

In light of established protocols used by fisheries management, some of which have international linkages, the adoption of new technologies can occur relatively slowly in the practices of assessing stock abundance and managing fisheries. Nevertheless, a primary goal of the project was to explore new potential applications of satellite remote sensing data in the hope of finding among them a few significant results that would merit an immediate review by the DFO Canadian Science Advisory Secretariat (CSAS) to validate them for operational use in DFO fisheries management.

While the goal of generating CSAS-endorsed results has not yet been achieved by the GRIP-funded projects, some projects were able to identify research opportunities where additional effort will likely to lead to success. One DFO research activity recently achieved the GRIP project objectives by developing a system to forecast salmon migration timing and migration route forecasts using an ocean circulation model and satellite derived data (DFO 2016).

Applications of satellite data to management of albacore tuna and Pacific hake fisheries were unable, at this stage, to develop predictive models, however, the results were a step in the development of a habitat model for albacore tuna. They demonstrated that temporal change along with other factors (e.g., proximity to frontal structures, winds, sea surface height) might be important characteristics of juvenile habitat within the normal SST band occupied by these fish. Habitat can be broadly characterized from

SST, but the finer-scale details of distribution and abundance within this habitat are based on other physical and possibly biological (e.g., food availability) attributes.

Oceanographic conditions are known to influence the extent of the northward migration of Pacific hake into Canadian waters (Ware and McFarlane 1995). Although Pacific hake are typically distributed in deeper waters (between 200-400 m), surface conditions provided by satellite data may be a proxy for factors influencing their distributions at depth. Their prey are likely influenced by a number of other factors so satellite data needs to be coupled with other sources of information to analyze trends.

The current sockeye salmon return forecasts for Barkley Sound stocks include a modification based on a binary characterization of the ocean as being either in a warm or cool state. Results obtained in this project suggest that additional information on SST and chlorophyll may prove useful, however, they do not yet provide justification for modification of the current forecasting approach. In-season forecast lead times could potentially be advanced by up to 6 months using Environment Canada’s newly released operational seasonal forecasts to determine the warm/cold characterization which may assist managers during fishery planning.

An important result is that the covariance of marine survival is stronger between stocks entering the ocean at Barkley Sound and Columbia River than between Barkley Sound and the Fraser River (or the Fraser River and the Columbia River). Since Barkley Sound and the mouth of the Columbia River are in a common marine domain (one that is dominated by ENSO and the PDO) which is distinct from the Strait of Georgia (Williams et al. 2014, McKinnell et al. 2014), there is support for an environmental index approach based on marine regimes that does not require a unique index for each river.

A good example of why DFO needs a satellite oceanography program is the advice to government that was developed by DFO scientists about the expected ecological effects of an intentional discharge of soluble iron into the NE Pacific in 2012. The technology provides a 24 h window on the ocean which allows rapid responses to ad hoc requests for advice. Furthermore, satellite data are very useful for detecting and describing unexpected events such as the sudden North Pacific warming of 2014 and the potential impacts of a winter with weak winds. When combined with shipboard measurements, vertically profiling floats, drifters, and gliders, satellite-based observations provide useful observations that lead to better advice to DFO, if for no other reason than their surveillance and measurement capabilities are so comprehensive.

3.2. OPPORTUNITIES CURRENTLY AVAILABLE

Two applications that could be pursued immediately with investments to develop business cases are:

3.2.1. Operational salmon migration timing forecasts

Satellites capture information from the surface layer of the ocean where salmon are often resident, but there is considerable ecosystem activity occurring below this layer.

Furthermore, the answers to many questions about behaviour require integrating the environment along the course taken by a fish over its life history. Integrating satellite data into three dimensional ocean models is a sensible (but complex) approach to addressing some of these problems. The development of the model to forecast run timing and diversion rate for Fraser River sockeye salmon is an excellent example of this. Its use of a 3-D ocean model is expected to be a pathway to successful routine operational use of satellite data. However, sustained investment is required to support the ocean model, the integration of satellite data, and the processes needed for implementing the biological modules (DFO 2016).

3.2.2. SALOSIS: Salmon Ocean Surveillance Information System (Project 5000)

The results of the salmon habitat mapping project were presented at two international meetings of the North Pacific Anadromous Fish Commission (http://www.npafc.org). There is interest in the application of the results to planning annual surveillance flights among enforcement agencies of the various members of the Commission. What is required is a business case to articulate the expected benefits to international and DFO Conservation and Protection (C&P), to provide justification for the required investment, to provide guidance on how the habitat mapping should proceed to satisfy the operational planning needs of C&P, and to define the primary design considerations for an operational system. A prototype was developed during the project.

4.0. PRODUCTS

4.1. DATABASES

Salmon Productivity Database - http://open.canada.ca/data/en/dataset/3d659575-4125-44b4-8d8f-c050d6624758

4.2. TECHNICAL PAPERS

Hyatt, K. D., Stiff, H.W., and Stockwell, M.M. 2016. *In preparation for* Covariance in spring phytoplankton bloom and marine survival for sockeye index stocks, 1998-2008. Can. Manuscr. Rep. Fish. Aquat. Sci.

McKinnell, S. 2014a. Thermal fronts in the eastern North Pacific in 2013. GRIP Project 3000 report. 16pp.

McKinnell, S. 2014b. Analysis of albacore tuna catches in relation to oceanic water properties observed by satellite remote sensing in 2013. GRIP Project 3000 report. 28pp.

McKinnell, S. 2014c. Chlorophyll phenology in the deeper waters of the NE Pacific. GRIP Project 6000 report. 45pp.

McKinnell, S.M. and Trudel, M. 2014. SALOSIS (Salmon Ocean Surveillance Information System NPAFC Doc. 1524. 22pp. Fisheries and Oceans Canada (Available at http://www.npafc.org).

McKinnell, S.M and Trudel, M. 2015. SALOSIS Project: Associations between hydrographic properties of the North Pacific Ocean and salmon catches on the high seas along 155°E, 175°E, and 145°W from 1988-2001. NPAFC Doc. 1593. 37 pp. (Available at http://www.npafc.org).

Ogden, A.D., Irvine, J.R., English, K.K., Grant, S., Hyatt, K.D., Godbout, L., and Holt, C.A. 2015. Productivity (recruits-per-spawner) data for sockeye, pink, and chum salmon from British Columbia. Can. Tech. Rep. Fish. Aquat. Sci. 3130: vi + 57 p.

4.3. PEER REVIEWED PAPERS SUBMITTED

Akenhead, S.A., Irvine, J.R., Hyatt, K., Johnson, S.C., and Grant, S.C.H. In Review. Less in More: Stock-Recruit Analyses of Fraser River Sockeye Salmon. NPAFC Bulletin 6.

Akenhead, S.A., Irvine, J.R., Hyatt, K., Johnson, S.C., and Grant, S.C.H. In Review. Freshwater Factors and Recruitment Variability: Confounded Effects from Salmon Enhancement at Chilko Lake, British Columbia. NPAFC Bulletin 6.

5.0. REFERENCES

Alverson, D.L. 1961. Ocean temperatures and their relation to albacore tuna (*Thunnus germo*) distribution in waters off the coast of Oregon, Washington, and British Columbia. J. Fish. Res. Bd. Can. 18: 1145-1152.

Batten, S.D. & Crawford, W.R. 2005. The influence of coastal origin eddies on oceanic plankton distributions in the eastern Gulf of Alaska. Deep-Sea Res. II: 52(7): 991-1009.

Batten, S.D. & Gower, J.F. 2014. Did the iron fertilization near Haida Gwaii in 2012 affect the pelagic lower trophic level ecosystem? J. Plankton Res. 36(4): 925-932.

Belkin, I. And O'Reilly, J.E. 2009. An algorithm for oceanic front detection in chlorophyll and SST satellite imagery. J. Mar. Sys. 78: 319-326.

Chandler, P.C., King, S.A., and Perry, R.I. (Eds.). 2015. State of the physical, biological and selected fishery resources of Pacific Canadian marine ecosystems in 2014. Can. Tech. Rep. Fish. Aquat. Sci. 3131: vi + 211 p.

Crawford, W.R. 2002. Physical characteristics of Haida eddies. J. Oceanogr. 58: 703–713.

Crawford, W.R., Brickley, P.J., Peterson, T.D., & Thomas, A.C. (2005). Impact of Haida Eddies on chlorophyll distribution in the Eastern Gulf of Alaska. Deep-Sea Res. II 52(7): 975-989.

Crawford, W.R., Brickley, P.J., & Thomas, A.C. (2007). Mesoscale eddies dominate surface phytoplankton in northern Gulf of Alaska. Prog. Oceanogr. 75(2), 287-303.

DFO. 2016. Run timing and diversion rate models for Fraser River sockeye. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2016/008.

DiLorenzo, E., Combes, V., Keister, J.E., Strub, T.P., Thomas, A.C., Franks, P.J., Parada, C. 2013. Synthesis of Pacific Ocean Climate and Ecosystem Dynamics. Oceanography 26(4): 32.

Freeland, H., & Whitney, F. 2014. Unusual warming in the Gulf of Alaska. PICES Press 22(2): p. 51.

Hyatt, K.D., McQueen, D.J., Shortreed, K.S., and Rankin, D.P. 2004. Sockeye salmon (Oncorhynchus nerka) nursery lake fertilization: Review and summary of results. Environ. Rev. 12:133–162. doi: 10.1139/A04-008

Irvine, J.R. & Crawford, W.R. 2013. State of physical, biological, and selected fishery resources of Pacific Canadian marine ecosystems in 2012. DFO Can. Sci. Advis. Sec. Res. Doc. 2013/032. viii + 140 p.

Laurs, R.M., Fiedler, P.C. and Montgomery, D.R. 1984. Albacore tuna catch distributions relative to environmental features observed from satellites. Deep-Sea Res. I 31: 1085-1099.

Mantua, N.R., Hare, S.R., Zhang, Z., Wallace, J.M., and Francis, R.C., 1997. A Pacific decadal oscillation with impacts on salmon production. Bull. Amer. Meteor. Soc. 78: 1069-1079.

Martin, J.H. and Fitzwater, S.E.1988. Iron deficiency limits phytoplankton growth in the north-east Pacific subarctic. Nature 331B: 341–343.

McKinnell, S. 1989. Canadian aerial observations of the North Pacific driftnet fleet. 6p. (Document submitted to the Annual Meeting of the International North Pacific Fisheries Commission, Seattle, Washington, U.S.A., October, 1989). Department of Fisheries and Oceans, Pacific Biological Station, Nanaimo, B.C., Canada V9R 5K6.

McKinnell, S.M. 2014a. Thermal fronts in the eastern North Pacific in 2013. Contract report to Charles Hannah, Institute of Ocean Sciences, Pat Bay.

McKinnell, S.M. 2014b. Analysis of albacore tuna catches in relation to oceanic water properties observed by satellite remote sensing in 2013. Contract report to Charles Hannah, Institute of Ocean Sciences, Pat Bay.

McKinnell, S. and Seki, M.P. 2016. Arcane epipelagic fishes of the Subtropical North Pacific and factors associated with their distribution. Prog. Oceanogr., In revision.

McKinnell, S.M. and Trudel, M. 2014. SALOSIS (Salmon Ocean Surveillance Information System NPAFC Doc. 1524. 22pp. Fisheries and Oceans Canada (Available at http://www.npafc.org).

McKinnell, S.M and Trudel, M. 2015. SALOSIS Project: Associations between hydrographic properties of the North Pacific Ocean and salmon catches on the high seas along 155°E, 175°E, and 145°W from 1988-2001. NPAFC Doc. 1593. 37 pp. (Available at http://www.npafc.org).

McKinnell, S.M., Curchitser, E., Groot, K., Kaeriyama, M., and Trudel, M. 2014. Oceanic and atmospheric extremes and marine survival of Fraser River sockeye salmon. Fisheries Oceanography 23(4): 322-341, doi: 10.1111/fog.12063.

Mueter, F.J., Peterman, R.M. and Pyper, B.J. 2002. Opposite effects of ocean temperature on survival rates of 120 stocks of Pacific salmon (*Oncorhynchus* spp.) in northern and southern areas. Can. J. Fish. Aquat. Sci. 59: 456–463.

Mueter, F.J., Pyper, B.J., Peterman, R.M. 2005. Relationships between coastal ocean conditions and survival rates of Northeast Pacific salmon at multiple lags. Trans. Am. Fish. Soc. 134:105–119.

Ogden, A.D., Irvine, J.R., English, K.K., Grant, S., Hyatt, K.D., Godbout, L., and Holt, C.A. 2015. Productivity (recruits-per-spawner) data for sockeye, pink, and chum salmon from British Columbia. Can. Tech. Rep. Fish. Aquat. Sci. 3130: vi + 57 p.

Ware, D.M. and G.A. McFarlane. 1995. Climate-induced changes in Pacific hake (*Merluccius productus*) abundance and pelagic community interactions in the Vancouver Island upwelling system. p. 509-521. *In* R.J. Beamish [ed.] Climate change and northern fish populations. Can. Spec. Publ. Fish. Aquat. Sci. 121.

Welch, D.W., Ishida, Y., and Nagasawa, K. 1998. Thermal limits and ocean migration of sockeye salmon (*Oncorhynchus nerka*). Can. J. Fish. Aquat. Sci. 55: 937–948.

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

Williams, J.G. Smith, S.G., Fryer, J.K., Scheuerell, M.D., Muir, W.D., Flagg, T.A., Zabel, R.W., Ferguson, J.W., and Casillas, E. 2014. Influence of ocean and freshwater conditions on Columbia River sockeye salmon *Oncorhynchus nerka* adult return rates. Fisheries Oceanography 23(3): 210-224. DOI: 10.1111/fog.12056.