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Original research article

Identifying potential marine climate change refugia: A case study in Canada's Pacific marine ecosystems



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HIGHLIGHTS

- Combining historical data, climate models, and expert opinion could identify refugia.
- We found limited evidence for potential climate refugia in the northeastern Pacific.
- Certain oceanographic features may be more stable as the climate changes.
- Areas of stability and overlap with features identified by experts may be refugia.

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ABSTRACT

The effects of climate change on marine ecosystems are accelerating. Identifying and protecting areas of the ocean where conditions are most stable may provide another tool for adaptation to climate change. To date, research on potential marine climate refugia has focused on tropical systems, particularly coral reefs. We examined a northeast Pacific temperate region – Canada's Pacific – to identify areas where physical conditions are stable or changing slowly. We analyzed the rate and consistency of change for climatic variables where recent historical data were available for the whole region, which included sea surface temperature, sea surface height, and chlorophyll *a*. We found that some regions have been relatively stable with respect to these variables. In discussions with experts in the oceanography of this region, we identified general characteristics that may limit exposure to climate change. We used climate models for sea surface temperature and sea surface height to assess projected future changes. Climate projections indicate that large or moderate changes will occur throughout virtually the entire area and that small changes will occur in only limited portions of the coast. Combining past and future areas of stability in all three examined variables to identify potential climate refugia indicates that only 0.27% of the study region may be insulated from current and projected future change. A greater proportion of the study region (11%) was stable in two of the three variables. Some of these areas overlap with oceanographic features that are thought to limit climate change exposure. This approach allowed for an assessment of potential climate refugia that could also have applications in other regions and systems, but revealed that there are unlikely to be many areas unaffected by climate change.

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1. Introduction

Despite rapid increases in understanding of climate change effects in the world's oceans, there is limited practical guidance on how to incorporate and address these challenges in spatial planning, management, and conservation strategies (Groves et al., 2012; Watson et al., 2012). Effects of climate change include increasing ocean temperatures, ocean acidification, changing patterns of ocean currents and productivity, sea level rise, and decreasing dissolved oxygen (IPCC, 2013). Conceptual responses to these changes to facilitate ecosystem adaptation include bolstering resilience through reducing non-climate stressors, protecting sufficient space, and fostering connectivity among habitats (Magris et al., 2014). Identifying areas of the ocean where some or all variables affected by climate change are stable or changing the least – which some have called “climate refugia” – may be one way to assist marine conservation efforts and planning in a changing climate.

The concept of climate refugia is not new and is fairly well-established in terrestrial ecosystems (Keppel et al., 2012; Noss, 2001; Taberlet and Cheddadi, 2002), even if its integration and implementation in conservation has been slow (Heller and Zavaleta, 2009). A contemporary definition offered by Keppel et al. (2012) is “habitats that components of biodiversity retreat to, persist in and can potentially expand from under changing environmental conditions”. Its original application was (and often continues to be) in reference to areas where some taxa were able to survive glacial periods (Bennett and Provan, 2008), and more recently, has been used in conservation planning to indicate places that may be less susceptible to expected future climate change impacts, including extreme or anomalous conditions (Barnosky, 2008; West and Salm, 2003). Macrorefugia (also called classical refugia) occur at regional scales, while microrefugia are smaller areas where the microclimate remains suitable within a region where conditions are generally becoming unsuitable (Ashcroft, 2010). In this paper, we will be considering regional-scale (i.e., macro) refugia. Hereafter, we use the term refugia to refer to areas in the ocean with relatively stable (e.g., the middle quintile in a normal distribution, where the mean is the historical average or standardized anomalies) physical and oceanographic properties that can continue to provide a suitable range of physical conditions for species to persist where surrounding or adjacent areas may be changing.

Conservation research to date has primarily focused on identifying marine climate refugia by assuming that historical patterns of change will continue into the future, and have focused on tropical ecosystems, particularly coral reefs (e.g., Ban et al., 2012; Chollett and Mumby, 2013) – but also see Magris et al. (2015) and Van Hooijdonk et al. (2013) for examples of longer-term analyses on coral reefs. For coral reefs, potential refugia from thermal bleaching have been identified from satellite data including sea surface temperature (SST) (Ban et al., 2012; Gove et al., 2013), wave height and period (Gove et al., 2013), chlorophyll *a* (Gove et al., 2013), and irradiance (Gove et al., 2013), and by using outputs from oceanographic models of current speeds and upwelling (Chollett and Mumby, 2013). Outside of coral reefs, there has been some exploration of cold, deep-water refugia for kelp in tropical waters (Graham et al., 2007), and of possible refugia in the Arctic for retained sea ice (Moore and Huntington, 2008). In temperate systems, seamounts have been proposed as potential refugia from acidification for stony corals (Tittensor et al., 2010), but little systematic evaluation of potential refugia exists as yet.

The purpose of the present paper was to use satellite data and model projections to identify potential marine climate refugia at a macro scale, and to evaluate the process and results using expert input. We used the northeast (NE) Pacific Ocean as a temperate case study region, focusing on British Columbia (BC), Canada. Canada's Pacific waters have been identified as a key area of observed climate change and associated ecosystem vulnerabilities (Ban et al., 2010; Jessen and Patton, 2008; Okey et al., 2015, 2014, 2012). For example, NE Pacific Ocean waters are the most acidic in the global ocean (DFO, 2008; Ianson, 2008), and changes in the depth of the oxygen minimum zone and overall oxygen concentrations have been particularly evident (Chan et al., 2008; DFO, 2013; Feely et al., 2008; Koslow et al., 2011; McClatchie et al., 2010; Whitney et al., 2007). Additionally, the high temporal and spatial heterogeneity of the oceanographic transition zone in this region may make the biota generally more responsive to oceanographic changes related to climate change (Okey et al., 2014, 2012).

Our objectives were to (1) analyze retrospective satellite data to identify trends to date, (2) examine and identify future trends from model projections, (3) identify areas of recent and future oceanographic change and stability from the historical analysis and expert input, (4) gather expert knowledge about the physical and oceanographic properties that might constitute potential refugia, and (5) identify whether candidate climate refugia exist for the region.

2. Methods

We identified potential climate refugia using the following steps: First, we identified datasets for the study region of features potentially affected by climate change and with sufficient temporal coverage, and analyzed climate trends to date to identify areas of stability and change (Table 1). We considered a spatial resolution of at least 4 km² to be sufficient because this is fine enough to capture most of the complexity of the coastline and associated differences in oceanographic patterns, although higher resolution data are preferred. Although a temporal resolution of 30 years is ideal to capture decadal trends (Cummins and Masson, 2014), we considered any time series with at least 10 years of uninterrupted data. Second, we identified downscaled climate model projections for some of those variables, and compared trends in the projections to those in recent historical records to assess present and future areas of stability. Third, we elicited feedback from experts on preliminary results and data used. Finally, we also solicited expert input on the physical and oceanographic characteristics in the region that may confer the ability of places to act as refugia and limit climate change exposure, and to identify whether such places exist on the BC coast.

Table 1
Oceanographic variables potentially affected by climate change, and their availability for both historical and projected timeframes and spatial and temporal coverage/resolution. Only data sources relevant to this study area are included, and not all potential data sources are listed. Datasets used in this analysis are bolded.

| Variables | Rationale | Source(s) | Historical | | Future | |
|--|---|---|--|---|------------------------------|------------------------------------|
| | | | At depth | Surface | At depth | Surface |
| Temperature | Affects species ranges, phytoplankton bloom timing, and fisheries productivity | AVHRR (historical) Foreman et al. (2014), Masson and Fine (2012) (future and hindcast) | 1995–2008 3 km ² for model hindcasts | 1985–2012, 4 km ² (satellite) 1995–2008, 3 km ² (model) | 2065–2078, 3 km ² | 2065–2078, 3 km² |
| Chlorophyll <i>a</i> | Indicator of productivity | SeaWIFS (historical) CMIP5 (future) | Spot sampling from ship transect and buoy data | 1997–2010 4 km² | n/a | 1° |
| Sea surface height | Indicator of up- and downwelling | AVISO, JASON 1,2, CCAR Composite (historical) Foreman et al. (2014), Masson and Fine (2012) (future and hindcast) | n/a | AVISO: 1993–2014, 0.12° (approx. 13 km²) JASON: 2002–Present, 6 km ² , CCAR 1986–Present, 0.25° | n/a | 2065–2078, 3 km ² |
| Acidification (pH) or aragonite saturation | Affects calcifying organisms, ranging from zooplankton to habitat-forming species such as coral | World Ocean Atlas (historical) CCSM3 model (Feely et al., 2009) (future) | 1910–2012, 1°–5° averaged, plus spot sampling from ship transect and buoy data | Spot sampling from ship transect and buoy data | n/a | 0.9°–3.6°, 2050 and 2095 |
| Oxygen levels (hypoxic areas) | Few species adapted to low oxygen levels | World Ocean Atlas (historical) Cocco et al. (2013) (future) | 1878–2012, 1°–5° averaged, plus spot sampling from ship transect and buoy data | 1° plus spot sampling from ship transect and buoy data | 1°, 2100 | 1°, 2100 |
| Salinity | Indicator of changes in hydrological cycle | Foreman et al. (2014), Masson and Fine (2012) (future and hindcast) | 1995–2008, 3 km ² | 1995–2008 (model), 3 km ² | 2065–2078, 3 km ² | 2065–2078, 3 km ² |
| Current speed and direction | Affects connectivity | Foreman et al. (2014), Masson and Fine (2012) (future and hindcast) | 1995–2008, 3 km ² | 1995–2008, 3 km ² | 2065–2078, 3 km ² | 2065–2078, 3 km ² |

* Very sparse/limited coverage prior to ~1960.

2.1. Analysis of satellite data to identify climate trends to date

We identified three satellite-derived datasets for NE Pacific: monthly sea surface temperature (SST) from the NOAA Pathfinder satellite (<http://www.nodc.noaa.gov/SatelliteData/pathfinder4km/>), monthly chlorophyll *a* ([chl *a*]) from the SeaWiFS satellite (<http://oceancolor.gsfc.nasa.gov/SeaWiFS/>), and monthly mean sea level anomaly (MSLA) from the AVISO satellite (<http://www.aviso.fr>) (also known as sea surface height, SSH). The temporal coverage of these data varied, from 27 years (1985–2012) for SST, 13 years (1997–2010) for chlorophyll *a*, and 17 years (1993–2014) for SSH. Sea surface temperature is one of the oceanographic characteristics with the clearest link to biotic impacts of climate change, as temperature influences the physiologies, phenologies, and distributions of species (Cheung et al., 2010; Hansen et al., 2006). Chlorophyll *a* is both a direct and indirect measure of biological productivity, although the mechanisms by which climate change influences it remain unclear (Henson et al., 2010). Not to be confused with sea level rise, local sea level anomalies reflect patterns in ocean circulation and can be used as a proxy to identify areas of up- and downwelling (Li and Clarke, 2007; Wilson and Adamec, 2001). Specifically, local SSH maxima indicate convergent flow (downwelling) and minima indicate divergence (upwelling). Areas of upwelling not only tend to be nutrient-rich, but also tend to contain hypoxic and more acidic deep-waters (Feely et al., 2008; Grantham et al., 2004). Climate change may have complex and variable effects on upwelling and downwelling patterns (Bakun, 1990; Doney et al., 2012; Harley et al., 2006; Snyder et al., 2003; Walther et al., 2002). Satellites can measure local variations in sea surface height (SSH) to an accuracy of 1–2 cm; variations in SSH associated with ocean circulation can exceed 1 m (Heck and Rummel, 1990). We tested for correlations between SST and SSH, and found that correlations ranged from negative to positive, and were spatially heterogeneous. Thus, we could be confident that these variables provided complementary information.

For each dataset, we calculated standardized anomalies (deviations from the time series mean) to identify the rate, direction, and consistency of change. This procedure effectively removes the effect of seasonality from the time series. Trend direction and consistency of change was identified using the Mann–Kendall monotonic trend statistic, a non-linear measure. The Mann–Kendall statistic ranges from -1 to $+1$, where -1 is always decreasing and $+1$ is always increasing (Eastman, 2009). We then classified the Mann–Kendall results into equal quintiles to yield five categories of oceanographic change: large decrease, small decrease, largely unchanged, small increase, and large increase. We selected those areas in the middle quintile (largely unchanged) as areas of stability, and then identified areas of overlap across all of the variables to obtain a map of areas of stability. While it would be ideal to account for differing ecological sensitivities to each of these variables, unfortunately this knowledge is not available, and hence we assumed equal contributions. We assessed the average rate of change, with linearity of trends using ordinary least-squares (OLS) regression. These analyses were conducted using the Earth Trends Modeler module in the software package IDRISI (Clark Labs, 2012).

2.2. Climate models

To compare the satellite data against climate model outputs, we obtained the outputs of a Regional Ocean Modeling System (ROMS) model simulation that used forcing from CMIP3, CMIP5 (http://cmip-pcmdi.llnl.gov/cmip5/data_description.html), and the North American Regional Climate Change Assessment Program (NARCCAP; <http://www.narccap.ucar.edu/>) for the waters of BC's continental shelf (Foreman et al., 2014; Morrison et al., 2014). These models contained SST and SSH values for two time periods: contemporary (1995–2008) and future (2065–2078) on a biweekly basis (i.e., 26 time periods per year); further details on these models, including evaluation of their skill, can be found in Masson and Fine (2012). Because the duration of the contemporary and future model runs were relatively short (14 years), to identify areas of relative stability, we subtracted the mean of the contemporary model timeframe from the mean of the future timeframe to obtain mean difference maps for both SST and SSH.

2.3. Comparison of historic and future conditions

We compared the results of the trend analyses from the satellite data to changes in the model data for SST and SSH (models of future chlorophyll *a* were not available). We spatially overlaid the areas with the least amount of change projected from the climate model with areas of least change from satellite data. We defined areas of least change – i.e., potential refugia – as follows. For SSH satellite data, we defined areas of stability as the middle quintile of the Mann–Kendall trend. For satellite data and projected SST, we defined areas of least change as those changing by $< \pm 1$ °C. In temperate regions, thresholds of temperature change that will affect many species are not understood. Thus we used the threshold of 1 °C commonly applied in tropical systems as a threshold for coral bleaching. For future change in SSH, we used an arbitrary threshold of the quintile of least change. To compare potential refugia across datasets with different spatial resolutions, the higher resolution datasets (models) were upsampled to the lowest common resolution (satellite data) by resampling using a nearest neighbor algorithm.

2.4. Expert consultation and input

We held two meetings with experts in February 2015 to obtain feedback on the analysis of satellite data, and to solicit input on the concept of marine climate refugia and what features may aid in their identification. Eleven scientists selected

on the basis of their regional experience and knowledge in physical oceanography, biological oceanography, acidification, species and habitat-specific responses, and ocean climate change were engaged across two meetings. Discussion themes included basic reality checks and data availability, asking, for example, whether the patterns from the analyses (SST, SSH, chl *a*) made sense; whether patterns were missing; whether the approach accounted for decadal-scale variations; and whether any additional data could be used in the region. Discussions around the overall approach included asking what oceanographic features are most relevant to identifying climate refugia; how analyses for areas of stability and change relate to existence of climate refugia; and whether areas of stability are a potential approach to identify climate refugia. Based on the feedback from the meetings, we sought additional sources of data, revised or conducted additional analyses, and incorporated expert knowledge on the local and regional oceanography to identify areas additional areas of change or stability.

3. Results

3.1. Analysis of satellite data

Sea surface temperature trends as measured by satellite from 1985 to 2012 generally showed a warming trend in nearshore and continental shelf areas, with a large cooling-trend patch offshore (Fig. 1a). [Note that the last year of data available at the time of analysis was 2012, before anomalously warm waters (“the Blob”) appeared in the Pacific Ocean (Kintisch, 2015).] The ordinary least squares (OLS) regression trend for the fastest warming areas was $0.97\text{ }^{\circ}\text{C}$ over the entire time series (average of $+0.003\text{ }^{\circ}\text{C}$ per month) and $-0.003\text{ }^{\circ}\text{C}$ per month in the fastest-cooling areas (Fig. 1b).

Trend analysis of mean sea level anomalies from 1993 to 2014 showed an area of generally increasing sea surface heights south of the 47th parallel, with neutral to decreasing sea surface heights north of that latitude (Fig. 2a). The average monthly change over the time period varied from a maximum increase of $1.0 \times 10^{-3}\text{ mm}$ to a maximum decrease of $6.0 \times 10^{-4}\text{ mm}$, yielding a total maximum increase of 0.264 mm and a total maximum decrease of 0.158 mm (Fig. 2b). Generally, decreases in sea surface heights are associated with increases in upwelling, and increases are associated with downwelling.

Chlorophyll *a* showed an increasing trend – indicating increasing productivity – in many nearshore and continental slope waters, as well as further offshore in lower latitudes (Fig. 3a). The magnitude of the changes was small, with a maximum average monthly increase of 0.009 mg m^{-3} and a maximum average monthly decrease of 0.008 mg m^{-3} , for a total maximum increase of 1.51 mg m^{-3} and a total maximum decrease of 1.34 mg m^{-3} (Fig. 3b).

Overlap across areas of least change (least change quintile, Mann–Kendall trend, for SSH and chl *a*; $<\pm 1\text{ }^{\circ}\text{C}$ for SST) for all satellite variables yielded a map of overlap of areas of stability (Fig. 4a). The largest areas were those that either contained neutral (i.e., least change) pixels for two out of three variables (34% of the study area), or those which contained neutral pixels in only one variable (30% of the study area). Areas containing three neutral pixels (28%) tended to occur either on or just offshore of the continental shelf break. Areas with zero neutral pixels tended to occur further offshore.

3.2. Climate models

Model outputs were confined to a smaller area than for satellite data; this area roughly corresponds to the exclusive economic zone (EEZ) of Canada’s Pacific waters, though it does extend south adjacent to Washington and Oregon and also slightly to the north into Southeast Alaskan waters. Cross-comparisons between satellite data and model outputs were thus based on the area of overlap between these datasets. Model projections for SST show that areas off the mid- and central coast of British Columbia are likely to see the greatest amount of warming, with minimal warming in the Strait of Georgia (Fig. 1c). Model projections for SSH generally show decreases offshore, with areas of increased relative SSH occurring in the far north and south of the study region, with other isolated spots potentially reflecting the changes in eddy formation and persistence (Fig. 2c).

Combining areas of minimal ($<\pm 1\text{ }^{\circ}\text{C}$) SST change with the lowest quintile of future SSH change, most of the offshore waters contained no areas of stability by our criteria (Fig. 4b). Inshore waters – particularly in the southern Strait of Georgia – generally contained areas where either one or two variables showed some stability. Areas where SSH remained stable existed along the shelf break as well as further offshore.

3.3. Correspondence between contemporary and future areas of stability

In total, 31% of the study area contained stable areas for SST and SSH in the contemporary period only; 9% contained stable areas for one variable in both the contemporary and future period; 10% of the area contained stable areas for both variables in the contemporary period and one variable in the future period; and 0.27% of the study area contained overlapping stable areas for both variables in both time periods (Fig. 4c). Offshore areas tended to lack areas of stability in one or both periods, except for offshore of the west coast of Vancouver Island and Washington State.

3.4. Expert input

3.4.1. Sense-checking and data availability

Feedback from experts indicated that the spatial patterns emerging from the contemporary analyses were consistent with known oceanographic phenomena such as eddies and upwelling areas (e.g., the Juan de Fuca eddy and upwelling off

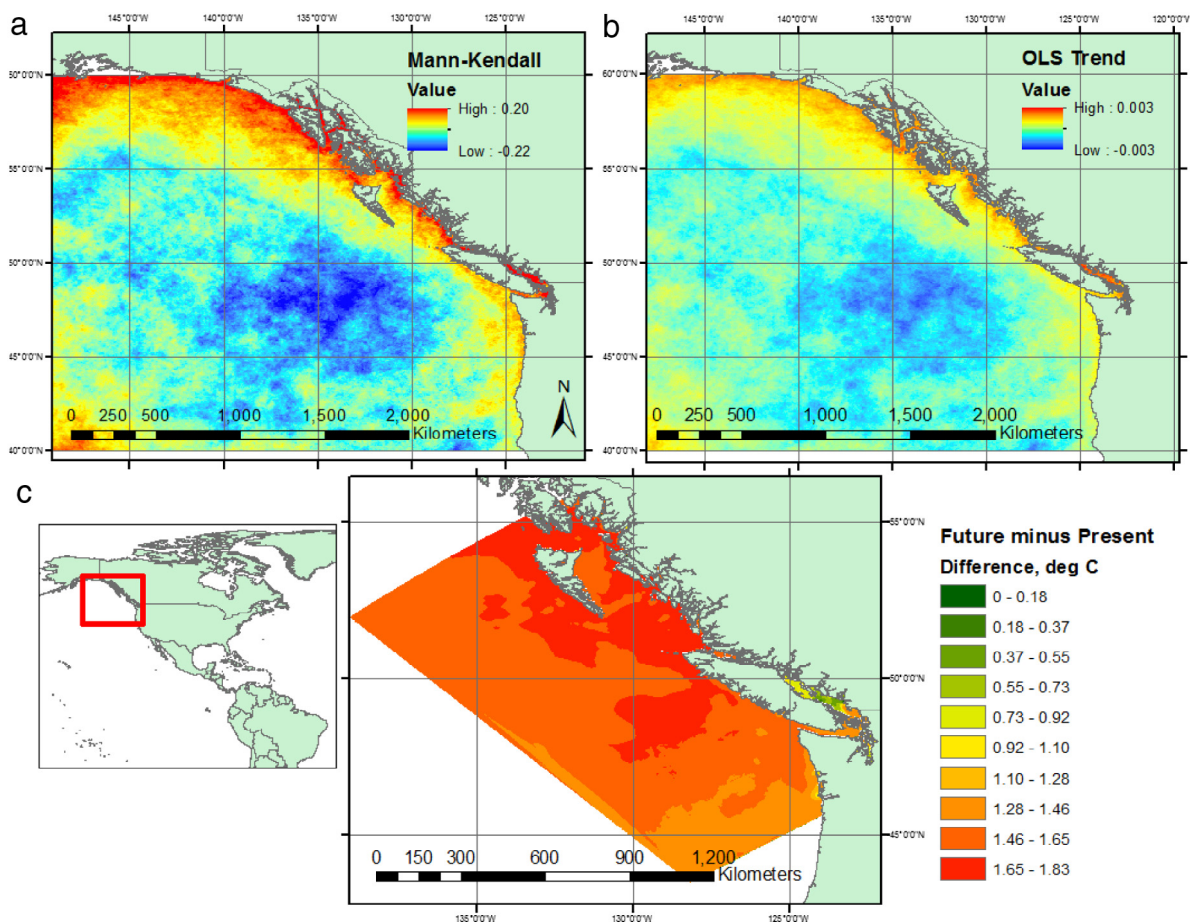


Fig. 1. Sea surface temperature (a) Mann-Kendall trend statistic for satellite SST, 1985–2012, calculated on a 4 km grid in the northern Northeast Pacific. Warm colors show areas with an increasing trend; cool colors show areas with a decreasing trend. Values for this statistic can range from -1 to $+1$, where -1 is always decreasing and $+1$ is always increasing. (b) Ordinary-least-squares trend for SST, indicating average rate of change of temperature (degrees Celsius per month). Warmer colors indicate areas of warming; cooler colors indicate areas of cooling. (c) Difference in modeled sea surface temperatures between future (2065–2078) and contemporary (1995–2008) runs; spatial resolution for models is 0.01° . Historical data generally show a warming trend in nearshore and continental shelf areas, with a large cooling-trend patch offshore, while model projections show that areas off the mid- and central coasts are likely to see the greatest amount of warming. For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.

the west coast of Vancouver Island) (Fig. 5). The main limitation of the analyses noted by experts was the limited data available at a regional scale. In particular, satellite data capture surface phenomena, and thus miss changes in the water column and at depth. Ideally measurements at-depth, oxygen concentration profiles, and aragonite saturation state or pH to track ocean acidification could be incorporated into the analyses, and with higher spatial resolution than satellite data provide, particularly in inshore areas. We followed the experts' suggestion to test the PDO/MEI correlations with time lags, thus verifying that a zero-lag correlation provided the best fit between these indices and the variables measured.

3.4.2. Oceanographic characteristics that exhibit stability or that may limit climate change exposure

In addition to reviewing the contemporary spatial analysis, we also sought input from the experts on the physical and oceanographic characteristics in Canada's Pacific waters that might limit exposure to observed and anticipated climate changes. The experts identified five such oceanographic characteristics relevant to the BC Coast, which we mapped from available data sources or proxies (Fig. 5), and then superimposed on the areas of stability (Fig. 6):

Areas of strong tidal forcing and mixing: In areas where tides exert a dominant influence, tidal forcing and mixing will continue in spite of climate change. Such areas may be expected to continue to support productivity regimes and associated processes that mix water and nutrients. For example, the formation of the Juan de Fuca eddy is primarily driven by tidal mixing and by freshwater input and estuarine outflows (affecting nearshore salinity and turbidity) (Foreman et al., 2008) and secondarily by upwelling winds (MacFadyen and Hickey, 2010; Peña, 2009). This mixing enhances nutrient availability and productivity (MacFadyen et al., 2008; Peña, 2009), likely ensuring some stability in biological productivity over time. Other areas of high

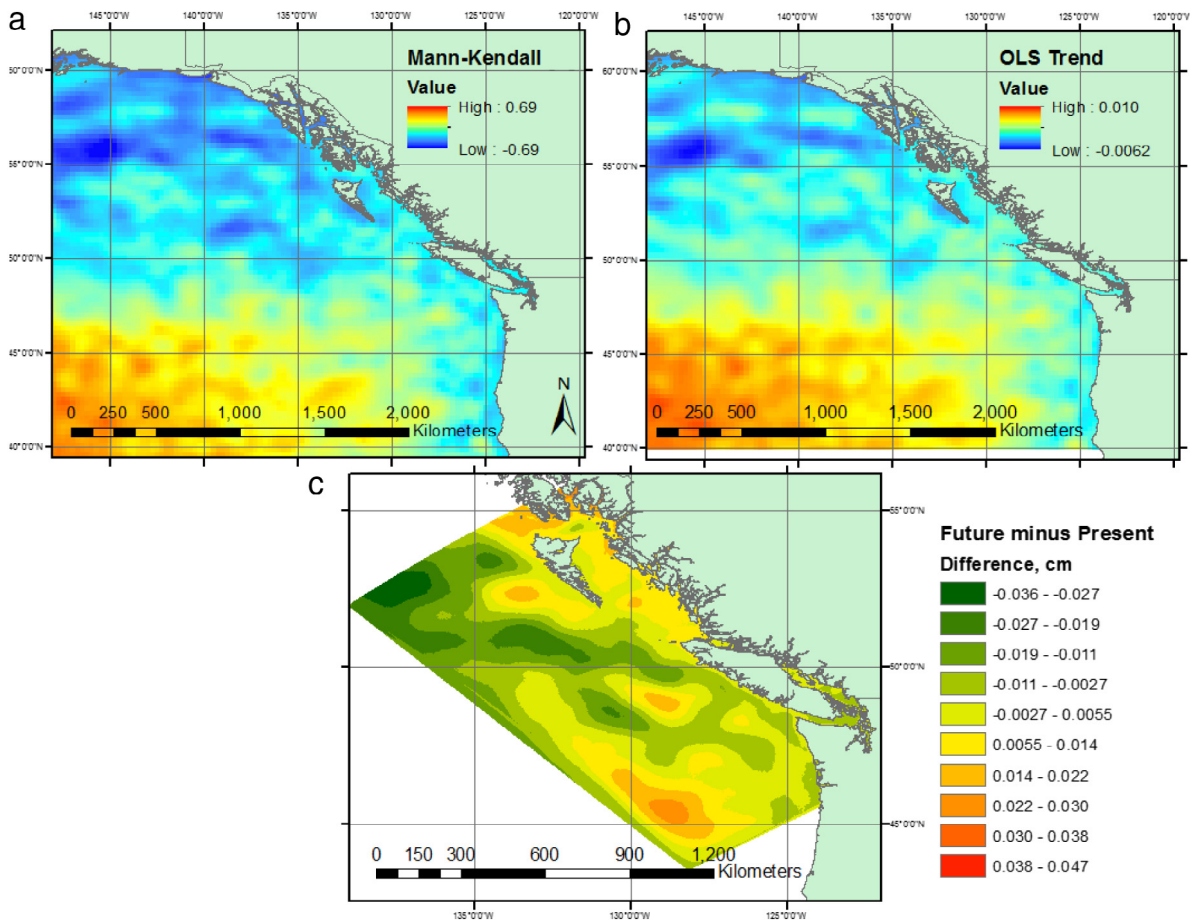


Fig. 2. Sea surface height (a) Mann–Kendall trend statistic of satellite MSLA, 1993–2014, calculated on a 4 km grid in the northern Northeast Pacific. Values for this statistic can range from -1 to $+1$, where -1 is always decreasing and $+1$ is always increasing. Warm colors show areas of increasing (higher) sea level anomalies; cool colors show areas of decreasing (lower) sea level anomalies. (b) Ordinary-least-squares trend of MSLA, indicating average rate of change; warmer colors show areas of increase, cooler colors show areas of decrease. (c) Difference in modeled sea surface height anomalies between future (2065–2078) and contemporary (1995–2008) runs; spatial resolution for models is 0.01° . These data show an area of generally increasing sea surface heights south of the 47th parallel, with neutral to decreasing sea surface heights north of that latitude. Model projections generally show decreases in SSH offshore, with areas of increased SSH occurring in the far north and south of the study region, with other isolated spots potentially reflecting the changes in eddy formation and persistence. For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.

tidal mixing include Johnstone Strait, giving rise to productivity in waters that move out of the Strait off the northern part of Vancouver Island, likely aided by freshwater inflows. Similarly, inlets with sills that have tidal mixing (Gargett et al., 2003; Griffin and LeBlond, 1990; Klymak and Gregg, 2004; Stigebrandt and Aure, 1989) might be less exposed to anoxic or hypoxic deep or offshore waters than other areas. We delineated areas of high tidal mixing using a tidal energy model of the Northeast Pacific (Foreman et al., 2006) depicting areas where tidal velocity was ≥ 0.35 m/s.

Marine areas influenced by freshwater discharges with high oxygen levels: Low oxygen areas primarily resulting from upwelled oxygen-depleted waters are common and problematic in Canada's Pacific waters (Whitney et al., 2007). Waters with higher-oxygen content from freshwater influence can counter the effects of oxygen depleted waters and provide some resilience. In addition, tidal mixing helps redistribute and oxygenate waters, countering impacts of anoxic upwelled water. The Strait of Georgia is one example; its freshwater discharges and tidal mixing (LeBlond et al., 1991; Masson, 2002; Waldichuk, 1957) makes it less vulnerable to warming and deoxygenated waters than other regions. Strong tidal mixing in Haro Strait limits the potential of upwelled shelf water moving into Georgia Strait to reduce oxygen concentrations in its deep waters (Johannessen et al., 2014). Hecate Strait is also subject to the influence of freshwater from mainland inlets, where downwelling of this water in autumn and winter may offset the influence of stagnant deeper deoxygenated water (Crawford and Thomson, 1991). We used mapped freshwater discharge plumes (Murray et al., 2015) and major riverine inflows on the BC coast (a streamorder ≥ 6). However, climate change is also likely to affect the hydrological cycle of British Columbia (Leith and Whitfield, 1998; Loukas et al., 2002; Merritt et al., 2006; Pike et al., 2008), which may manifest in changes in rainfall patterns, increased storm

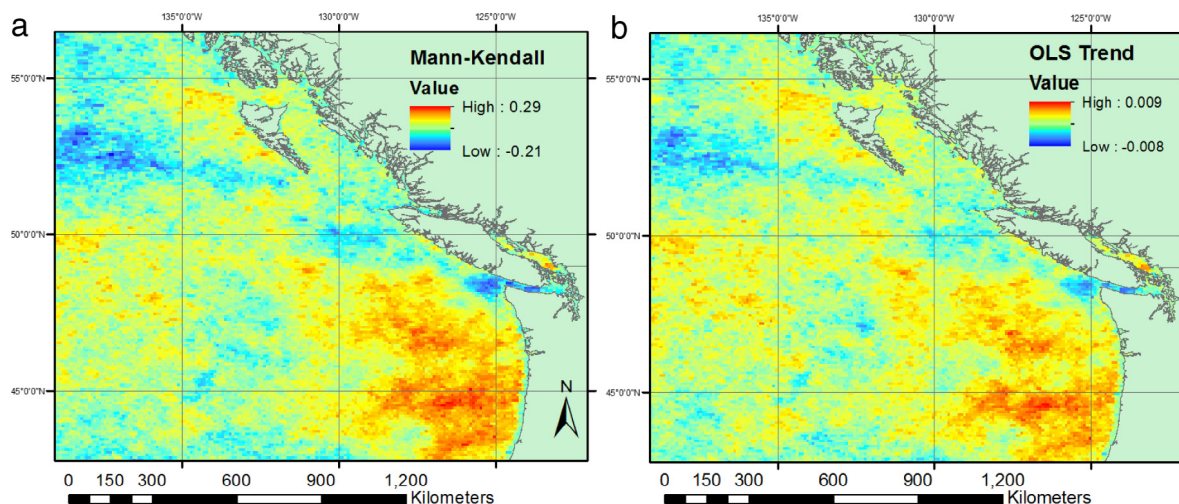


Fig. 3. Chlorophyll *a* (a) Mann–Kendall trend of chlorophyll *a* concentration, 1997–2010, calculated on a 4 km grid in the northern Northeast Pacific. Values for this statistic can range from -1 to $+1$, where -1 is always decreasing and $+1$ is always increasing. (b) Ordinary Least Squares trend, indicating average rate of change over the entire time period. Warm colors indicate an increasing trend; cool colors indicate a decreasing trend. Note that no modeled chlorophyll data were available, thus there is no comparison with future trends. These data show an increasing trend – indicating increasing productivity – in many nearshore and continental slope waters, as well as further offshore in lower latitudes. For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.

events, and altered timing and magnitude of streamflow, all of which will affect nearshore salinity, turbidity, and alkalinity. Except in high-latitude oceans, the effects of freshwater runoff on local ocean acidification are likely to be negligible (Denman et al., 2011). However, the extent to which there may be synergistic or threshold effects from the cumulative effect of all of these changes, and how they may interact with oceanographic features and processes is largely uncertain.

Seamounts: Seamounts may serve as areas of oceanographic stability. Shallower seamounts in particular have circulation patterns (Taylor columns) that tend to retain organisms on and near the seamount (Boehlert and Genin, 1987; Dower et al., 1992). Some also suggested that seamounts could provide refugia from acidification for deepwater corals (Tittensor et al., 2010). Bowie Seamount is one such example in Canada's Pacific waters. We delineated the 3 shallowest seamounts in or immediately adjacent to Canadian waters: Bowie (summit depth ~ -24 m), Cobb (-34 m) and Union Seamount (-293 m).

Underwater Banks: Underwater banks have circulation processes that create retention areas (Boehlert and Mundy, 1993; Ladd et al., 2005; Rooper and Boldt, 2005), and that circulation pattern – driven by bathymetry – is unlikely to change. Two examples are found in Hecate Strait – Moresby and Goose Island Banks – which were delineated with available bathymetric data.

Protective currents: Coastal (buoyancy) currents form a barrier that prevents (or reduces) upwelled waters from penetrating close to shore. For example, the buoyancy current along the Vancouver Island Shelf (Crawford and Thomson, 1991; Foreman and Thomson, 1997; Hickey et al., 1991; Thomson et al., 1989) blocks the acidic and low oxygen waters from affecting flora and fauna on the inner Vancouver Island Shelf. The portion of the Vancouver Island Shelf protected by the buoyancy current was approximated and delineated from the shelf break using available bathymetric data.

While there was general agreement that the above five oceanographic characteristics are worthy of further investigation, other characteristics were more complex. Upwelling areas provide cooler, nutrient-rich waters from deep to shallow waters, generally a benefit to productivity. However, Canada's Pacific deeper waters have some of the most acidic and oxygen-depleted waters globally. Thus, while upwelling areas might provide important nutrients, when coupled with global acidification, these oxygen-depleted acidic waters might breach a tipping point for many marine organisms. Eddies were also discussed. Eddies will continue to form even if climate changes, and they provide elevated primary productivity compared to surrounding waters. However, eddies are transient, mobile, and have a limited lifespan, so are not geographically stable as potential refugia for species with limited mobility.

Experts also cautioned against over-interpreting trends calculated from time series that are not necessarily long enough to represent true “ocean climates” (~ 30 years in length). There is little doubt that regional sea surface temperatures have shown a long-term increase (Cummins and Masson, 2014), but at present, there is no means of comparing historic and projected future trends over extended timeframes in a spatially comprehensive manner. Some suggested that the notion of refugia should be species-specific, with the pertinent question being “refugia for what?”. Habitat requirements of species differ, and therefore species-specific potential refugia need to consider oceanographic characteristics in addition to less ephemeral characteristics, such as substrate type, depth and community composition, and the ability of species to reproduce

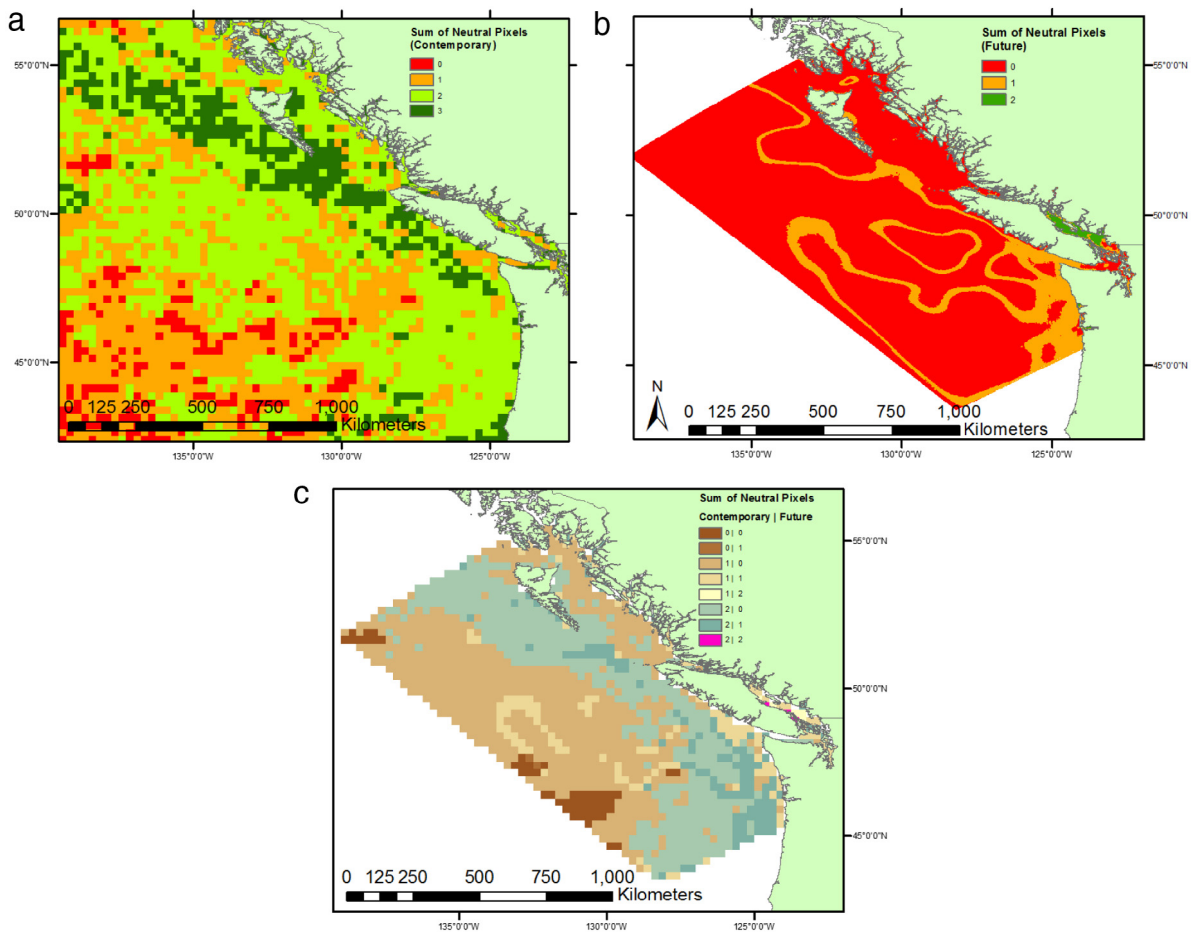


Fig. 4. Analysis of areas of stability (a) Sum of neutral (neither positive nor negative trending) pixels across the contemporary variables of SST, SSH, and chlorophyll *a*. Areas in red did not contain any neutral pixels; areas in dark green contained neutral pixels in all 3 variables. (b) Sum of potential future areas of stability (sum of projected SST and SSH pixels exhibiting little or no change), 2065–2078. (c) Comparison of contemporary SST (1985–2012) and SSH (1993–2014) areas of stability with model projections of potential areas of stability (2065–2078). Areas of stability for both SSH and SST in both time periods are noted in pink. Note that values near the very edge of the study area should be interpreted with caution due to the effects of the artificial boundary. The largest areas contain neutral pixels for two out of three variables followed by those with neutral pixels in only one variable. Areas containing three neutral pixels tend to occur near the continental shelf break. Areas with zero neutral pixels tended to occur further offshore. For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.

and disperse within and between suitable habitats. Some experts suggested that the idea of refugia is more relevant to less mobile species than mobile ones, as they will be unable (or have limited ability) to move to more suitable habitats. However, detailed information on species distributions, habitat preferences, and physiological tolerances (e.g., to temperatures, acidic waters) is generally not compiled for species in Canada's Pacific waters.

Some overlap exists between the areas of stability identified using past and modeled future climate conditions, and expert identified features. The limited overlap is not surprising, as experts were drawing on additional variables and different types of information than we used in the spatial analysis. For example, features identified by experts as potentially offering some attributes of resilience under climate change include areas at depth, for which we did not have data and therefore were not included in our spatial analysis.

4. Discussion

In this paper, we implement an approach for identifying potential marine refugia from the effects of climate change as derived from satellite imagery and as projected with climate models. We complemented these analytical efforts with input from regional experts who reviewed our preliminary findings and methodologies. Three aspects of this work distinguish it from previous work to date on marine climate refugia. First is the application of this concept to a temperate region. Because fewer studies exist about climate-related thresholds in temperate marine ecosystems, our criteria for refugia are intended as

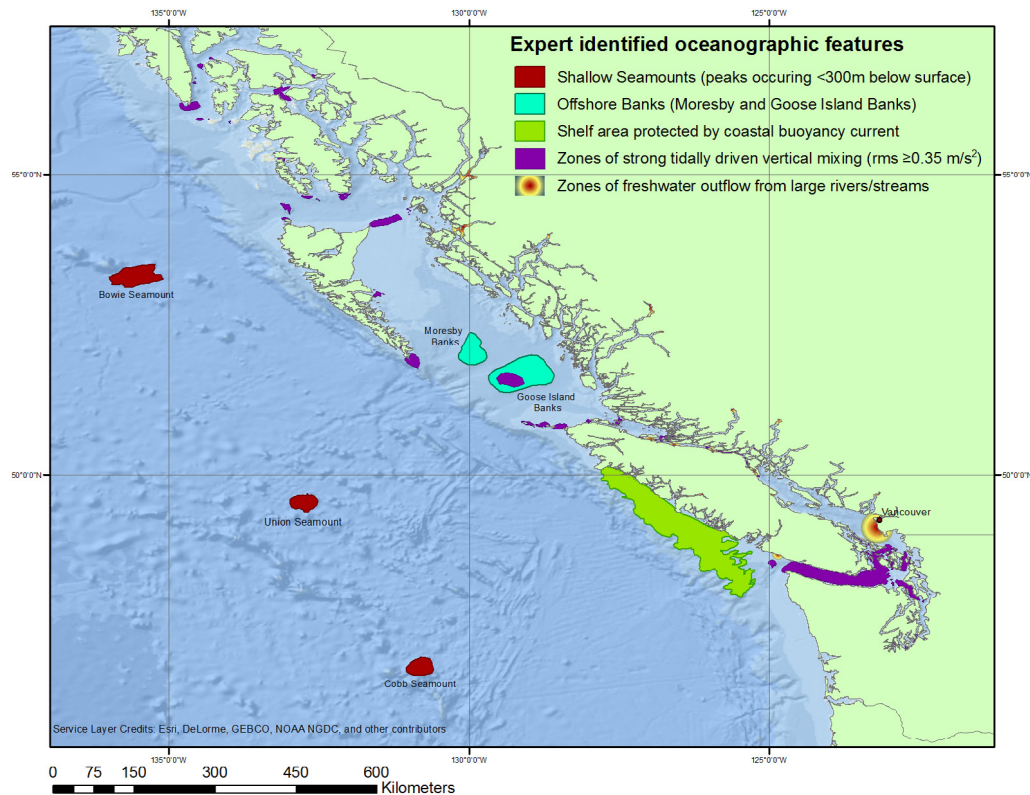


Fig. 5. Significant oceanographic features of the Canadian Pacific coast that were identified at expert meetings. Seamounts may serve as areas of oceanographic stability and could provide refugia from acidification for deepwater corals. Underwater banks have circulation processes that create retention areas. Coastal (buoyancy) currents form a barrier that prevents upwelled waters from penetrating close to shore. Areas of strong tidal forcing and mixing may be expected to continue to support productivity regimes and associated processes that mix water and nutrients. Waters with freshwater influence can counter the effects of oxygen depleted waters and helps redistribute and oxygenate waters, countering impacts of anoxic upwelled water.

a basis for discussion rather than serving as definitive thresholds. Second and third, discussed below, our study used expert input in conjunction with empirical data, and compared contemporary changes with anticipated future changes from climate models, which has not been done in a temperate context.

Comparing model projections of future conditions to changes already seen, we found little absolute overlap in areas of stability between the contemporary (present) and the future where variables were stable. If one defines potential climate refugia as areas of stability in all variables in contemporary and future time periods, then only 0.27% of the region qualifies. If areas that are changing in one variable during one time period are also included, then 11% might be worthy of consideration as potential refugia. Our research extends investigations of marine climate refugia in temperate systems, as most work to date that has attempted to identify climate refugia has focused on retrospective analyses without projecting future conditions (e.g. Ban et al., 2012; Chollett and Mumby, 2013; Graham et al., 2007; West and Salm, 2003), and those that have used projections of future conditions have been focused on tropical systems (e.g. Chollett et al., 2012; Magris et al., 2015). Using both contemporary and future change, the potential duration and permanency of climate refugia in the marine realm – as identified by other studies to date – may be minimal in our study region, and remain an open question for other regions.

Definitions and analyses of marine refugia are in early stages, especially in temperate regions, and hence our research contains many limitations and is meant as a basis for discussing and refining the concept. A major limitation of our analysis was the lack of evidence for specific thresholds that may characterize refugia. For SSH and chlorophyll *a*, we used the quintile of least change as our definition of refugia, and for SST we borrowed the 1 °C threshold from tropical systems (Hughes et al., 2003). Our intention in taking a best guess approach at thresholds was to generate discussion about potential refugia, and spur additional studies. Clearly further research is needed in temperate systems to identify such thresholds, if they exist.

If our preliminary thresholds are accepted, our spatial analysis of potential climate refugia likely overestimates their prevalence in some aspects and underestimates it in others. First, we did not have data for many important variables affected by climate change in the region (see Table 1, e.g., acidification, oxygen-limited areas; Feely et al., 2008; Koslow et al., 2011; Okey et al., 2014; Whitney et al., 2007). Unfortunately such data do not yet exist at a regional scale. Data are also not at a suitable resolution to identify changes in the timing of spring, as indicated by either changes in SST, changes in upwelling, or changes in wind patterns. Thus we likely overestimate the existence of climate refugia.

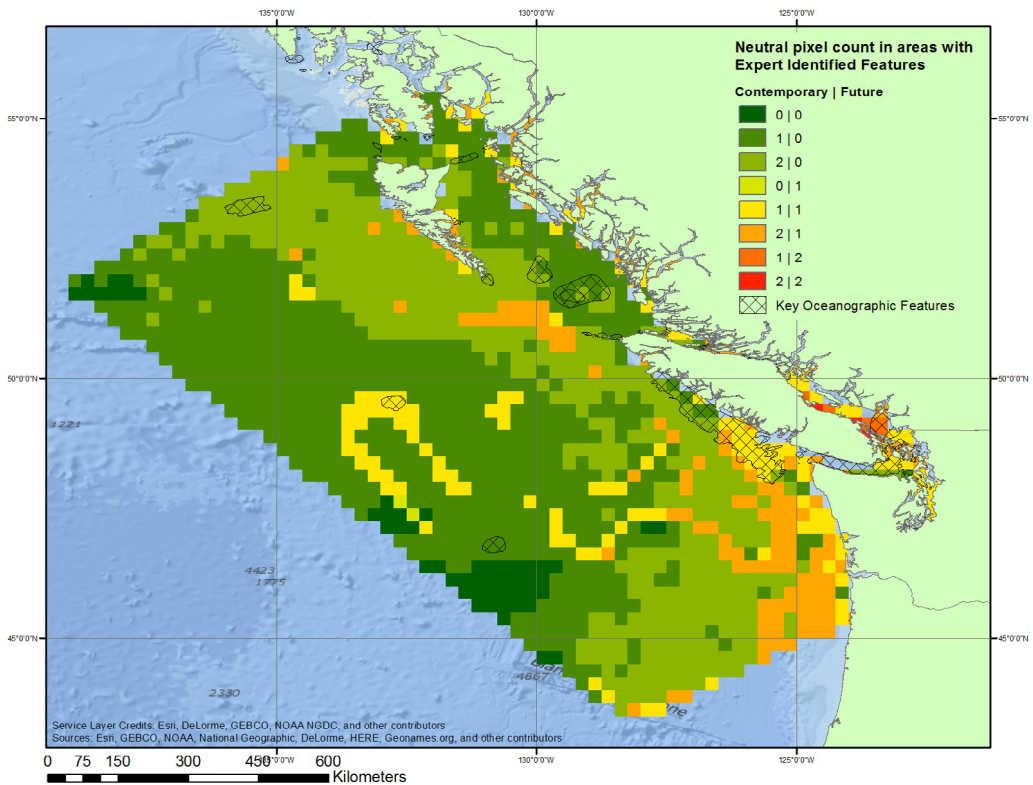


Fig. 6. Overlap of areas of contemporary and future areas of stability for SST and SSH with expert identified features from Fig. 5. Some features identified by experts include areas at depth, which were not captured by the satellite or model data.

Second, the limited length of historical data for characterizing change to date precluded determination of definitive refugia. As regional experts pointed out, satellite records to date are generally too short to detect a trend against the background of natural variability, where 30 years is usually considered the minimum. For example, analysis of SST measurements from lighthouses that go back as far as the 1930s show overall warming trends across a number of these stations that correspond to an average rate of warming of 0.9°C per century, but natural variability means that the probability of a cooling trend occurring over any given 30-year period is as high as 28% (Cummins and Masson, 2014). Extending the time scale of contemporary model outputs (i.e. hindcasts) could partially fill some of these gaps, and a further 5–10 years of satellite data collection will allow for more robust analysis of climatological trends. Furthermore, SST data used in our analysis pre-date the appearance of the pool of warm water in the NE Pacific Ocean (Kintisch, 2015).

Third, available datasets are also lacking in other ways, such as in temporal and spatial coverage, or providing at-depth measurements (Table 1). The algorithms for some data (such as SST and chlorophyll *a*) tend to be less reliable in inshore areas, especially where inlets and fjords may be narrower than the spatial resolution of a sensor (Nababan, 2010). This limitation could be at least partially addressed with the use of oceanographic models with more finely-resolved at-depth forecasts (and hindcasts), perhaps cross-validated against long-term local oceanographic data profiles. The availability and analysis of fine spatial scale data would allow for the identification of microrefugia which would not be captured by the data we used. The climate model did not include projections for chlorophyll *a*; although changes in productivity are clearly relevant to species, we could not compare satellite data to climate projections. Thus it is questionable as to how much of the minimal area of potential climate refugia can indeed be considered refugia. While we found little overlap in contemporary and future areas of stability, the approach is applicable for other regions of the world where identification of potential climate refugia might be of interest.

We found using expert knowledge of regional oceanographic characteristics a useful way to identify oceanographic characteristics that might confer some buffering potential to climate change for variables where quantitative data are absent or insufficient. Other studies investigating climate change have also used expert elicitation to fill data gaps (e.g. Ban et al., 2014; Morgan et al., 2001). By combining quantitative data analysis with expert knowledge of local oceanographic conditions – an approach that does not appear to have been documented in the literature as yet – we were also able to identify some oceanographic features (such as areas of high tidal mixing and underwater banks) that are worthy of further examination for their potential buffering effects.

The concept of refugia that we have investigated here is general, using oceanographic variables, and is not species-specific. Ideally, habitat envelope models would be constructed using some or all of these parameters (e.g., [Cheung et al., 2009](#)), but also taking into account other species-specific habitat requirements such as substrate type, community composition, and distributions of prey or forage species ([Cheung et al., 2015, 2013](#)). Biotic components are likely to move with abiotic components – perhaps in unexpected ways ([Harley et al., 2006](#); [Scott et al., 2012](#)). Implications will differ for sessile, motile, and migratory species, and it may not be possible to identify refugia that would maintain every component of extant communities in their present form. Thus, each species or species assemblage may have a different distribution of potential refugia based on both specific resistance/resilience characteristics and the resistance/resilience of the ecosystem as a whole to change. The concept of refugia may have a different definition (or may not exist at all) for species that are adapted to (or reliant on) constantly changing conditions, and opportunistic, colonizing, and invasive species may be able to take advantage of environmental shifts due to climate change, which may result in changes in ecological community structure. If some areas are good refugia for some species, but not for others, major shifts may occur as species re-shuffle and are mismatched, separating co-evolved species and combining species that are less acquainted ([Harley et al., 2006](#)).

The general paucity of detected oceanographic refugia, and the recognition that many species are likely to change their distributions or patterns of movement in response to changes in oceanographic conditions leads us to question whether a search for spatial refugia is the most useful approach. Indeed the approach ascribes a high value to stasis, and assumes that equilibrium is a useful goal, in an environment that we know will be non-stationary into the future. Indeed, such refugia are likely to benefit only sessile species and those of limited mobility (e.g., bivalves, sea cucumber, rockfishes). However, a useful question might relate to the extent of community re-shuffling, mismatches, and thus tipping points in the functional integrity of affected biological communities, and the resulting spatial distributions of these community shifts. Although such questions might be more important in light of our results, they are much more difficult to approach, requiring more progress in the integration of whole biological community modeling with physical projections ([Ainsworth et al., 2011](#); [Cheung et al., 2015](#); [Hollowed et al., 2013](#)).

Climate refugia on their own are unlikely to be a panacea for marine ecosystems, at least in the NE Pacific, and other conservation planning strategies should be pursued concurrently with other adaptation actions to reduce the effects of non-climate factors that affect stability and change, such as pollution and habitat degradation. In our study region, well-designed networks of marine protected areas that are representative of species and habitat types, well-connected, and of sufficient size and level of protection, coupled with ecosystem-based fisheries management in areas outside of protected areas, is a standard and achievable avenue forward. Representation of species and habitat types can include current distributions and future projections to ensure connectivity through time ([Levy and Ban, 2013](#); [Makino et al., 2014](#)). In other regions, identifying potential climate refugia is worth pursuing as part of a suite of conservation planning tools, as their identification could aid conservation planning, especially if climate refugia emerge more clearly in those examples than in this preliminary analysis in Canada's Pacific. Even if refugia are not found to be present or prevalent generally, datasets used to analyze refugia may be used in systematic conservation planning efforts that link current and future distributions of oceanographic features, habitat, and species distributions ([Levy and Ban, 2013](#); [Magris et al., 2014](#); [Makino et al., 2014](#)).

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