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Twenty years of satellite observations describing phytoplankton blooms in seas adjacent to Gwaii Haanas National Park Reserve, Canada

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Abstract. Visible satellite imagery is used to estimate the variability of chlorophyll concentration and "brightness" events in surface waters within and adjacent to the proposed National Marine Conservation Area associated with the Gwaii Haanas National Park Reserve and Haida Heritage Site in northern British Columbia, Canada. We examine ocean colour imagery from the coastal zone colour scanner (CZCS; 1979–1985) and sea-viewing wide field-of-view sensor (SeaWiFS; 1998–2000) and visible imagery from the advanced very high resolution radiometer (AVHRR; 1982–2000) to document variability in these parameters because few ship-based observations of phytoplankton exist for this region. The AVHRR imagery indicates that large bright surface patches occur in most summers on the east coast but not the west coast of the Gwaii Haanas National Marine Conservation Area (GHNMCA). The bright patches originate from three main sources: Dogfish Bank to the north, Queen Charlotte Sound to the south, and within the GHNMCA. The ocean colour data reveal large potential interannual variations in satellite-derived chlorophyll for three regions in the GHNMCA and indicate that the Hecate region typically has the highest estimated chlorophyll. Seasonally, all three regions show a bimodal pattern in chlorophyll concentrations, with a spring peak in April–May and a second peak in August–September. At present, few field samples exist to verify the phytoplankton species or seasonal trends in chlorophyll identified by satellite sensors.

Résumé. Les images satellitaires dans le visible ont été utilisées pour évaluer la variabilité de la concentration de chlorophylle et les événements de « brillance » dans les eaux de surface à l'intérieur et à proximité de la Zone de conservation marine nationale associée à la Réserve de parc national et Site patrimonial Haïda de Gwaii Haanas dans le nord de la Colombie-Britannique, Canada. Nous examinons les images de la couleur de l'océan acquises par le capteur CZCS (« coastal zone colour scanner »; 1979–1985), le capteur SeaWiFS (« sea-viewing wide field-of-view sensor »; 1998–2000) et des images dans le visible du capteur AVHRR (« advanced very high resolution radiometer »; 1982–2000) pour documenter la variabilité de ces paramètres étant donné qu'il existe peu d'observations de phytoplancton acquises par navire dans cette région. Les images AVHRR indiquent que des plaques importantes de surface brillante se manifestent la plupart des étés sur la côte est mais pas sur la côte ouest de la région de la GHNMCA. Les plaques brillantes proviennent de trois sources principales : la zone de Dogfish Bank au nord, le détroit de la Reine Charlotte au sud et de l'intérieur de la zone de la GHNMCA. Les données de couleur de l'océan révèlent des variations potentielles inter-annuelles importantes dans la chlorophylle dérivée des données satellitaires pour trois régions de la GHNMCA et indiquent que la région de Hecate présente la plus haute concentration estimée de chlorophylle. De façon saisonnière, les trois régions montrent un patron bimodal dans la concentration de chlorophylle avec un pic printanier en avril–mai et un second pic durant la période août/septembre. À l'heure actuelle, il existe peu d'échantillons acquis sur le terrain pour vérifier les variétés de phytoplancton ou les tendances saisonnières de la chlorophylle identifiées à l'aide des capteurs satellitaires.
[Traduit par la Rédaction]

Introduction

The Gwaii Haanas National Park Reserve (GHNPR) and Haida Heritage Site comprise the southern one third of the Queen Charlotte Islands off the northern mainland coast of British Columbia, Canada (**Figure 1**). The GHNPR incorporates approximately 1470 km^2 of protected land (to the high-tide line) that was secured in 1988 through a federal–provincial government cooperative called the South Moresby Agreement. A commitment for the designation of sea space extending about 10 km offshore and encompassing 3500 km^2 of ocean with 1700 km of shoreline was also made in the South Morseby Agreement but, as of early 2003, is not yet established under Parks Canada National Marine Conservation Area (NMCA) legislation. Under Parks Canada policy, NMCAs will be managed and used in a sustainable manner that meets the needs of present and future generations, without compromising the structure and function of the ecosystems including the submerged lands and water column with which they are associated. Clearly a major challenge faced by Parks Canada is

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understanding the natural variability in the structure and function of nearshore marine ecosystems and understanding how the impacts of marine-based activities (e.g., fishing), and land-based activities (e.g., logging) are nested within this natural background variability.

Field-based information regarding the spatial and temporal variability at the base of marine food webs, such as phytoplankton, is virtually nonexistent for this region. In this study, ocean colour imagery was used to develop a basic understanding of the seasonal and interannual variability in phytoplankton population properties (e.g., chlorophyll). Satellites provide a regional synoptic view of the spatial and temporal variability in phytoplankton populations because they view large spatial areas (e.g., >1000 by 1000 km) that can be sampled repeatedly over relatively short time intervals (e.g., days) at relatively high spatial resolution (e.g., 1 km^2). In this study we begin to address the lack of basic information about phytoplankton populations by assembling and analyzing chlorophyll and water-leaving radiance (sea-viewing wide field-of-view sensor (SeaWiFS) and coastal zone colour scanner (CZCS)) and reflectance (advanced very high resolution radiometer (AVHRR)) images for oceanic regions that encompass waters of the proposed Gwaii Haanas National Marine Conservation Area (GHNMCA) and for seas adjacent to its boundaries.

Study area

The proposed boundaries of the GHNMCA encompass about 3500 km^2 of sea space around the southern Queen Charlotte Islands, British Columbia, Canada (**Figure 1**). This study considers a greater region extending to northern Hecate Strait, Queen Charlotte Sound, and adjacent areas of the North Pacific Ocean. This larger spatial domain was selected because it is covered by AVHRR and SeaWiFS imagery received at the Institute of Ocean Sciences, Sidney, British Columbia, and because seas within the proposed GHNMCA are oceanographically connected to surrounding regions (Crawford, 1996). Seas within and adjacent to the proposed GHNMCA boundaries can be divided into three general regions on the basis of dominant oceanographic processes. During the May–September summer period, seas along the west coast of the GHNMCA ("Gowgaia") are primarily influenced by upwelling of cool, nutrient-rich waters along the continental slope and narrow continental shelf (<5 km wide). Seas at the southern end of the GHNMCA ("Kunghit") are influenced by regions of major tidal mixing (M_2 currents at Cape St. James reach speeds of 60 $cm \cdot s^{-1}$). The seas to the east of the GHNMCA ("Hecate") are shallow (<100 m) and influenced by oceanographic events occurring in Hecate Strait and Queen Charlotte Sound. **Figure 2** shows the typical surface thermal structure for the three oceanic regions during summer. In this paper we present

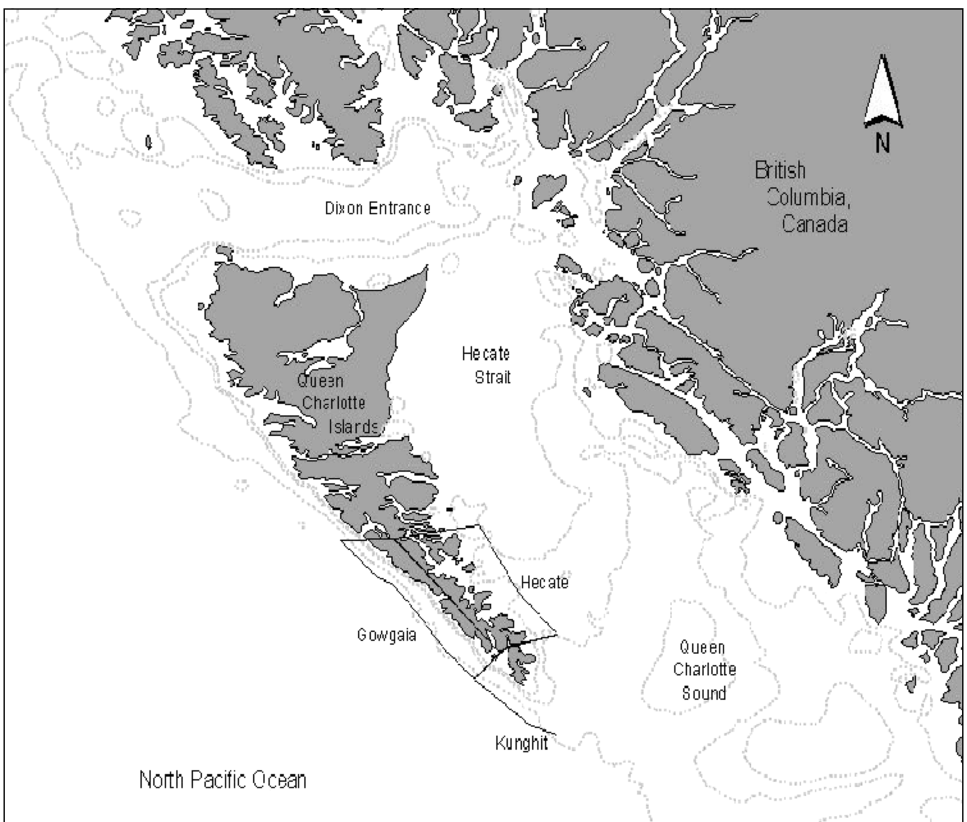

Figure 1. General location and boundaries of the proposed Gwaii Haanas National Marine Conservation Area (GHNMCA) in northern British Columbia, Canada. Also shown are the three oceanographic regions Hecate, Kunghit, and Gowgaia.

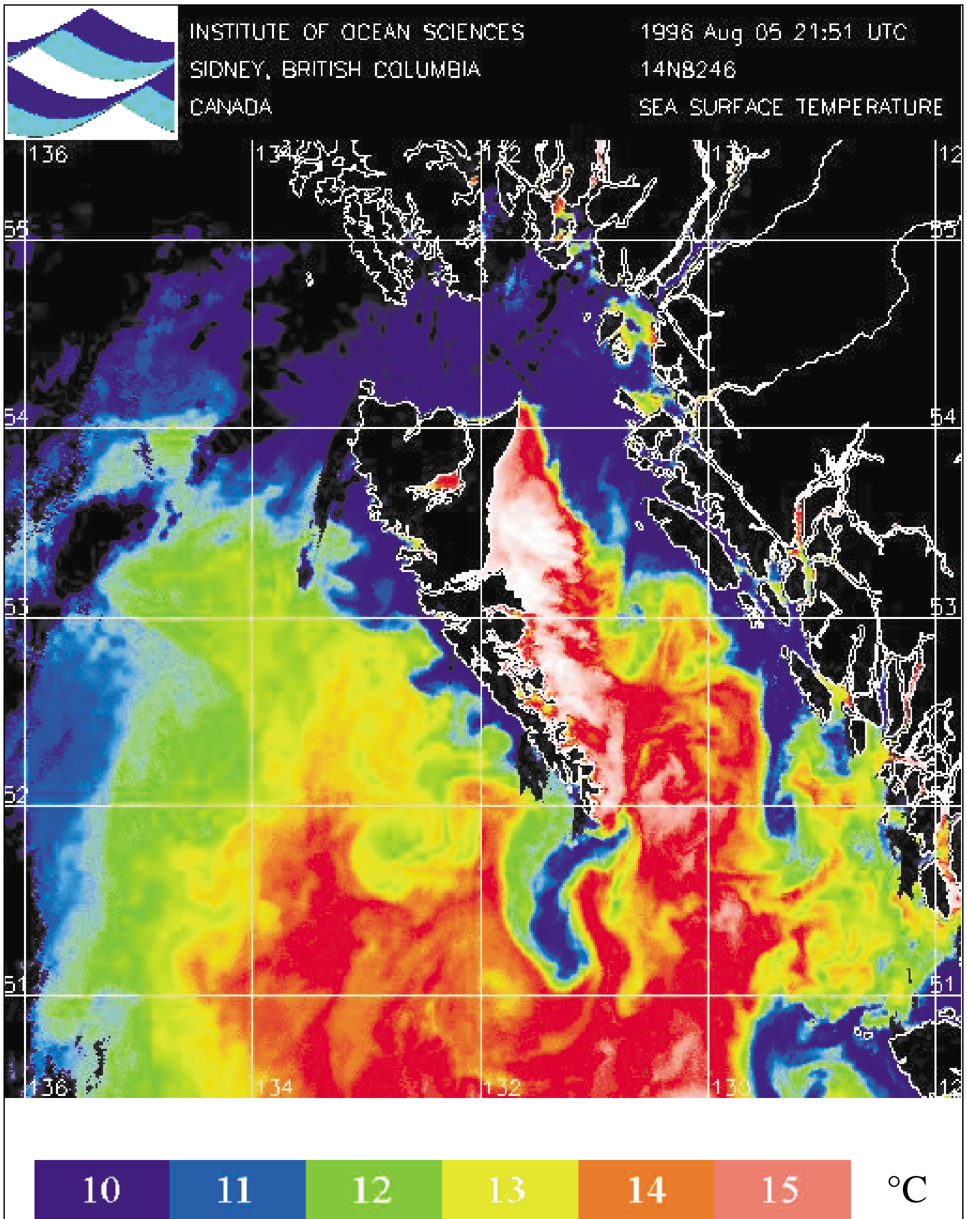

Figure 2. A NOAA weather satellite thermal image (5 August 1996) illustrating differences among three oceanographic regions around the proposed GHNMCA. Gowgaia includes a band of cool (blue) upwelled water, Kunghit is a mixing region, and Hecate consists primarily of warmer (red, white) water. Cloud and land are masked to black. Refer to **Figure 1**.

the results of the temporal analysis of satellite imagery within the context of these three major oceanographic regions.

Methods

Coastal zone colour scanner (CZCS)

Level 3 monthly global composites of surface chlorophyll (18 km × 18 km) were obtained from the Distributed Active Archive Center (DAAC) of the Goddard Space Flight Center for the period November 1978 to April 1986. Monthly images for a region corresponding to the British Columbia coast (45.7–55.9°N, 120.4–136.8°W) were georeferenced using the coordinates specified in the CZCS files. Mean chlorophyll concentrations were calculated from monthly CZCS composites for each of the three oceanographic regions surrounding the GHNMCA, but only if >20% of the pixels were cloud-free, and excluding null pixels.

Advanced very high resolution radiometer (AVHRR)

The archive of the Institute of Ocean Sciences, Sidney, British Columbia, of AVHRR imagery (1992–2000) and earlier data from the National Oceanic and Atmospheric Administration (NOAA) AVHRR Satellite Active Archive

(1982–1991) were searched for scenes with low cloud cover centred on the Queen Charlotte Islands (**Figures 2** and **3**). The images extended southward to the northern tip of Vancouver Island and northward including Dixon Entrance and the southern portion of Prince William Island, Alaska. The pixel resolution is about 4 km × 4 km for the 1982–1991 (global area coverage (GAC)) AVHRR imagery and about 1 km × 1 km for the 1992–2000 imagery. AVHRR reflectance imagery was processed using a technique developed by Groom and Holligan (1987), with improvements for the British Columbia coast (Gower, 1994; 1997). This method involves combining the visible band with the near-infrared band to reduce cloud, haze, and sun glint. The visible band (band 1: 580–680 nm) is sensitive to solar radiance back-scattered from water by suspended material and shows an increased signal with high concentrations of suspended matter. The near-infrared band (band 2: 725–1100 nm) is much less sensitive to suspended matter; however, atmospheric effects such as thin cirrus cloud, haze, aerosols, and sun glint all cause equal increases in the two bands. A weighted-difference image, using these two bands, shows differences in water-leaving radiance minus the effects of the atmosphere. The images were processed to show as much detail as possible around the Queen Charlotte Islands, with high reflectance representing high sediment concentrations. The images show brightening at the wavelength of AVHRR band 1 (580–680 nm) but give no indication of the spectral nature of the signal. The signal may be of inorganic or organic (i.e., phytoplankton) origins. However, if the brightness signal is

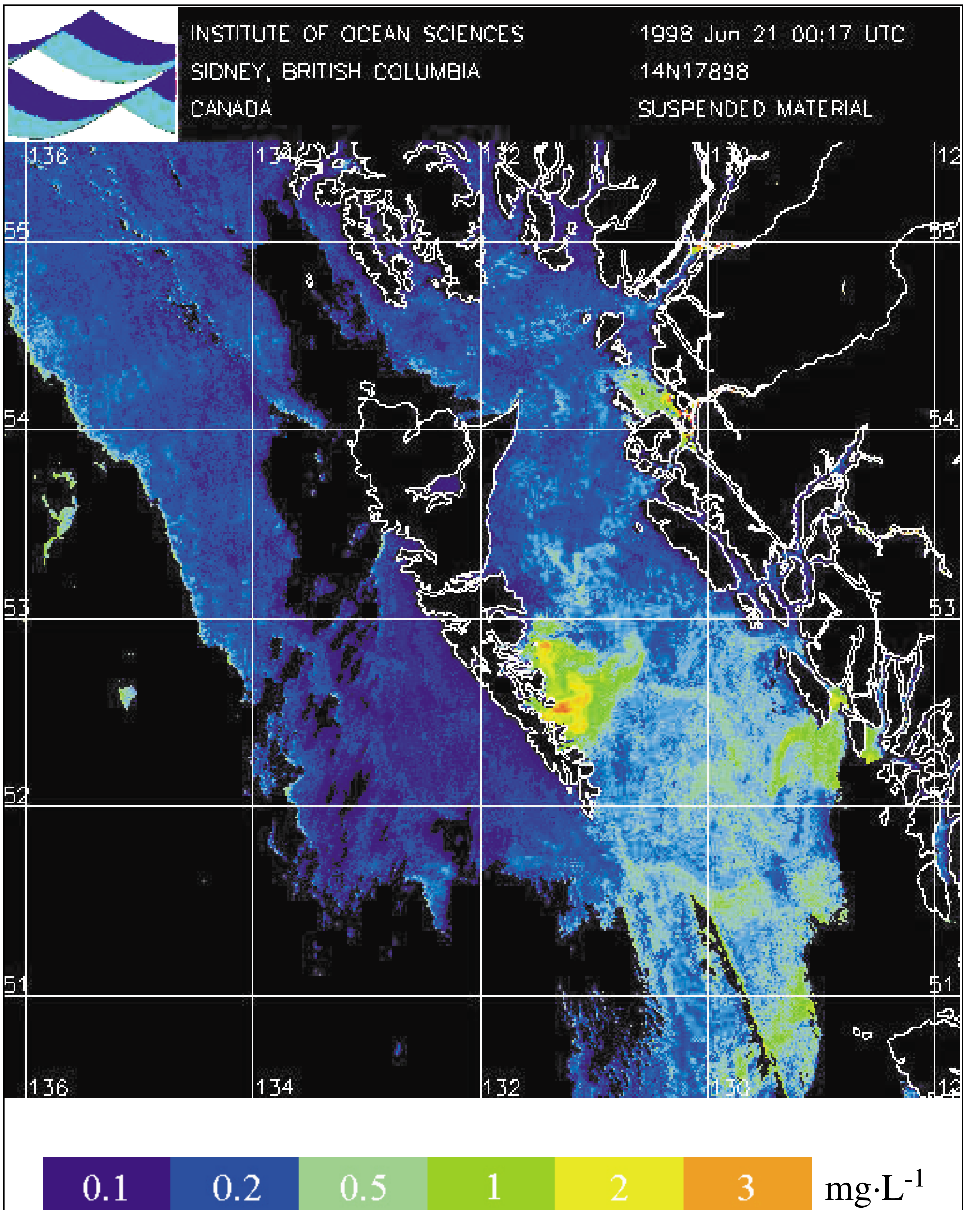

Figure 3. An example of a processed AVHRR suspended material image for 21 June 1998. Note the bright bloom event (orange–green) off the east coast of the proposed GHNMCA. Cloud and land are masked to black. Refer to **Figure 1**.

observed away from a river mouth (as for the GHNMCA) or the intensity increases in an area that persists over several days in an area not susceptible to bottom-sediment resuspension, then it is assumed that the suspended material is biological. The image data sequence is uncalibrated and relies on a constant sensitivity and spectral response in the sequence of NOAA AVHRR scanners. Calibration for these instruments has been monitored by Rao and Chen (1995; 1999), who report degradations less than 5% per year over the typical 4-year life of any one sensor. This is a relatively small change compared with the increases by factors 3–10 that characterize the events we are reporting here.

Sea-viewing wide field-of-view sensor (SeaWiFS)

SeaWiFS data are transmitted directly to ground stations, such as the Institute of Ocean Sciences (IOS), Sidney, British Columbia, and are also recorded and centrally processed by the National Aeronautics and Space Administration (NASA). The IOS has routinely received SeaWiFS imagery since the satellite became operational (September 1997 to present). All imagery was processed using GSFC SeaDAS software version 4.01, using climatological ancillary data. The software includes an improved atmospheric correction algorithm for coastal waters. It is used to produce images with the same projection and coverage as for AVHRR data, with the full SeaWiFS resolution of about 1 km × 1 km, showing chlorophyll concentrations and water-leaving radiances at 443, 490, and 555 nm.

Lower spatial resolution global (level 3) SeaWiFS data (10 km × 10 km) were also acquired from NASA. These SeaWiFS images were used to generate monthly averages of chlorophyll and normalized water-leaving radiance at 555 nm for an area 100 km north–south by 70 km east–west, centred at 53°N, 131°W to provide time series representative of the centre of Hecate Strait. The NASA data are compiled using the full coverage of global data recorded on the satellite. This is an advantage, given the extensive cloud cover in the GHNMCA area, which seriously limits the interpretation of temporal variability in water-leaving radiance. For example, about 40% of the study area, on average, is typically covered in cloud.

Results and discussion

AVHRR imagery was processed for the period 1982–2000 to describe the seasonal and interannual variability observed in brightness events for each of three major oceanic regions of the GHNMCA. **Figure 3** shows an example of a brightness event detected in June 1998. Analysis of the 19-year time series of AVHRR imagery (**Figure 4**) indicates that in most years bright patches have been detected in the Hecate region of the GHNMCA, though no bright patches of significant duration were observed in 1986, 1988, or 1991. One-day brightness events were identified in 1982, 1983, 1985, and 1994, but without confirmation on successive days these are suspected of being spurious effects due to aerosols or cloud edges. For the Hecate region, it appears that most of the brightness events of greatest duration occurred during the 1989–1999 period, though the lower spatial resolution of the earlier archived data may have caused more events to be missed. Thus, we do not know if this observation is related to changes in oceanographic conditions (e.g., water temperature or upwelling) or to the

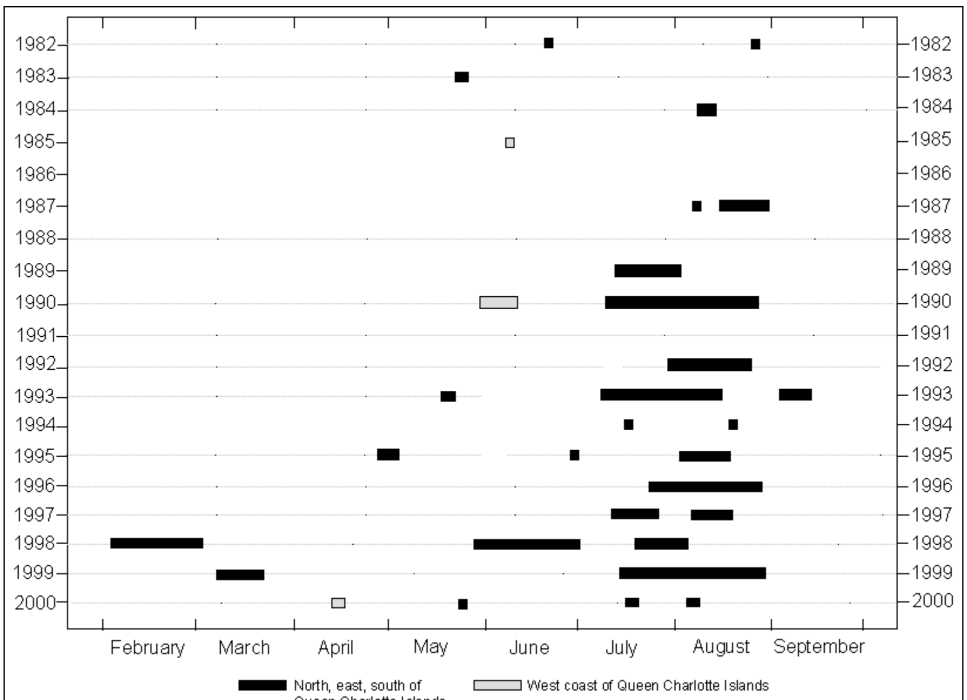

Figure 4. Timing and duration of brightness events detected off the Queen Charlotte Islands derived from AVHRR imagery for the period 1982–2000 (after Gower, 1997).

changing detection ability of the satellite data. Few brightness events were observed in 2000 or 2001 (not shown), perhaps indicating a return to pre-1989 oceanographic conditions. In contrast to the Hecate region of the GHNMCA, short-duration brightness events were detected in only 3 of 20 years in oceanic regions to the west of the GHNPR. One offshore brightness event was detected south of Kunghit in 1996 (Gower, 1997). Thus, it appears that oceanographic conditions are most conducive for brightness event development in the Hecate region of the GHNMCA. In the future, we plan to examine oceanographic data in detail to understand mechanisms driving the evolution of these events.

The majority of images processed over the 19-year times series occurred in summer. Relatively few brightness events were detected in winter or spring. These periods have low solar elevation and high cloud cover, making such events hard to detect (Gower, 1994). Brightness events in the Hecate region typically occurred from early June to late August (**Figure 4**). On several occasions, brightness events appeared to originate from shallow (<20 m) regions of Dogfish Bank in northern Hecate Strait, and these may be abiotic in origin, owing to resuspension of bottom sediments. A few brightness events appeared to be generated in Queen Charlotte Sound (e.g., 1993 and 1996). Gower (1997) noted that the during the events observed in 1992 and 1995 bright water emerged from the coastal inlets on the eastern shore of the GHNMCA, spreading out into Hecate Strait. The 1992 brightness event was imaged on 11 of 21 days from the end of July to mid-August. Examination of a high-resolution (20 m) Satellite pour l'observation de la terre (SPOT) image, which covers part of the study area on 31 July 1992, shows bright water east of Lyell Island and in Laskeek Bay. Bright water in Dana Inlet just north of the GHNMCA and in McEchran Cove in Klunkwoi Bay in the GHNMCA suggests that the bloom may have started in small areas of sheltered waters before being carried offshore.

The brightness event observed in Hecate in 1995 lasted about 19 days and started at the end of July (Gower, 1997). No field data exist to confirm the phytoplankton species responsible for this event, but Fisheries and Oceans Canada collected water samples for a brightness event detected off the west coast of Vancouver Island in June of that year. The samples were dominated by *Emiliana huxleyi* (Gower, 1997). Parks Canada collected a few samples from around the GHNMCA in early July 2000 and found that one station sampled in the southern Hecate Strait had a cell count of 87 000 cells·L^{-1} for *E. huxleyi*. The Hecate Strait station cell count was 4–20 times higher than those at two stations sampled in Gowgaia and 10–20 times higher than those at three stations sampled in Queen Charlotte Sound. This cell count is relatively low and likely constitutes background concentrations of *E. huxleyi*. A more rigorous sampling program of 20 nearshore stations in the proposed GHNMCA started in 2001, but unfortunately there were no concurrent brightness events.

Data from the CZCS for the period 1979–1985 still provide the longest available time-series of satellite-derived chlorophyll estimates for the GHNMCA area. Analysis of the CZCS-derived estimates of chlorophyll for the three oceanographic regions surrounding the GHNMCA indicates that the Hecate region has highest chlorophyll estimates during summer (June to August) in 5 of 6 years for which data were available (**Figure 5a**). There appears to be a general decline in the summer-averaged chlorophyll for all three regions from 1979 to the El Ninõ year of 1983. Satellite-derived estimates of chlorophyll returned to pre-El Ninõ values in 1985.

Seasonally, there was a peak in satellite-derived chlorophyll in the Hecate and Kunghit regions in April and in the Gowgaia region in March. A second peak in chlorophyll occurred in the first two regions in July and in Gowgaia in August (**Figure 5b**). It appears that the spring phytoplankton bloom occurs earlier along the west coast compared with along the east coast of the GHNMCA. We note that weekly chlorophyll values derived from the ocean colour and temperature scanner (OCTS) for this region in spring of 1997 also indicate that the peak in spring chlorophyll occurred 1 week earlier in Gowgaia compared with Hecate. The oceanographic mechanism responsible for the earlier blooms along the west coast of the GHNMCA is not known and requires further study. The similarity in summer chlorophyll patterns detected in CZCS imagery between the Hecate and Kunghit regions is consistent with recent oceanographic studies. Crawford (1996) used radio-tracked drifters to show a narrow (within 12 km of shore) nontidal outflow current that carries water from Hecate Strait into the Pacific Ocean past Cape St. James (Kunghit region). We also note that CZCS-derived monthly chlorophyll values were highly correlated among the three regions from January to May (correlation coefficient $r > 0.8$), but the regions were

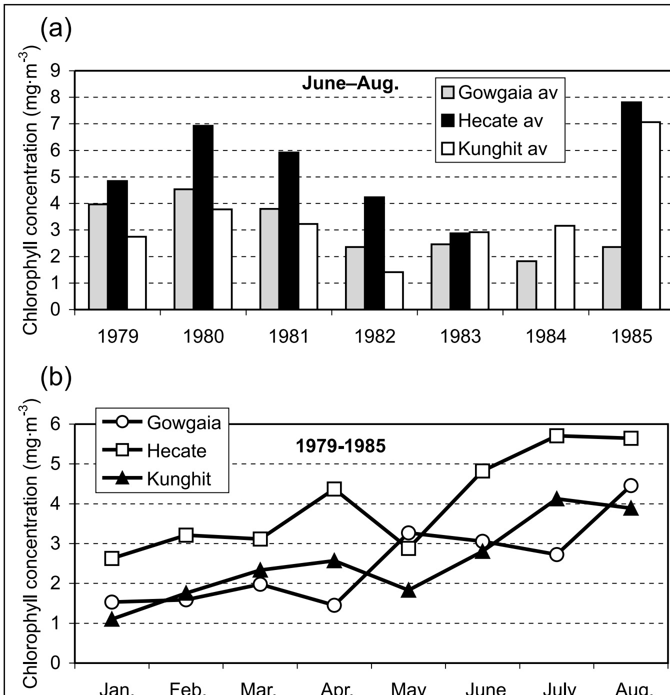

Figure 5. Summer-averaged (a) and monthly (b) CZCS-derived estimates of chlorophyll for three major oceanographic regions surrounding the GHNMCA.

substantially less correlated by July ($r < 0.1$). This suggests that phytoplankton may respond to similar oceanographic mechanisms operating throughout the three regions for most of the year. Oceanographic conditions among the three regions in July, however, are different enough to result in distinctive chlorophyll values. The differences among regions may be driven by the onset of strong northwest winds in summer that result in upwelling in Gowgaia and mixing of waters from eastern Hecate Strait that meander across and merge with waters in the Hecate and Kunghit regions (Jardine et al., 1993; Crawford, 1996).

Unfortunately, very few historical ship-based data exist for direct comparison with satellite-derived chlorophyll values for coastal British Columbia. Pan et al. (1988) estimated that chlorophyll concentration derived from 1979 CZCS satellite images were within plus or minus 40% of ship data in the 0.5–3.0 $mg \cdot m^{-3}$ range. The satellite sensor appeared to underestimate the much higher chlorophyll values (up to 20 $mg \cdot m^{-3}$) recorded by ships on the continental shelf. As part of the present study, the relationships between surface chlorophyll for ship-based and CZCS observations for three regions of the British Columbia coast were examined. The data for stations lying off Vancouver Island were found to most closely follow the 1:1 CZCS – in situ line, whereas for those stations from Georgia Strait and Hecate Strait the CZCS generally overestimated chlorophyll by ≥1 $mg \cdot m^{-3}$. This was most likely due to the influence of particulate matter and coloured dissolved organic matter (gelbstoff) from runoff. Note that for the inside waters the slope of the regression line was close to 1, suggesting that the influence of runoff was relatively constant over the areas sampled. The regression equation for all regions is as follows: CZCS chlorophyll ($mg \cdot m^{-3}$) = 1.03 (in situ chlorophyll; $mg \cdot m^{-3}$) + 1.05 ($r^2 = 0.63$).

Imagery from the SeaWiFS sensor provides more recent information about phytoplankton bloom dynamics in the GHNMCA region. The added bands for atmospheric correction and detection of gelbstoff improve the accuracy of the data from this instrument, though refinements in calibration and processing algorithms are continuing.

A series of normalized water-leaving radiance images (at 490 nm) for the GHNMCA in 1998 shows a highly reflecting phytoplankton bloom developing from mid-June to early July 1998 (**Figure 6**). The spatial resolution of the sensor is similar to that of the CZCS and AVHRR. **Figure 6** shows high water-leaving radiance off the mouth of Juan Perez Sound on 11 and 19 June and areas of bright water in Hecate Strait on 29 June. During its evolution, the core of the brightness event (orange colour in the middle panel of **Figure 6**) covered an area of about 2200 km^2, and the centre of the event moved about 60 km in 10 days. This is one of the few time series of images documenting the generation of a brightness event in the GHNMCA and subsequent movement into Hecate Strait.

Figure 7 shows the monthly average chlorophyll and normalized water-leaving radiance at 555 nm for Hecate Strait from the NASA SeaWiFS global (level 3) monthly product. Overall, these data indicate a bimodal seasonal pattern in

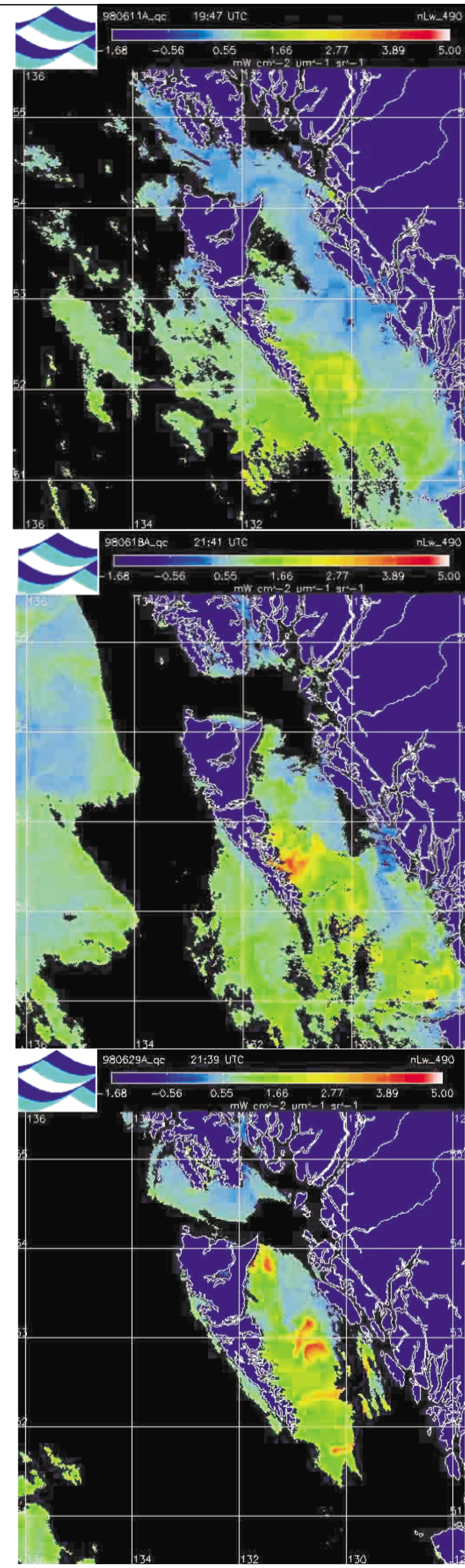

Figure 6. A time sequence of SeaWiFS images (nLw 490 nm) for oceanic regions of the Gwaii Haanas National Park Reserve documenting the evolution of a phytoplankton bloom that originated from within the proposed GHNMCA during June 1998. Black denotes cloud, and blue is land.

chlorophyll for the Hecate Strait region, with interannual variability in the timing (or presence) of modes. The data show a very minor spring bloom and a late-summer bloom in Hecate Strait during the strong El Ninõ year 1998. In both 1999 and 2000, a major spring bloom occurred in May and June, and a second major late-summer peak in chlorophyll occurred in September. During 2001, the bimodal pattern in chlorophyll observed in the 1999 and 2000 SeaWiFS monthly averages was not apparent. The average chlorophyll concentration detected by the satellite in Hecate Strait during July 2000 was about 1.4 $mg \cdot m^{-3}$. Two separate ship-of-opportunity cruises over a broad region of Hecate Strait during the same period produced average chlorophyll concentrations of 1.1 $mg \cdot m^{-3}$ (standard deviation (SD) = 1.1, number of observations (n) = 32) and 1.4 $mg \cdot m^{-3}$ (SD = 1.5, n = 23). Maximum chlorophyll values detected in the ship samples from Hecate Strait ranged between 4.5 and 6.4 $mg \cdot m^{-3}$.

High average water-leaving radiance at 555 nm was detected in June and July 1998 and August 1999 (**Figure 7**), confirming the brightness events documented by AVHRR and SeaWiFS (see **Figures 3** and **6**). Note that the nLw (normalized water-leaving radiance) 555 nm data in **Figure 7** also concur with the processed AVHRR imagery by showing no significant brightness events in Hecate Strait during the summers of 2000 and 2001.

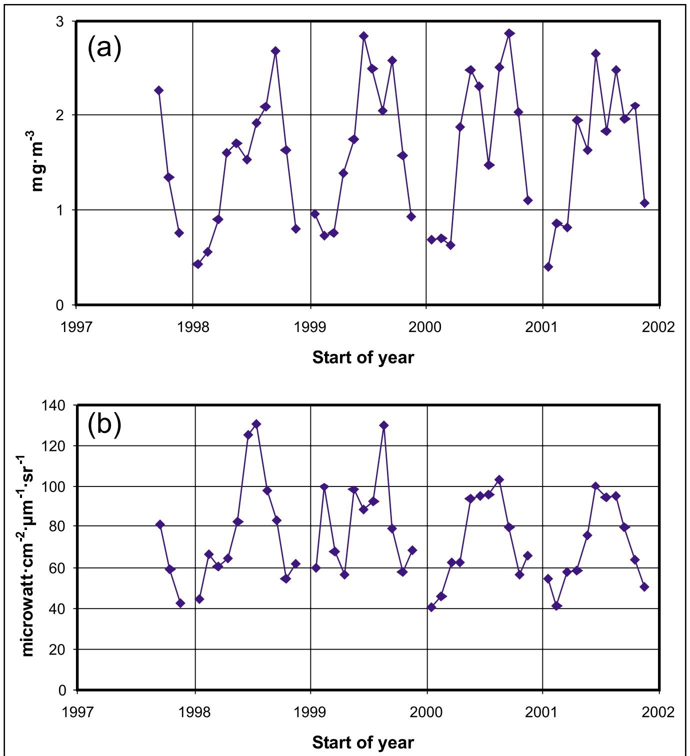

Figure 7. Monthly average chlorophyll (a) and nLw 555 nm (b) for Hecate Strait derived from the SeaWiFS level 3 imagery from the fall of 1997 to the end of 2001. Note the high average water-leaving radiance in June and July 1998 and August 1999, confirming the brightness events detected using AVHRR imagery (refer to **Figures 4** and **6**).

Conclusions

In this paper, we present results from a qualitative analysis of satellite imagery to document the temporal dynamics of phytoplankton populations in seas within and adjacent to the Gwaii Haanas National Marine Conservation Area in northern British Columbia, Canada. Combined information from several sensors has revealed that the Hecate region differs from the Gowgaia and Kunghit regions in several important ways. The Hecate region has, on average, higher monthly chlorophyll values, a later spring bloom, and a greater frequency, duration, and spatial extent of bright events. Large-area and bright plankton bloom events are observed in the historical satellite image record, though with few confirming in situ observations. Identification of the spatial and temporal variation in these satellite-derived bloom events is useful to park managers from several perspectives. First, the park will need to identify and monitor the phytoplankton species associated with the blooms in the Hecate region to ensure there is no health risk to humans. Second, the satellite imagery provides important information that can be used to identify potential areas within the proposed NMCA that may be linked to high concentrations of foraging fish, seabirds, and marine mammals. Lastly, results from this study will guide future field studies that will be needed to collect representative biodiversity information, and thus help achieve the Parks Canada marine conservation mandate.

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