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PHYTOPLANKTON EARLY WARNING APPROACHES FOR FINFISH AQUACULTURE IN SOUTHWESTERN NEW BRUNSWICK: UTILITY OF SATELLITE-BASED REMOTE-SENSING OF OCEAN COLOUR

by

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ABSTRACT

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Satellite (SeaWiFS) ocean colour data were evaluated for their utility in detecting and tracking HABs in the Bay of Fundy. Satellite data provide an indicator of the bulk biomass (chlorophyll) of phytoplankton residing in surface waters. From >5900 satellite over-flights during the study period (1997-2004), 500-700 passes produced usable data. Non-phytoplankton constituents accounted for 50% or more of the satellite signal. Corrected satellite data described a bi-model chlorophyll seasonal cycle, at The Wolves phytoplankton monitoring station in the southwestern New Brunswick region of the Bay of Fundy, with peaks in spring and fall. The seasonal abundance cycle of the prevalent harmful algal bloom (HAB) dinoflagellate, *Alexandrium fundyense*, on the other hand, peaked in summer-fall, ~2 weeks after the spring chlorophyll peak but before the fall peak. The timing of the spring chlorophyll and *A. fundyense* maxima appeared to occur progressively later over the study period. In addition, *A. fundyense* peak cell densities were highest in 2003 and 2004. Satellite chlorophyll delineates the gyre at the mouth of the Bay of Fundy which is thought to be an area of *A. fundyense* vegetative cell retention and a source of cysts for the Bay of Fundy that would help explain the recurrent HABs in the region. Although current satellite ocean colour data products may not be suitable for detecting and tracking HABs, they are still useful in developing a better understanding of the dynamics and links between HABs and the “background” phytoplankton communities.

RÉSUMÉ

Nous avons évalué l’utilité des données satellitaires sur la couleur de l’océan (obtenues avec le satellite SeaWiFS) pour la détection et le suivi des proliférations d’algues nuisibles dans la baie de Fundy. Les données satellitaires fournissent un indice de la biomasse globale de phytoplancton (chlorophylle) dans les eaux de surface. Parmi les plus de 5 900 passages de satellite durant la période d’étude (de 1997 à 2004), de 500 à 700 passages ont donné des données utilisables. Les composants autres que le phytoplancton comptaient pour 50 % ou plus du signal satellite. Les données satellitaires corrigées ont décrit un cycle saisonnier de la chlorophylle à deux modes, à la station de surveillance du phytoplancton des îles The Wolves dans le sud-ouest du Nouveau-Brunswick (baie de Fundy), avec des sommets au printemps et à l’automne. Par contre, le cycle d’abondance saisonnière du dinoflagellé dominant dans les proliférations d’algues nuisibles, *Alexandrium fundyense*, a atteint un sommet à la période été-automne, soit environ deux semaines après le sommet printanier de la chlorophylle, mais avant le sommet automnal. Au fil des ans durant la période d’étude, le maximum printanier de la chlorophylle et de *A. fundyense* a semblé se produire de plus en plus tard dans l’année. De plus, les

densités maximales de *A. fundyense* ont été les plus élevées en 2003 et en 2004. Les données satellitaires sur la chlorophylle délimitent le tourbillon à l'embouchure de la baie de Fundy, qui est perçu comme une zone de rétention des cellules végétales de *A. fundyense* et comme une source de spores pour la baie de Fundy qui aiderait à expliquer la récurrence des proliférations d'algues nuisibles dans la région. Bien que les données satellitaires actuelles sur la couleur de l'océan ne soient peut-être pas adéquates pour détecter et suivre les proliférations, elles sont tout de même utiles pour approfondir les connaissances sur la dynamique et les liens entre les proliférations d'algues nuisibles et les communautés phytoplanctoniques.

INTRODUCTION

Phytoplankton blooms occur annually in southwest New Brunswick (SWNB) coastal waters of the Bay of Fundy where extensive aquaculture operations (salmon farming) are located. Several times in the past decade harmful algal blooms (HABs) have negatively impacted the health of the caged salmon by reducing environmental oxygen levels, physically damaging the gills of the fish and/or by introducing toxins into the fish, resulting in reduced growth, stress or mortality. As a result of the negative economic consequences of HABs on the environment and aquaculture industry, the salmon industry and DFO initiated a collaborative project, funded by the Aquaculture Collaborative Research and Development Program (ACRDP), to investigate the feasibility and cost-effectiveness of several potential early warning approaches for HABs and to estimate concentration thresholds (for causing losses in farmed salmon production) of some of the dominant harmful algal species, such as the toxic dinoflagellate, *Alexandrium fundyense,* the organism implicated in salmon mortalities in 2003 (Martin et al. 2006a).

It is well known that phytoplankton blooms are difficult to predict. Scientists in various parts of the world have been working on this for decades with limited success. Two decades of monitoring phytoplankton within the southwestern New Brunswick area of the Bay of Fundy has indicated that the general seasonal timing of the blooms of some species is consistent and predictable to some extent. The inter-annual deviations in the magnitude of the blooms and variations in the timing, onset and magnitude of a bloom in a given year, however, are not as predictable from data collected at bi-weekly or weekly intervals. Therefore, present understanding of regional phytoplankton dynamics and patterns leads to the conclusion that:

- higher frequency sampling programs are needed at critical locations and at critical times of the year,
- statistical analyses approaches need to be applied to time series of individual phytoplankton species to determine the potential for forecasting bloom events,
- the usefulness of satellite imagery for detecting offshore phytoplankton blooms in the Bay of Fundy needs to be investigated, and
- we need information on the critical threshold levels of harmful algae which cause harm to farmed salmon.

The aim of this collaborative project is not to predict the formation of phytoplankton blooms from mechanistic considerations but, rather, to implement several sampling and data analyses strategies that will provide information concerning

1) the temporal and spatial scales of variability in the concentration of potentially harmful phytoplankton species,

2) the effectiveness of sampling and data analyses approaches for detecting the presence of potentially harmful phytoplankton species,
3) the effectiveness of the sampling and data analyses approaches for detecting and projecting a temporal trend in the abundance of a harmful algal species;
4) the algal cell concentrations that trigger changes in the behaviour and health of contained salmon, and
5) the ability of a tidal circulation model to estimate the susceptibility of a farm to a nearby plankton bloom.

This information can then be used as a foundation for the consideration of designs for a cost-effective phytoplankton monitoring and early warning system that could potentially be implemented and maintained by the industry with the appropriate involvement of others (e.g. provincial-federal departments).

This report summarizes one component of the overall project: an evaluation of the usefulness of satellite-based ocean colour data as a tool for detecting and tracking offshore-originating phytoplankton blooms, specifically HABs, in the Bay of Fundy.

Ocean colour satellite imagery and electronic data products for the entire NW Atlantic ocean have routinely been collected and processed at the DFO Bedford Institute of Oceanography (BIO) since late 1997 (http://www.mar.dfo-mpo.gc.ca/science/ocean/ias/seawifs/seawifs_1.html). The satellite data are used to quantitatively estimate the total biomass of phytoplankton (as chlorophyll) in near-surface waters. This component of the collaborative project was intended to help address the situation in which blooms originate offshore of the fish farming areas of SWNB and ideally would indicate the movement of a bloom toward the inshore areas and, along with finer scale tidal models, estimate the transport pathways of the blooms into the fish farms once the blooms reach the inshore.

At the present stage of technological development, satellite data cannot discriminate individual phytoplankton species but is viewed as a valuable supplement to more traditional phytoplankton monitoring approaches, giving a broader spatial-temporal synoptic scale context for localized observations.

MATERIALS AND METHODS

SATELLITE DATA

Image Processing

Since September 1997, BIO have been receiving Sea-Viewing Wide Field of View (SeaWiFS) ocean colour data from the Orbview-2 Satellite through an HRPT receiver dish. From 1997 until December 23, 2004, NASA granted permission to process and use these data for research purposes, free of charge but subject to a 2-week embargo. Images for the data which have been processed are available online (http://www.mar.dfo-mpo.gc.ca/science/ocean/ias/seawifs/seawifs_1.html), and the corresponding data is available for research without limitations.

BIO generally receives 2-3 SeaWiFS passes per day which covers the part of the North Atlantic region bounded by (39-62.5° N, 42-71° W) during daylight hours. These data are received in encrypted format, and are processed when the appropriate decryption key is made available by NASA.

On a daily basis, the decrypted SeaWiFS data are processed using a software package called SeaDAS. SeaDAS was written and provided free of charge by a team of researchers and programmers at the NASA Goddard Space Flight Center. It is regularly updated for reprocessing purposes. The SeaDAS support team is now part of the NASA Ocean Color Team. To correct for atmospheric influences, SeaDAS uses a look-up table which was generated by running the Gordon and Wang (1994) radiative transfer model for over 25000 different combinations of solar and viewing geometries, aerosol and microphysical properties. The model is based on the assumption that water-leaving reflectances at the two SeaWiFS near infra-red bands (centered at 765 and 865 nm) are negligible, due to high water absorption. Because of this, the radiance signals received at these bands are considered to represent only the atmospheric contributions. The atmospheric contributions in the visible SeaWiFS bands are estimated by extrapolating from the two near infra-red bands. The extrapolation algorithm and sensitivity analysis of the algorithm is discussed in detail in Gordon and Wang (1994).

Pixels are masked if they are associated with land, clouds and ice. NASA's default albedo for applying the cloud-ice mask is 0.027, but BIO uses a value of 0.015, which for our region was determined to be optimal in terms of minimizing cloud-edge contamination without losing significant amounts of valid data output. BIO applies the high satellite zenith angle mask, so as to avoid problems associated with processing pixels at the edge of a pass, where there can be problems with estimating the atmospheric correction. For consistency with the algorithms of previous SeaWiFS processing streams, BIO continues to apply the stray light mask. All other masks are used according to the default settings outlined by SeaDAS. These masks include sun-glint, high aerosol optical thickness at 865 nm, and radiance values exceeding knee value. The algorithms for determining which pixels are associated with these masks, are discussed in detail in McClain et al. (1995). Some recent updates to masking approaches are described in more detail at the following website: http://oceancolor.gsfc.nasa.gov/REPROCESSING/SeaWiFS/R4/masks_n_flags.html. After applying the masks and atmospheric corrections, the current standard SeaDAS chlorophyll product chl_oc4 (since 2001) is estimated by making use of a maximum band-ratio which incorporates the reflectances at 443, 490 and 510 nm. More details about this algorithm can be found at: http://oceancolor.gsfc.nasa.gov/SeaWiFS/TECH_REPORTS/PLVol11.pdf. BIO's entire SeaWiFS time series from 1997 through 2004 has been reprocessed with the current chl_oc4 algorithm.

Data products

The processed data are remapped onto a Mercator projection at a pixel resolution of 1.5 km^2. Additionally, they are remapped as HDF files onto nine standard sub-regions defined on BIO's website: http://www.mar.dfo-mpo.gc.ca/science/ocean/ias/seawifs/seawifs_1.html.

Standard composite images are produced for every half-month. Only non-masked pixels with valid chlorophyll data are included in the averaging for each pixel in the final composite product. For each composite, a remapped HDF file is produced with a corresponding jpeg file for viewing on the BIO website (above). For this study, in addition to standardized images, custom images were produced for the outer Bay of Fundy region (defined by the rectangle bounded by 43.5-45.9° N, 64.5-68.0° W) for each satellite pass for which sufficient data were recovered to generate a useful image (Fig. 1).

For numerical data, a SeaDAS command script was written to access the chlorophyll and navigation information for a given mapped HDF file representing an individual satellite pass or semi-monthly composite. The script then calls an IDL routine which performs the following steps to calculate statistics for any defined geographic region.

a) The valid pixels from which to compute the statistics are determined. A valid pixel must fall within the region, not be masked out by land, and not be flagged as having missing or bad data. This final criterion ensures that no pixels covered with any masks used in the daily processing algorithms, were included. In addition, the chlorophyll value has to exceed the lower limit of 0.0001 μg/L. All valid chlorophyll values exceeding an upper limit of 32 μg/L are set to this upper limit.
b) From the set of valid pixels, the mean, median and standard deviation are computed using IDL code, and output along with the number of valid pixels in the region, as well as a frequency distribution for eight sub-ranges of chlorophyll values.

In this study, statistics were computed for individual satellite passes for four defined sub-regions of the Bay of Fundy for each semi-monthly period from September 1997 through December 2004. The sub-regions were: The outer Bay of Fundy bounded by (43.5-45.9° N, 64.5-68.0° W; 6785 pixels or 15,266 km^2), the western Bay of Fundy bounded by (44.30-45.38° N, 66.31-67.33° W; 1917 pixels, or 4,313 km^2) and fixed locations, Prince-5 and The Wolves, nine pixels (20 km^2) each centered on (44.927° N, 66.853° W) and 44.989° N, 66.746° W), respectively (Figs. 1, inset). Data from individual passes were logged only if there was at least 50% pixel coverage for a particular region.

IN SITU DATA

Both *in situ* chlorophyll and *A. fundyense* abundance data from fixed sites in the western Bay of Fundy, collected during the satellite observation period (1997-2004), were used in this analysis. Chlorophyll data from the Prince-5 site, collected on a bi-weekly to monthly schedule (January, 1999 - December 2004) as part of the Atlantic Zone Monitoring Program (Therriault et al. 1998), were used. In addition, chlorophyll data collected from The Wolves site, on an approximately weekly schedule (July 2000 – November 2001) as part of the long-term Bay of Fundy phytoplankton monitoring program (Martin et al. 1995, 1999, 2001, 2006b), were used. *A. fundyense* abundance data, also collected as part of the HABs monitoring program, were used in this analysis. Although sampling was done from a number of sites inside the Quoddy Region of the Bay of Fundy (Fig. 1, inset), only abundance data from The Wolves site were used in this study because of the difficulty recovering reliable satellite data from the shallower inshore stations.

RESULTS

SATELLITE DATA

Over the 7^+ years (September 1997 – December 2004) of observations reported here, there were >5,900 passes of the SeaWiFS ocean colour satellite over the Bay of Fundy region. However, due to clouds, fog and other factors, only a small fraction of those passes resulted in usable data (i.e. with at least 50% pixel coverage). For the four regions for which we made an assessment (outer Bay of Fundy, western Bay of Fundy, Prince-5 and The Wolves, see Fig. 1), 1516 (26%), 1229 (20%), 524 (9%) and 705 (12%) observations were recovered, respectively, with percent recovery decreasing with geographic area of coverage (Fig. 2a-d). Despite the low percentages, these data still represent a significant enhancement over conventional sampling of frequencies, at best, once weekly. The limitation of the satellite data, however, is that coverage is typically irregular in time with multiple images over short periods (days or less) followed, often, by long periods (days or greater) with no data. Another feature of satellite data is that the variability (extreme high and low chlorophyll levels) are dampened (averaged out) as the area of coverage increases. Note, for example, the smaller range in chlorophyll values in the outer Bay of Fundy (Fig. 2a) time-series (~6800 pixels) compared with the western Bay of Fundy (Fig. 2b) time-series (~1900 pixels) and the Prince-5 (Fig. 2c) and The Wolves (Fig. 2d) time-series (9 pixels). What is also apparent is that the important seasonal cycle in chlorophyll concentrations is significantly attenuated in the large-area data products. For that reason, and the fact that “ground-truth’ data of comparable geographic dimensions is unavailable, subsequent analyses have concentrated on the satellite data for the two fixed sites, Prince-5 and The Wolves, only. Seasonal satellite chlorophyll cycles were clear at both Prince-5 and The Wolves with maxima (up to 30 μg L^{-1}) in spring-fall and minima (<5 μg L^{-1}) in winter; chlorophyll levels were generally higher at The Wolves than at Prince-5.

IN SITU DATA

The time-series of *in situ* (surface) chlorophyll data from Prince-5 (Fig. 3a) and The Wolves (Fig. 3b) also showed clear seasonality with spring and fall maxima and winter minima. In this case, however, maxima (~5-10 μg L^{-1}) and minima (<1 μg L^{-1}) were significantly lower than the satellite estimates. Unfortunately, these time-series covered only part of the period for which the satellite data were available.

Time-series of *A. fundyense* were only available from The Wolves site for comparison with satellite data, however, the time-series covered the entire satellite coverage period, 1997-2004 (Fig. 3c). *A. fundyense* abundances peaked in summer-fall (Fig. 3d) and cells were generally absent the remainder of the year. Compared with inshore monitoring stations (see Fig. 1), highest abundances of *A. fundyense* have been observed at The Wolves offshore site, particularly in the recent years (Figs. 4a-d).

SATELLITE CHLOROHYLL CALIBRATION

The discrepancy in chlorophyll levels between the satellite and *in situ* measurements provide supporting evidence for one of the well-established problems of applying standard oceanic water (Case-1) algorithms to inshore (Case-2) waters; that being, satellite estimates tend to overestimate true chlorophyll levels as a result of “contamination” from suspended inorganic and organic particulates and sediments, coloured dissolved organic matter, bottom reflectance in shallow waters, etc. In this study we have done a first-order calibration for the Bay of Fundy by “ground-truthing” the satellite chlorophyll estimates with *in situ* surface chlorophyll measurements. This was accomplished by matching (within a few hours) satellite over-flights with *in situ* measurements at Prince-5 and The Wolves. Of the 135 potential matches (total number of *in situ* chlorophyll measurements at the two sites, see Figs. 3a-b), 36 sampling dates (18 from each of the two sites) met the criterion, i.e. on average, satellite passes were within 3h of *in situ* measurements). Model II (Reduced Major Axis, RMA) regression analysis of the data pairs revealed a significant positive intercept on the Satellite Chlorophyll axis, indicating that a majority (>50%) of the Satellite estimates of chlorophyll are due to other substances (Fig. 5). The regression, however, explained only about half of the variation in estimated chlorophyll. Applying this calibration equation to the Prince-5 and The Wolves satellite data brought the chlorophyll levels more closely in line with the *in situ* data (Figs. 6a-b) and revealed bi-modal peaks in seasonal chlorophyll cycles at both stations (Figs. 7a-b). Non-chlorophyll constituents of the satellite signal (difference between calibrated chlorophyll and 'total' satellite signal) varied seasonally at both sites as well but in the opposite sense to chlorophyll, representing 70-80% of the signal in winter and ~50% in summer.

SATELLITE CHLOROPHYLL AND *A. FUNDYENSE*

Time-series of calibrated satellite chlorophyll were compared with *A. fundyense* time-series from The Wolves and, generally speaking, the seasonal patterns were similar with maximum chlorophyll and *A. fundyense* maximum cell densities in summer and minimums in winter (Fig. 8a); an exception was 2004 where record high *A. fundyense* abundances were observed coincident with record low chlorophyll levels. A closer inspection of the seasonal cycles, however, indicated that, on average, the *A. fundyense* peak (August) followed the late spring (May) chlorophyll peak but preceded the fall (September) chlorophyll peak (Fig. 8b). This pattern varied considerably by year as well with the temporal separation between the early season chlorophyll and *A. fundyense* peaks ranging from 3-50 days, avg = 17days (Fig. 9).

SPATIAL PATTERNS OF SATELLITE DATA

A series of SeaWiFS individual-pass images were produced for the larger outer Bay of Fundy region (see Fig. 1) for the summer-fall of 2003 and 2004 to determine if the development and distribution of *A. fundyense* could be inferred from satellite chlorophyll distributions during these two years when the peak abundance of this HAB was at record high levels (at The Wolves). The annual growth cycle of *A. fundyense* was significantly different between the two years. In 2003, although cells began appearing in July, the maximum abundances (>90,000 cells L^{-1}) were not seen until September (Fig. 10). In contrast, maximum cell abundances (>300,000 cells L^{-1}) in 2004 occurred in early August, more than a month earlier. The series of outer Bay of Fundy satellite images for July-September, 2003 (Figs. 11-13) suggest a phytoplankton growth "event" starting about mid-August and persisting until early September. This feature was most prominent off Passamaquoddy Bay and extended to the Nova Scotia coast (Fig. 12). Remnants of this feature, annular in shape, were evident throughout the first half of September with a possible increase in chlorophyll again on the 14th (Fig. 13). These features did not appear to coincide with *A. fundyense* growth dynamics for that year where peak abundances were observed on 9 and 23 September although data gaps excluded more precise comparisons (see also Figs. 8a and 9). Satellite images between July and September, 2004 (Figs. 14-15) indicated significantly different chlorophyll dynamics than in 2003. Overall, chlorophyll levels through the outer Bay of Fundy were much lower in 2004 than seen in any of the previous years (see also Figs. 8a and 9). A notable phytoplankton growth "event" started in Mid-August and persisted for about a week but was largely confined to the western Bay of Fundy northeast of Passamaquoddy Bay; there was some suggestion of an annular shape near the end of that event (Fig. 14). For most of September, relatively high chlorophyll levels were again seen in the same general location in the western Bay of Fundy with a suggestion of annular shape near the end of the month (Fig. 15). The spectacular *A. fundyense* bloom in early August in 2004 (Figs. 8a and 9) was not evident in the satellite imagery.

The feasibility of using these satellite data products to detect and track *A. fundyense* blooms, since the standard satellite algorithms retrieve “bulk” (all phytoplankton species) chlorophyll, is dependent on the HAB species accounting for a significant fraction of the chlorophyll content of surface waters. Based on knowledge of the typical cellular chlorophyll content of *A. fundyense* cells, i.e. ~20 pg CHL cell^{-1} (e.g. Anderson et al. 1990), and cell abundance during this study, it is clear that these HABs, even at their peak abundance, accounted for only a small fraction (~10%, see Fig. 8b) of the bulk chlorophyll. As a rule of thumb, it would take ~50,000 *A. fundyense* cells to account for 1 μg CHL and chlorophyll concentrations in the Bay of Fundy are considerably higher than that during the major spring-fall phytoplankton growth period (see Fig. 3). It is not surprising, therefore, that these standard satellite data products are not particularly useful for tracking HABs, at least in this study area.

DISCUSSION

THE CASE FOR SATELLITE DATA

The satellite (SeaWiFS) ocean colour data products processed routinely by BIO were developed using algorithms for “Case 1” waters – where phytoplankton (and co-varying matter of biogenic origin) are the major contributors to the seawater’s optical properties. The Bay of Fundy, on the other hand, is optically complex “Case-2” waters with major contributions from independently varying non-phytoplankton particulates (e.g. suspended sediments), coloured dissolved organic matter (CDOM), i.e. “yellow substances”, and often contributions from bottom reflectance in shallow waters (Sathyendranath 2000). For this reason, the standard SeaWiFS products significantly over-estimated the chlorophyll concentrations in the Bay of Fundy. Calibration against *in situ* chlorophyll measurements at two fixed sites improved the satellite chlorophyll estimates but still explained only ~50% of the variability. The inherently high small-scale spatial and temporal variability of these waters, where large tidal amplitudes are a significant contributing factor, make “ground-truthing” a particular challenge. Optical properties in these highly dynamical waters, for example, may vary an order of magnitude or more over the spatial scale of a single satellite pixel (~1.5 km).

Another limitation of satellite ocean colour data is its capability for detecting only near surface (~1 optical depth) properties. This is particularly a problem in ocean regions where the water-column is well-stratified and phytoplankton biomass is aggregated sub-surface. In many parts of the Bay of Fundy, however, this is less of a concern because of the strong tidally-induced vertical mixing which tends to break down vertical structure. Moreover, most phytoplankton blooms (including vegetative stages of HABs) originate and persist for much of their growth cycle in near-surface waters that are accessible to satellite sensors.

One of the most significant limitations of satellite data is the inability to penetrate clouds, fog and other atmospheric attenuators. As a result, the realized data recovery is usually only a small fraction of the number of satellite over-flights. This is clearly a problem in cold north-temperate coastal waters, such as the Bay of Fundy, where clouds/fog are prevalent year-round; in this study, only ~10-25% of the satellite passes produced usable data. Still, 500-700 satellite observations, even at small spatial scales, represented almost a doubling of observations made from more conventional monitoring programs.

One of the most notable attributes of satellite data is the unprecedented spatial scale of coverage. In this study, chlorophyll conditions over the entire Bay of Fundy region could potentially be assessed with each satellite over-flight. Detailed evaluation of satellite imagery of the outer Bay of Fundy from the summer-fall months of 2003 and 2004, for example, showed a persistent and clearly delineated bay-wide annular feature off the mouth of Passamaquoddy Bay. This feature is likely a biological manifestation of the Fundy “gyre” described in early studies of the ocean circulation of the region (Godin 1968) and more recent modeling studies (e.g. Lynch et al. 1997, Hannah et al. 2001).

Despite limitations outlined above, this study has shown conclusively that satellite data substantially enhances, over conventional observations, information on the temporal and spatial distribution and variability of chlorophyll and adds to our understanding of the dynamics of phytoplankton populations in the Bay of Fundy.

SATELLITE OCEAN COLOUR AND HABs

The principal goal of this study was to investigate and evaluate the utility of standard satellite ocean colour data products, produced at BIO, for detection and tracking of HABs, such as the frequently implicated dinoflagellate, *A. fundyense*, in the Bay of Fundy. Detailed comparisons of seasonal to interannual variability in satellite chlorophyll and *A. fundyense* abundance showed convincingly that current satellite data products are not adequate for tracking individual HAB species, even when densities are extremely high. During peak bloom conditions, *A. fundyense* accounted for only ~10% of the bulk satellite chlorophyll observed in surface waters between 1997 and 2004. Furthermore, if these HAB species tend to aggregate below surface in stratified waters (Martin et al. 2005, Townsend at al. 2005), the satellite will not detect them at all.

Aside from these drawbacks, satellite data may still have some value in investigating the growth dynamics of HABs to the extent that HABs are linked to other components of the phytoplankton community (Page et al. 2001, 2006, Dowd et al. 2004). It is clear from this study that the summer-fall *A. fundyense* blooms are always preceded by a spring phytoplankton bloom, generally comprised of diatoms (Martin et al. 1995, 1999, 2001, 2006b) and followed by a fall bloom and this relationship has been seen repeatedly, at least since the phytoplankton monitoring was initiated and over the 1998-2004 period of satellite observations. Over that time period, the magnitude of the spring bloom varied greatly with no obvious temporal trend (Fig. 16a). On the other hand, the timing of the bloom (Fig. 16b) appeared to occur later in more recent years, by >2 months. Similarly, the *A. fundyense* bloom occurred later (Fig. 16d) and increased in magnitude as well (Fig. 16c). In the last couple of years (2005 and 2006), however, the bloom timing has reverted to the more typical June/July period (J. Martin unpubl.) so that any significance to the temporal trends described here should be interpreted with caution (see also Page et al. 2006). The increased severity of these HABs blooms in recent years was noted in the summary of accomplishments of the ECOHAB-Gulf of Maine program (Anderson et al. 2005a) and the link between the spring bloom and occurrence of HABs confirmed (Townsend et al. 2005). However, there appear to be cyclical periods where A. *fundyense* blooms tend to have increased cell densities and resulting shellfish toxicity. White (1987) documented periods of higher shellfish toxicity during the mid 1940's, early 1960's, and late 1970's. This occurred again in 2003-04 (J. Martin unpubl.) During the 8-yr period of the late 1970's – early '80's shellfish toxicities and *A. fundyense* blooms were documented as more intense than at any time in the preceding 30 years. This suggests that the population is experiencing another period of increased cell density.

The satellite data have also clearly documented the conspicuous and persistent enhancement of chlorophyll concentrations associated with a gyre near the mouth of the Bay of Fundy. These satellite data lend support to the idea that this retentive eddy system is a site of *A. fundyense* vegetative cells accumulation that feeds the major cyst seabed in the region and is a localized incubator for the recurring HABs blooms in southwestern Bay of Fundy (White 1982a,b, Anderson et al. 2005b, McGillicuddy et al. 2005).

CONCLUSIONS

Analysis of 7^+ years of SeaWiFS ocean colour data for the Bay of Fundy to evaluate the utility of standard data products (chlorophyll) for early detection of HABs has generated the following conclusions/recommendations:

1. Due to atmospheric conditions (clouds, fog) prevalent in these north temperate coastal regions, only a relatively small fraction (~10-25%) of the >5,900 satellite passes over the region during the 7^+ years surveyed produced usable data. Still, this improved significantly temporal coverage over conventional algal monitoring programs in the region (by at least a factor of two); spatial coverage by satellites (1.5 km resolution) is unattainable by conventional monitoring methods.

2. Because of the complexity of water constituents (phytoplankton, inorganic particulates, coloured dissolved substances), of inshore (Case-2) waters characteristic of the Bay of Fundy, standard SeaWiFS algorithms significantly over-estimated chlorophyll at low levels; at least half of the satellite signal was not associated with phytoplankton based on “ground-truth” from *in situ* chlorophyll calibrations.
3. Despite these technical issues, corrected satellite chlorophyll concentrations were valuable in establishing scales of temporal and spatial variability and the recurring bimodal (spring-summer and fall peaks) seasonal cycles in phytoplankton (chlorophyll) in the Bay of Fundy.
4. *A. fundyense* abundance was broadly correlated with satellite chlorophyll but, upon closer inspection, peak cell abundance followed the late spring-early summer chlorophyll peak and preceded the fall chlorophyll peak; median time delay between chlorophyll and *A. fundyense* peaks was ~17 days but ranged from 5-50 days. No pronounced spring or fall satellite chlorophyll peaks were observed in 2004, a year of record *A. fundyense* bloom concentrations.
5. The spatial resolution of SeaWiFS imagery (1.5 km) is suitable for characterizing only very large (10s of km) bloom patches and would discriminate HABs only if their concentrations were high enough to mask the already high background satellite ocean colour levels typical for the Bay of Fundy. SeaWiFS imagery did, however, clearly delineate (enhanced satellite chlorophyll levels) the Fundy “gyre” off the mouth of Passamaquoddy Bay that is thought to propagate one of the major Gulf of Maine *A. fundyense* cyst seedbeds that accounts for the recurrent regional HABs.
6. Although current satellite ocean colour data products may not be suitable as early warning tools for HABs, they are still useful in developing a better understanding of the dynamics and links between HABs and the “background” phytoplankton communities. The analyses presented here, for example, suggest that between 1998 and 2004, the magnitude of the spring-summer phytoplankton blooms has been highly variable but the timing of those blooms has tended to be later in more recent years. *A. fundyense* blooms, similarly, tend to be occurring later and were of greater intensity in 2003-04. This might suggest that the dynamics of HABs can be related to the dynamics of blooms that are amenable to observation by satellite.

Despite current limitations in applying satellite ocean colour data to HABs problems in optically complex Case-2 coastal waters, new methodologies and sensors are being tested or are on the horizon. Promising new algorithms using SeaWiFS data have been developed and successfully applied in coastal waters of Korea and China (Ahn and Shanmugam 2006). Their Red Tide index Chlorophyll Algorithm (RCA) has been tested against *in situ* data over a chlorophyll range of 0.4-71 μg L^{-1} with a correlation coefficient of $R^2 = 0.92$. Hu et al. (2005), using a different sensor and approach, have investigated the utility of solar-stimulated fluorescence of phytoplankton to assess HABs off the coast of Florida. They evaluated the capabilities of the MODIS satellite's flourescence line height (FLH) product as an alternative to the standard band-ratio chlorophyll products of SeaWiFS. The fluorescence signal is relatively unaffected by the Case-2 water constituents that interfere with the band-ratio methods. For chlorophyll in the range of 0.4-4 μg L^{-1}, they found a correlation with *in situ* data of R^2=0.96. Both approaches are being considered at BIO to improve satellite ocean colour data products for addressing regional HAB issues. Additionally, new satellite sensors with considerably higher spatial resolution, ~300 m (e.g., MERIS) and geo-stationary platforms for high temporal resolution sampling, hourly (e.g. HiRVIS) are either already operational or will be launched in the next few years (http://www.ioccg.org/sensors_ioccg.html).

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FIGURE LEGENDS

Figure 1. Study area, showing the nested geographic regions and fixed sites chosen for SeaWiFS ocean colour satellite data analysis.

Figure 2. Time-series of satellite chlorophyll concentrations (un-calibrated) for: (A) the outer Bay of Fundy, (B) the western Bay of Fundy, (C) the Prince-5 site and (D) The Wolves site (see Fig. 1).

Figure 3. Time-series of *in situ* surface chlorophyll concentrations for: (A) Prince-5 and (B) The Wolves and (C) *A. fundyense* abundance in surface waters at The Wolves during the period of satellite coverage (1997-2004). Mean monthly (1988-2004) *A. fundyense* abundance (D).

Figure 4. Time-series of *A. fundyense* abundance in surface waters at the four standard HABs monitoring stations (see Fig. 1 inset).

Figure 5. Model II (RMA) regression of *in situ* chlorophyll versus un-calibrated satellite chlorophyll from Prince-5 and The Wolves. Only data pairs where satellite over-flights and *in situ* sampling were within a few hours were used (see MATERIALS AND METHODS section for details).

Figure 6. Monthly mean (1998-2004) satellite chlorophyll concentrations (calibrated) and non-chlorophyll constituents (see MATERIALS AND METHODS section for details) at (A) Prince-5 and (B) The Wolves. Vertical lines are standard errors.

Figure 7. Time-series of calibrated satellite chlorophyll and *in situ* chlorophyll in surface waters at (A) Prince-5 and (B) The Wolves.

Figure 8. Time-series of calibrated satellite chlorophyll and *A. fundyense* abundance in surface waters at The Wolves (A). Monthly mean (1998-2004) calibrated satellite chlorophyll concentrations, *A. fundyense* abundance and % of chlorophyll contributed by *A. fundyense* at The Wolves (B). Vertical lines are standard errors.

Figure 9. Time-series of calibrated satellite chlorophyll and *A. fundyense* abundance by year, 1998-2004.

Figure 10. *A. fundyense* abundance at The Wolves, July-September, 2003 and 2004.

Figure 11. Satellite images of chlorophyll distribution in the outer Bay of Fundy (see Fig. 1) recovered for July, 2003.

Figure 12. Satellite images of chlorophyll distribution in the outer Bay of Fundy (see Fig. 1) recovered for August, 2003.

Figure 13. Satellite images of chlorophyll distribution in the outer Bay of Fundy (see Fig. 1) recovered for September, 2003.

Figure 14. Satellite images of chlorophyll distribution in the outer Bay of Fundy (see Fig. 1) recovered for July and August, 2004.

Figure 15. Satellite images of chlorophyll distribution in the outer Bay of Fundy (see Fig. 1) recovered for September, 2004.

Figure 16. Time-series of: (A) magnitude of the spring satellite chlorophyll maximum, (B) timing of the spring chlorophyll maximum, (C) maximum summer-fall *A. fundyense* abundance and (D) timing of the *A. fundyense* maximum at The Wolves during the period of satellite coverage (1998-2004). Line is least squares linear regression.

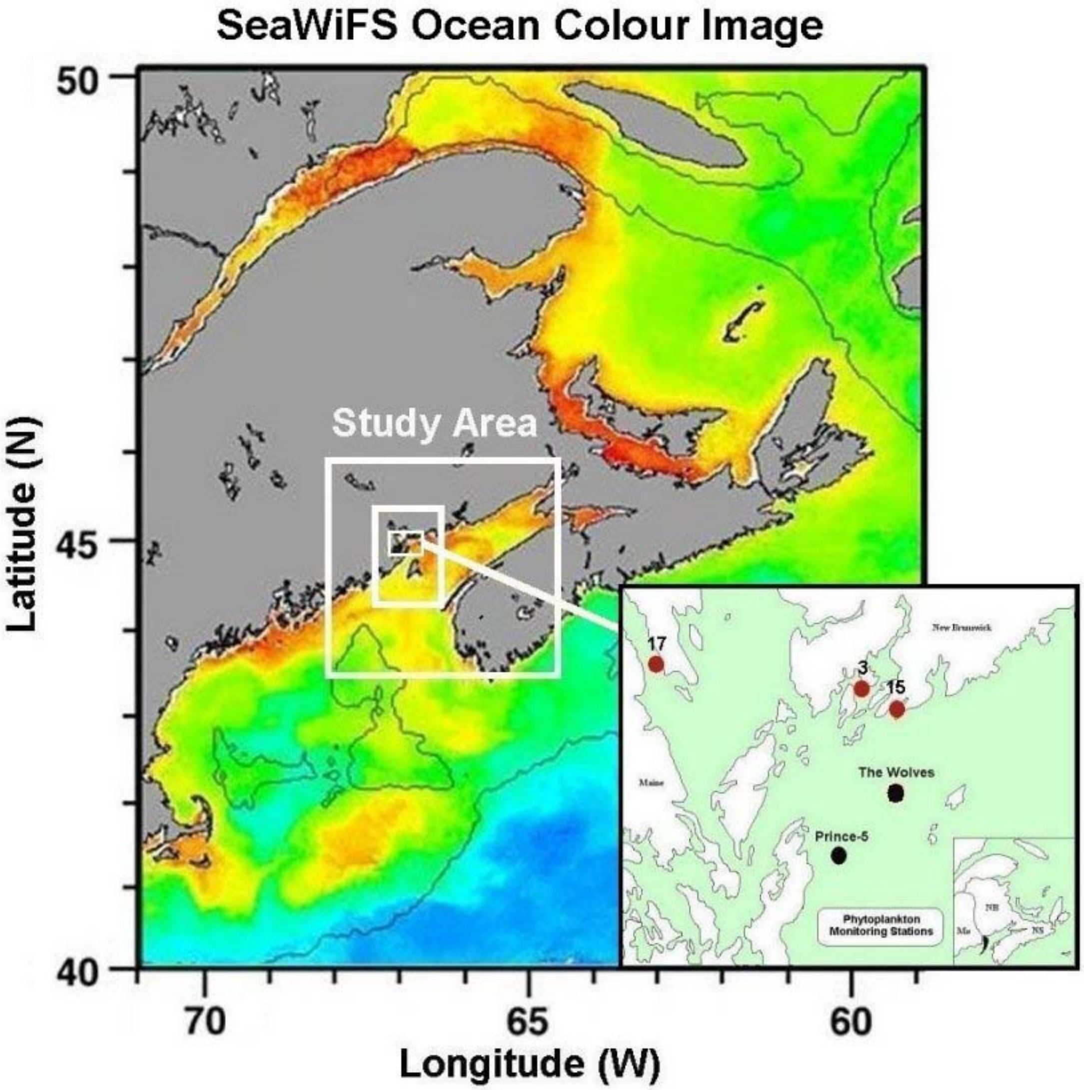
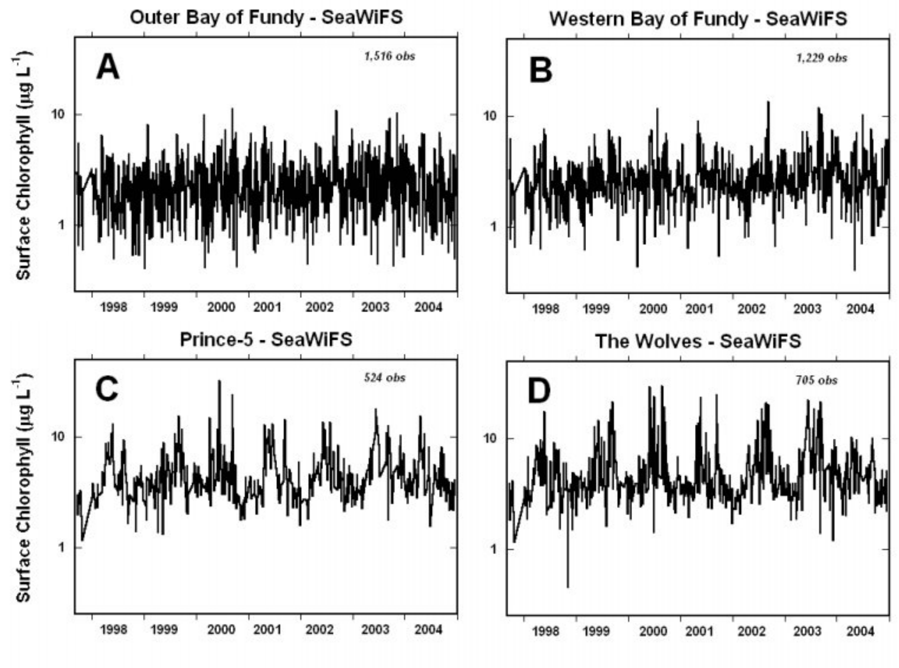

SeaWiFS Ocean Colour Image
Study Area
50
45
40
Latitude (N)
70
65
60
Longitude (W)
17
3
15
New Brunswick
Maine
The Wolves
Prince-5
Phytoplankton Monitoring Stations
NB
Me
NS

Figure 1



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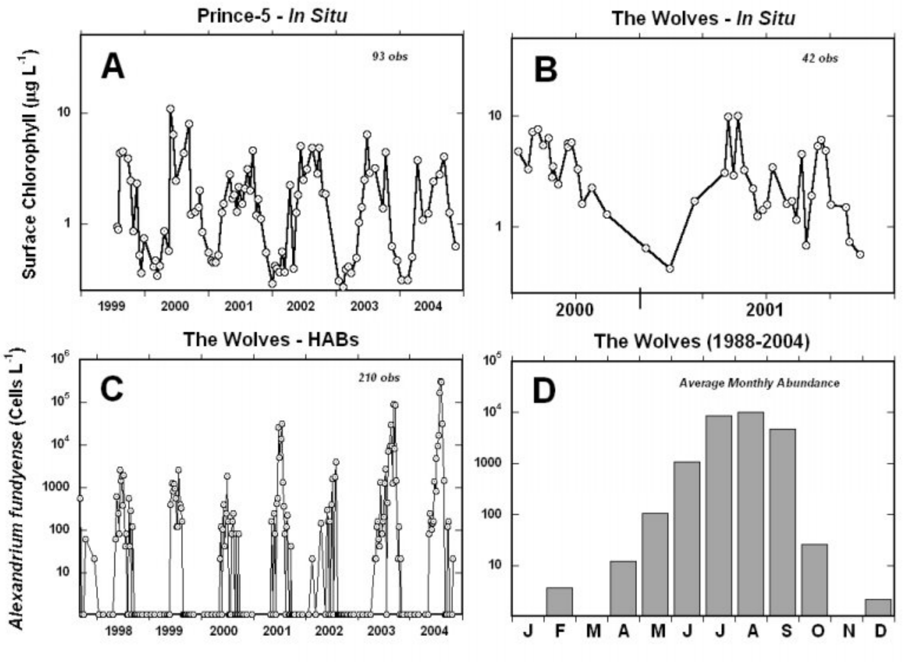
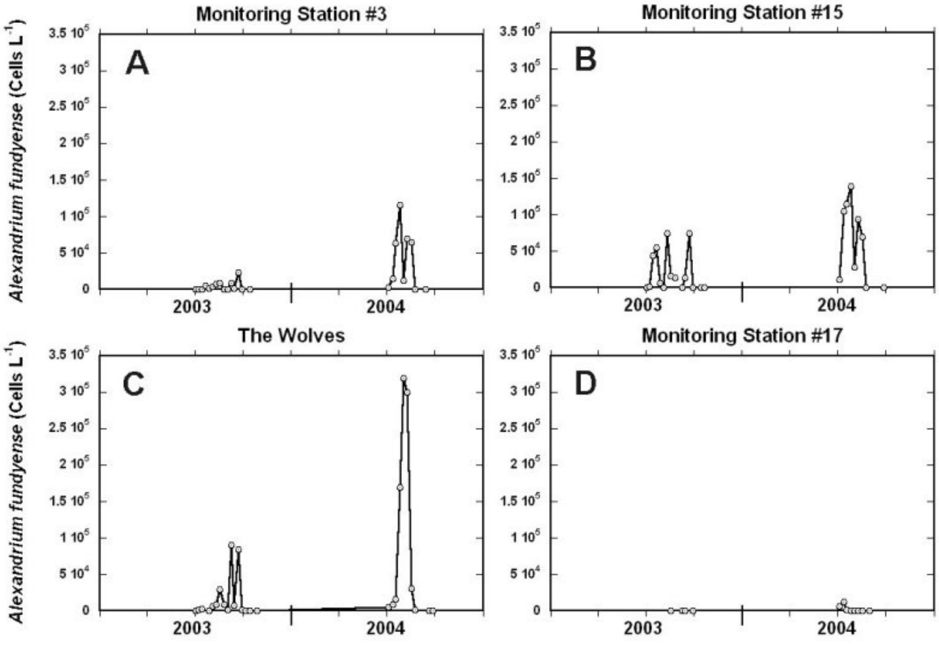


Figure 3



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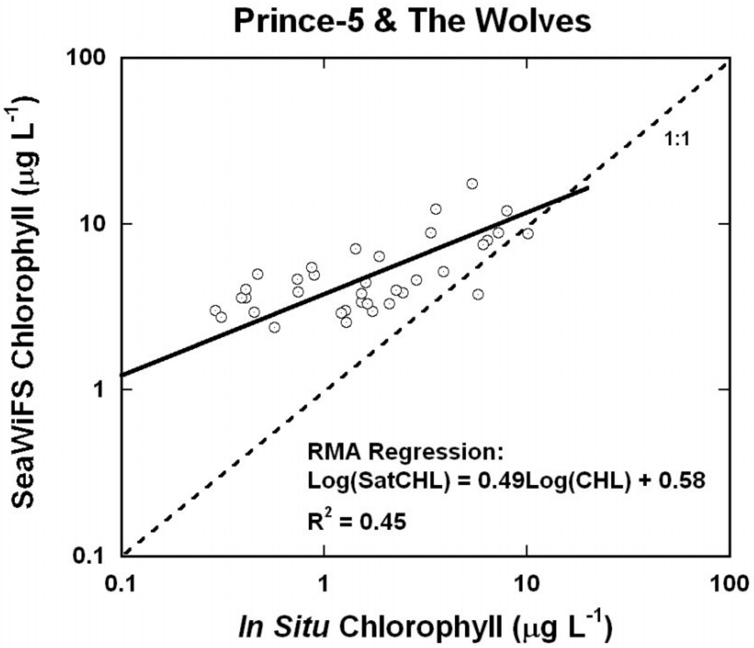

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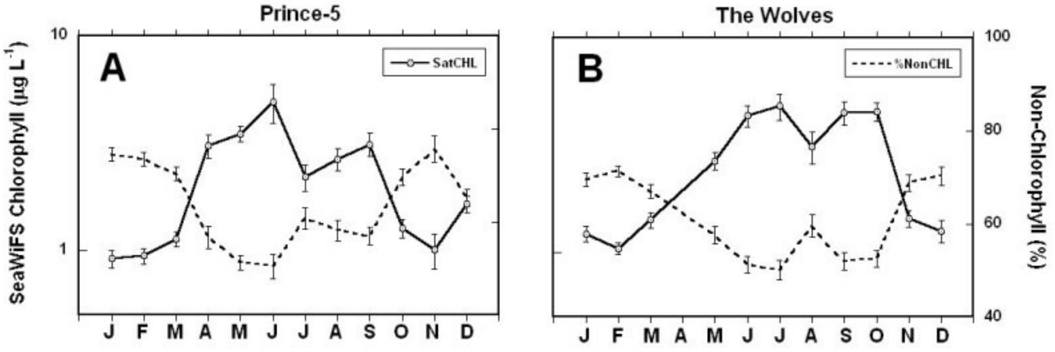

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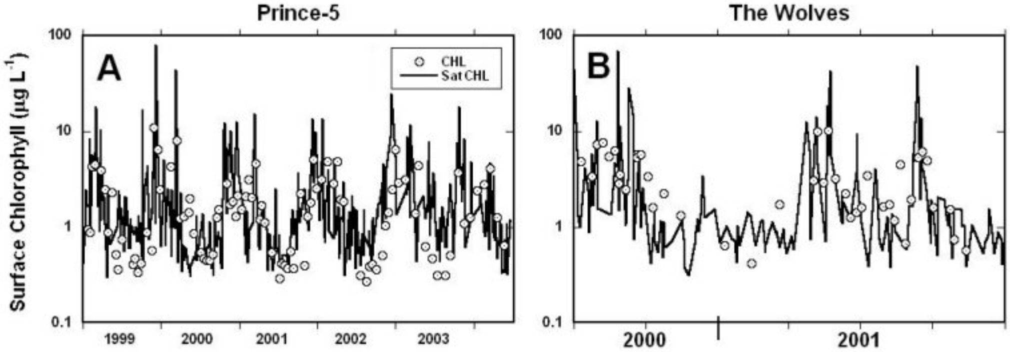

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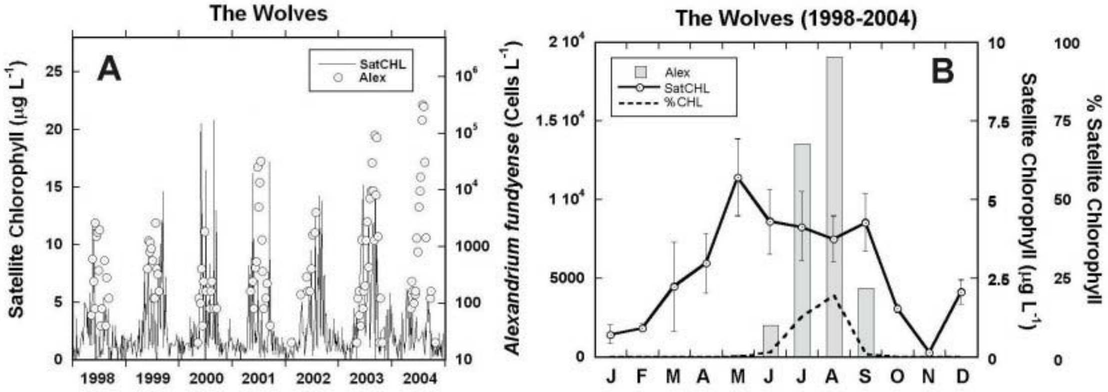

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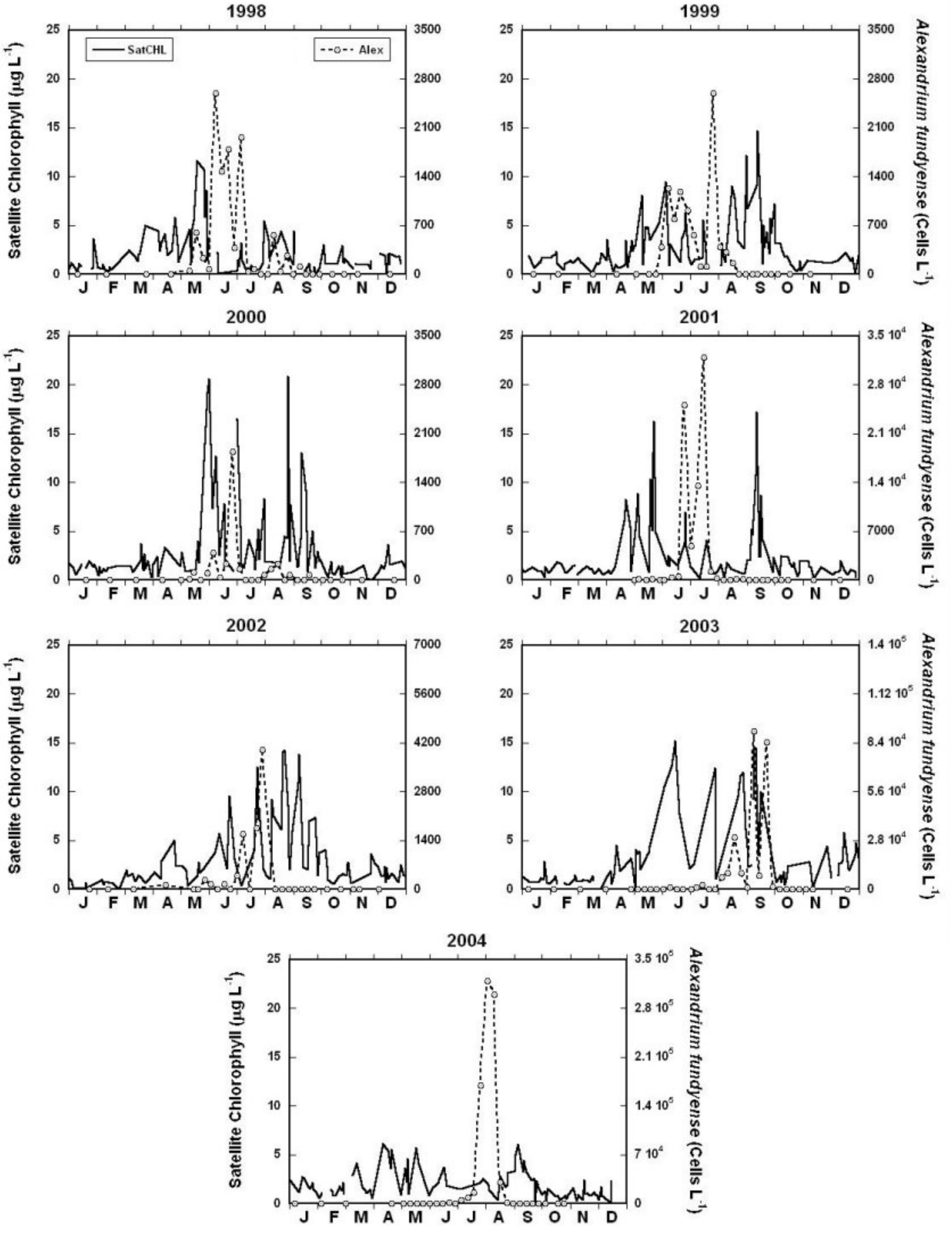

1998
1999
2000
2001
2002
2003
2004
SatCHL
Alex
Satellite Chlorophyll (μg L-1)
Alexandrium fundyense (Cells L-1)
0
5
10
15
20
25
0
700
1400
2100
2800
3500
3.5 10^4
2.8 10^4
2.1 10^4
1.4 10^4
7000
7000
5600
4200
2800
1400
1.4 10^5
1.12 10^5
8.4 10^4
5.6 10^4
2.8 10^4
3.5 10^5
2.8 10^5
2.1 10^5
1.4 10^5
7 10^4
J F M A M J J A S O N D

Figure 9

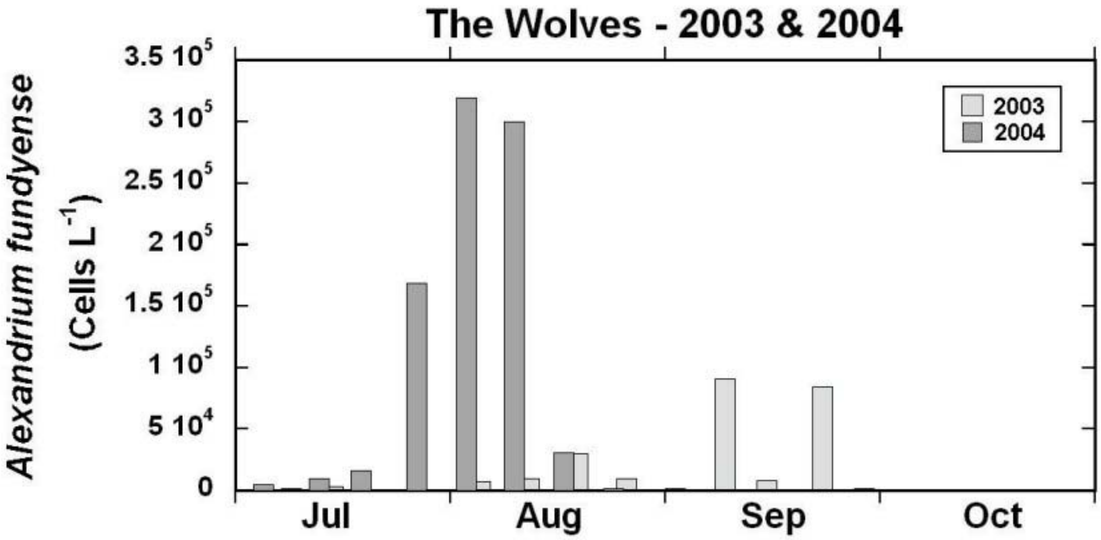


Figure 10

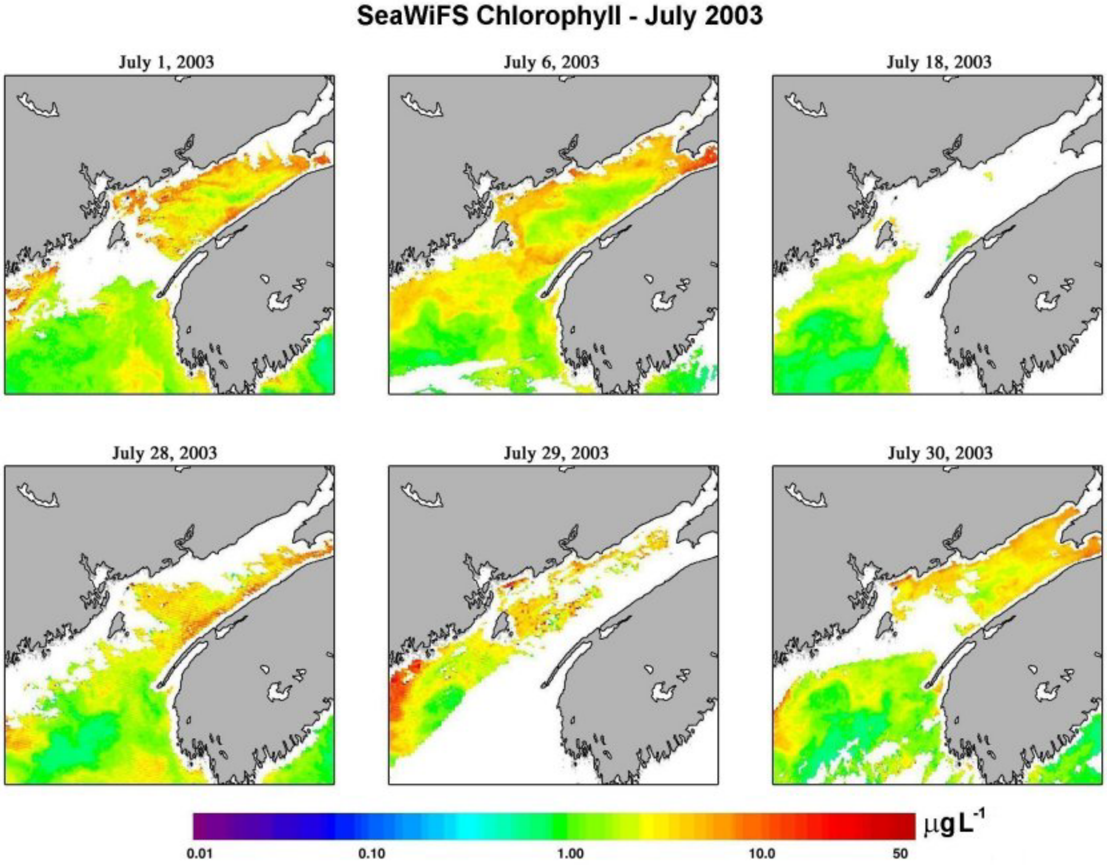


Figure 11

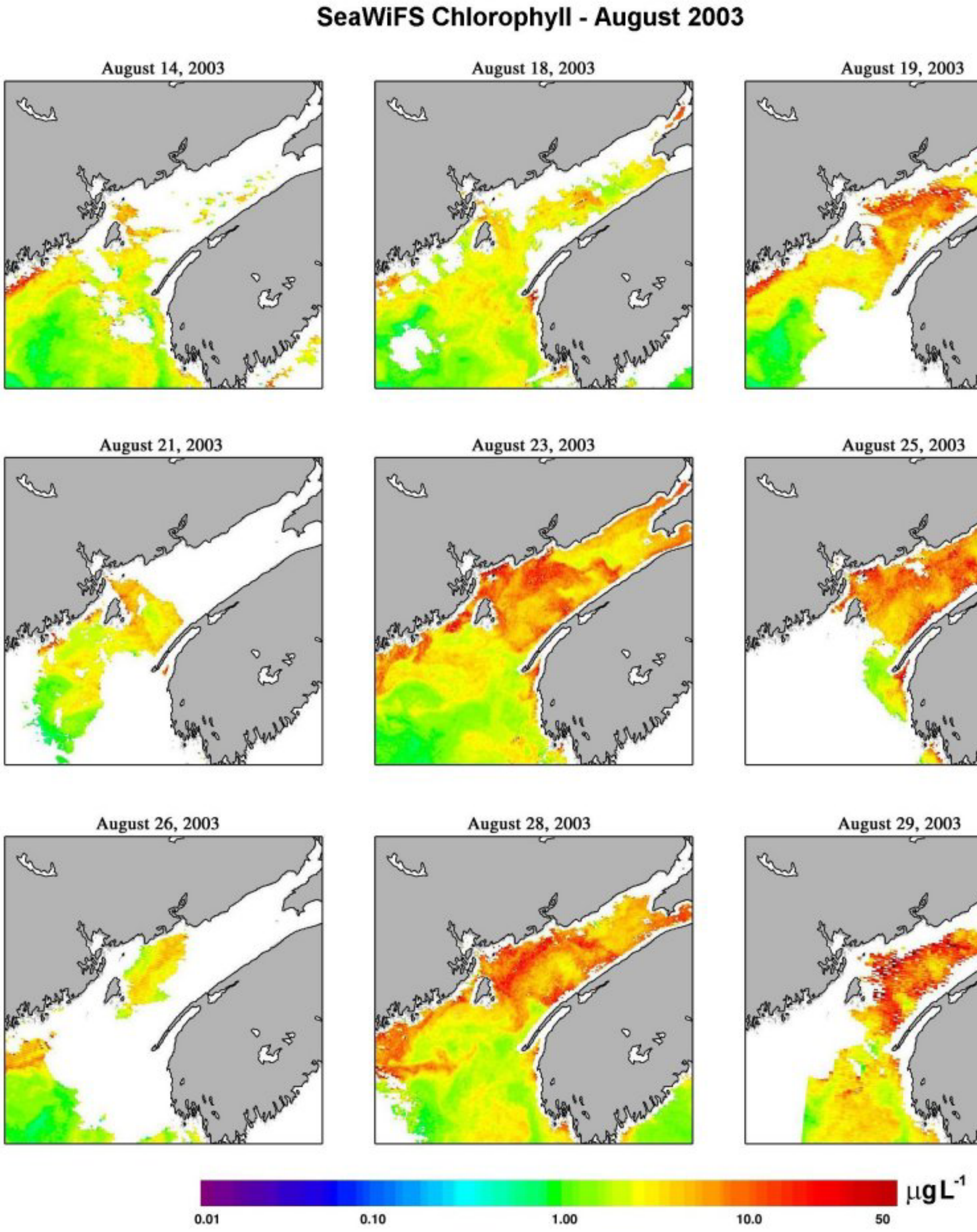
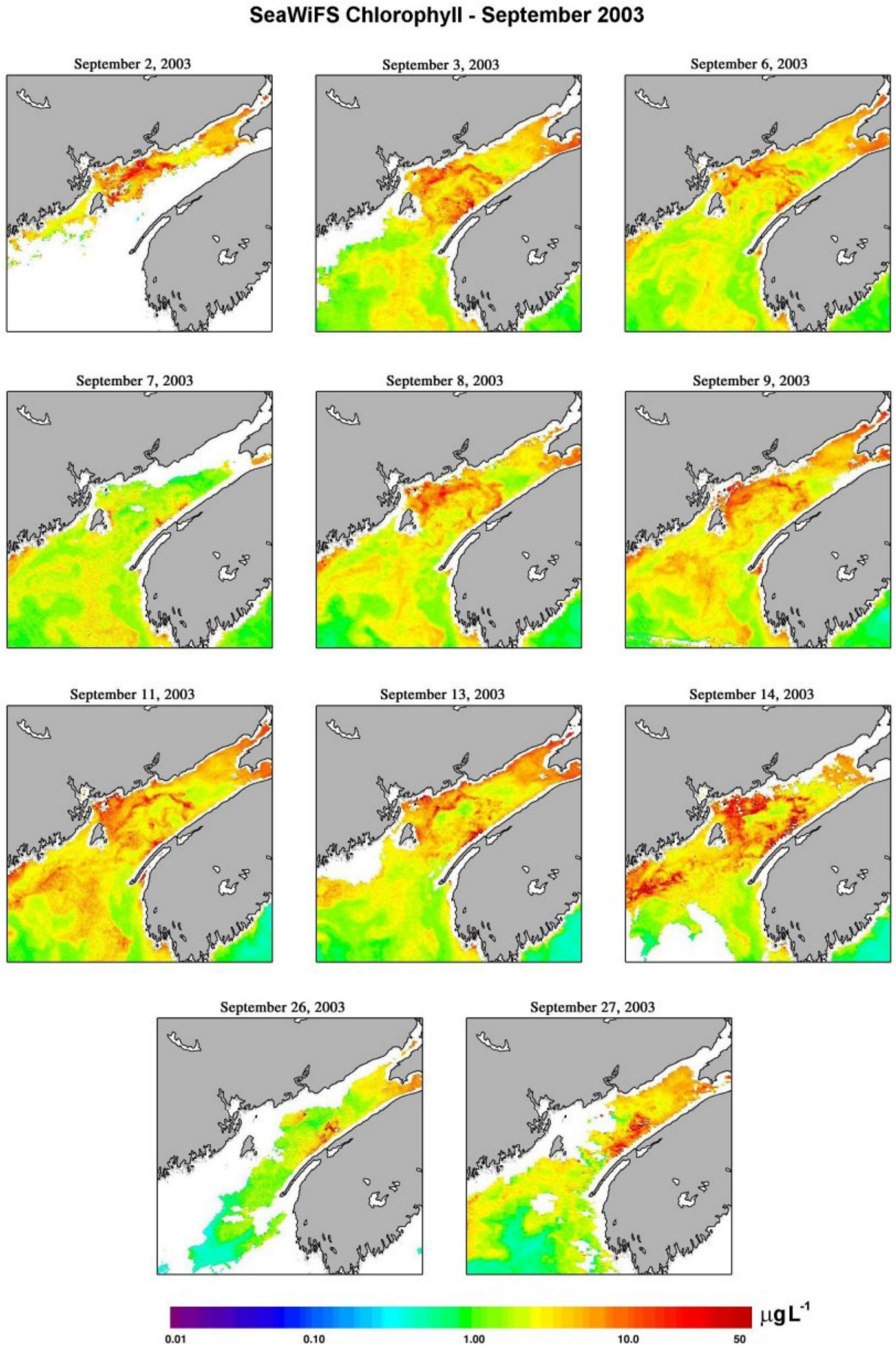

SeaWiFS Chlorophyll - August 2003
August 14, 2003
August 18, 2003
August 19, 2003
August 21, 2003
August 23, 2003
August 25, 2003
August 26, 2003
August 28, 2003
August 29, 2003
μgL-1
0.01
0.10
1.00
10.0
50

Figure 12



SeaWiFS Chlorophyll - September 2003

September 2, 2003

September 3, 2003

September 6, 2003

September 7, 2003

September 8, 2003

September 9, 2003

September 11, 2003

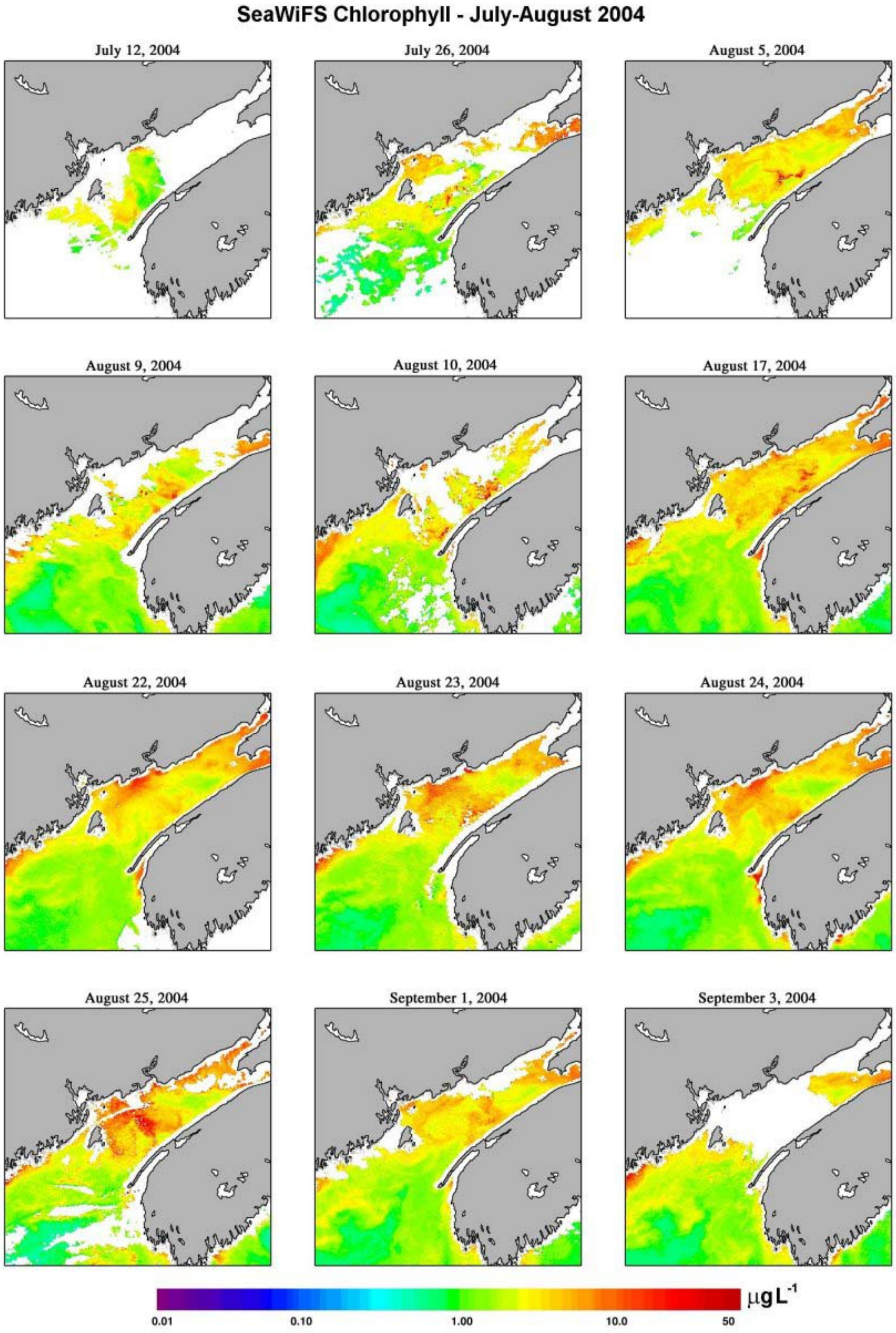
September 13, 2003

September 14, 2003

September 26, 2003

September 27, 2003

Figure 13


SeaWiFS Chlorophyll - July-August 2004

July 12, 2004

July 26, 2004

August 5, 2004

August 9, 2004

August 10, 2004

August 17, 2004

August 22, 2004

August 23, 2004

August 24, 2004

August 25, 2004

September 1, 2004

September 3, 2004

Figure 14

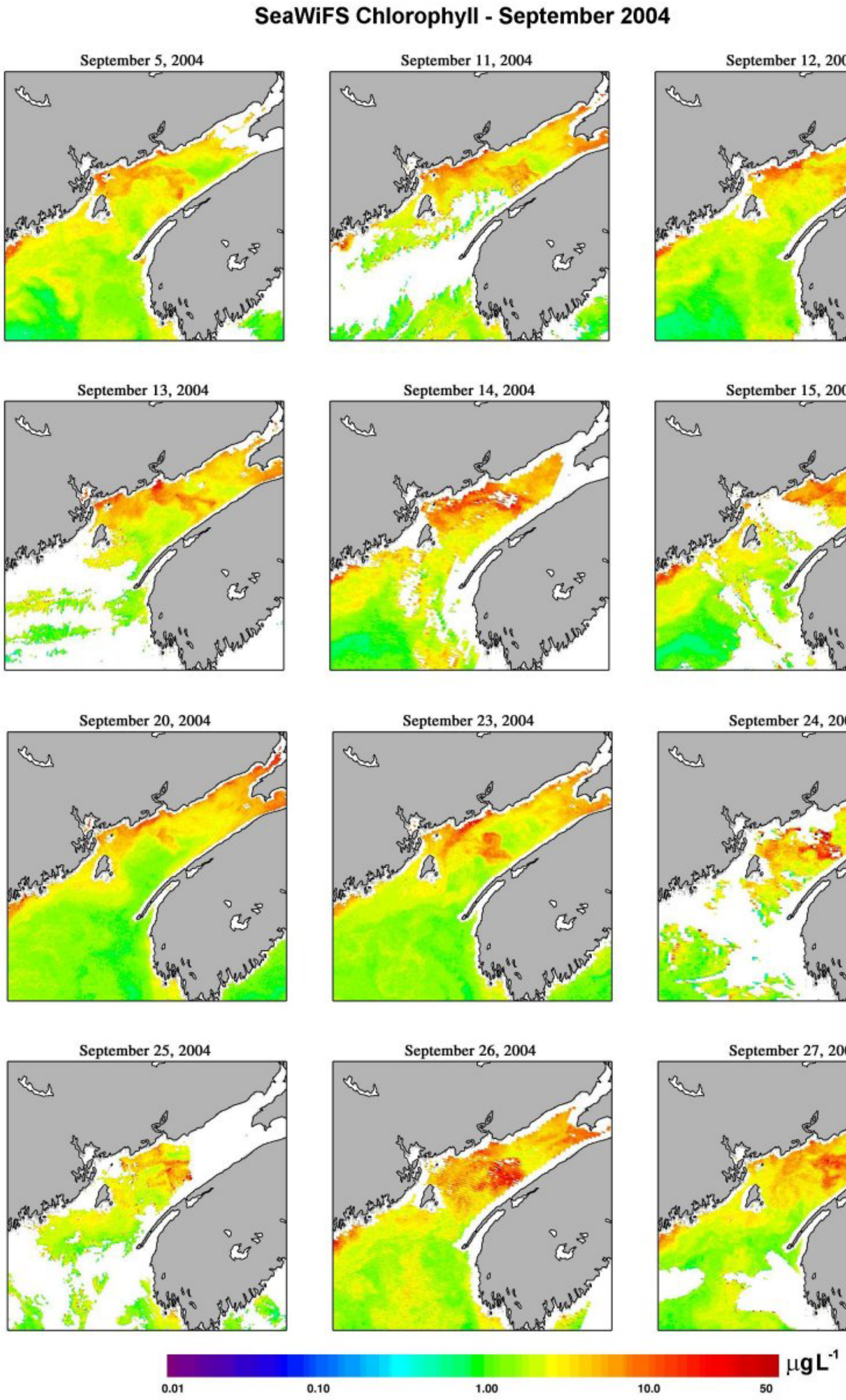

SeaWiFS Chlorophyll - September 2004
September 5, 2004
September 11, 2004
September 12, 2004
September 13, 2004
September 14, 2004
September 15, 2004
September 20, 2004
September 23, 2004
September 24, 2004
September 25, 2004
September 26, 2004
September 27, 2004
μgL⁻¹
0.01
0.10
1.00
10.0
50

Figure 15

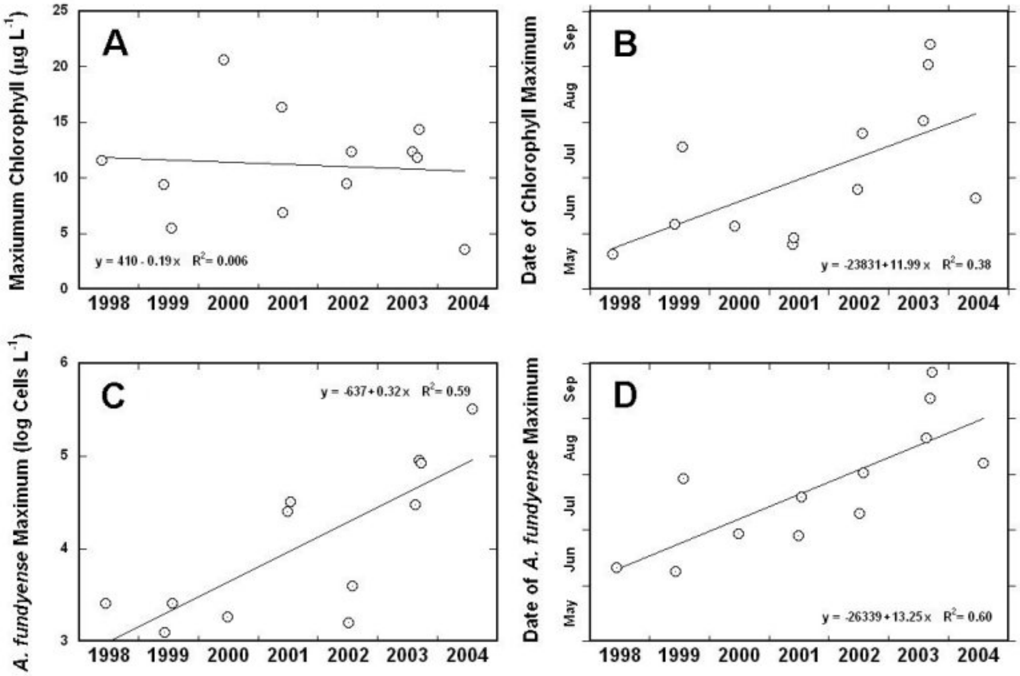

A
Maxiumum Chlorophyll (µg L-1)
25
20
15
10
5
0
y = 410 - 0.19x R2= 0.006
1998
1999
2000
2001
2002
2003
2004
B
Date of Chlorophyll Maximum
Sep
Aug
Jul
Jun
May
y = -23831+11.99x R2= 0.38
C
A. fundyense Maximum (log Cells L-1)
6
5
4
3
y = -637+0.32x R2= 0.59
D
Date of A. fundyense Maximum
y = -26339+13.25x R2= 0.60

Figure 16