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Title: Large Scale Variability of Phytoplankton Blooms in the Arctic and Peripheral Seas: Relationships with Sea Ice, Temperature, Clouds, and Wind

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Abstract: Spatially detailed satellite data of ocean color, sea ice concentration, surface temperature, clouds, and wind have been analyzed to quantify and study the large scale regional and temporal variability of phytoplankton blooms in the Arctic and peripheral seas from 1998 to 2002. In the Arctic basin, phytoplankton chlorophyll displays a large asymmetry with the Eastern Arctic having about fivefold higher concentrations than those of the Western Arctic. Large monthly and yearly variability is also observed in the peripheral seas with the largest blooms occurring in the Bering Sea, Sea of Okhotsk, and the Barents Sea during spring. There is large interannual and seasonal variability in biomass with average chlorophyll concentrations in 2002 and 2001 being higher than earlier years in spring and summer. The seasonality in the latitudinal distribution of blooms is also very different such that the North Atlantic is usually most expansive in spring while the North Pacific is more extensive in autumn. Environmental factors that influence phytoplankton growth were examined, and results show relatively high negative correlation with sea ice retreat and strong positive correlation with temperature in early spring. Plankton growth, as indicated by biomass accumulation, in the Arctic and subarctic increases up to a threshold surface temperature of about 276-277° K (3-4° C) beyond which the concentrations start to decrease suggesting an optimal temperature or nutrient depletion. The correlation with clouds is significant in some areas but negligible in other areas, while the correlations with wind speed and its components are generally weak. The effects of clouds and winds are less predictable with weekly climatologies because of unknown effects of averaging variable and intermittent physical forcing (e.g. over storm event scales with mixing and upwelling of nutrients) and the time scales of acclimation by the phytoplankton.

Popular Science Summary

Some of the most intense phytoplankton blooms that are observed from satellite ocean color imagery are located in the Arctic and its peripheral seas. A good understanding of the panarctic variability of ocean color and other parameters is important in light of recent observations of a changing Arctic. Spatially detailed satellite data of ocean color, sea ice concentration, surface temperature, clouds, and wind have been analyzed to quantify and study the large scale regional and temporal variability of phytoplankton blooms in the Arctic and peripheral seas from 1998 to 2002. In the Arctic basin, it is intruiging to find a large asymmetry in phytoplankton concentrations with the Eastern Arctic having about fivefold higher concentrations than those of the Western Arctic. Large monthly and yearly variability is also observed in the peripheral seas with the largest blooms occurring in the Bering Sea, Sea of Okhotsk, and the Barents Sea during spring. Environmental factors that influence phytoplankton growth were examined, and results show as expected, relatively high negative correlation with sea ice retreat and strong positive correlation with temperature in early spring. What is not expected is that after a certain threshold surface temperature of about 276-277° K (3-4° C) the concentrations start to decrease suggesting an optimal temperature for phytoplankton growth. This could also be attributed to nutrient depletion but the correlations with temperature are very strong and are consistent in all peripheral seas. The correlation with clouds is significant in some areas but negligible in other areas, while the correlations with wind speed and its components are generally weak. The effects of clouds and winds are less predictable with weekly climatologies because of unknown effects of averaging variable and intermittent physical forcing (e.g. over storm event scales with mixing and upwelling of nutrients) and the time scales of acclimation by the phytoplankton.

Significant Findings:

The large scale regional and temporal variability of phytoplankton blooms in the Arctic and peripheral seas have been analyzed in detail using SeaWiFS data from 1998 to 2002. In the Arctic basin, pigment concentrations in the Eastern Arctic are shown to be fivefold higher on the average than those of the Western Arctic. Large monthly and yearly variability is also observed in the peripheral seas with the largest blooms occurring in the Bering Sea, Sea of Okhotsk, and the Barents Sea during spring. Environmental factors that influence phytoplankton growth were examined, and results show as expected, relatively high negative correlation with sea ice retreat and strong positive correlation with temperature in early spring. What is not expected is that after a certain threshold surface temperature of about 276-277° K (3-4° C), the concentrations start to decrease suggesting an optimal temperature for phytoplankton growth. This result could explain previous studies showing decadal decrease in the productivity of the oceans on account of global warming. While the effect could also be attributed to nutrient depletion the correlations with temperature are very strong and are consistent in all peripheral seas. The correlation with clouds is significant in some areas but negligible in other areas, while the correlations with wind speed and its components are generally weak. The effects of clouds and winds are less predictable with weekly climatologies because of unknown influence of intermittent physical forcing (e.g. over storm event scales with mixing and upwelling of nutrients) and the time scales of acclimation by the phytoplankton.

Large Scale Variability of Phytoplankton Blooms in the Arctic and Peripheral Seas: Relationships with Sea Ice, Temperature, Clouds, and Wind

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1. Introduction

Some of the most intense phytoplankton blooms that are observed from satellite ocean color imagery are located in the Arctic and its peripheral seas. A better understanding of the panarctic variability of ocean color and other parameters is important in light of recent observations of a changing Arctic (e.g., Parkinson et al., 1999; Rothrock et al., 1999; Tucker et al., 2001). During the satellite era from 1978 to 2000 the perennial sea ice cover in the central Arctic Ocean has been declining rapidly at a rate of about 9% per decade (Comiso, 2002), and moreover, the summer ice cover in 2002 was the least extensive ever observed. Has increased ice melt and more open water in the Arctic impacted phytoplankton distributions and productivity? With shorter and discontinuous satellite ocean color records it is still difficult to answer such questions, but biological responses to environmental changes need to be better quantified and evaluated.

Seasonality is most pronounced in polar regions, but polar phytoplankton appear to be well adapted to their environment (Sakshaug 1989). The availability of light and nutrients tend to regulate phytoplankton photosynthesis and biomass accumulation, respectively. Hence, any environmental variables that influence the fluxes of light and nutrients are of particular interest in phytoplankton ecology. The seasonal retreat of sea ice in spring-summer is an important event in phytoplankton dynamics because the albedo drops sharply, the amount of light available for phytoplankton photosynthesis increases dramatically, and melt water induced stratification reduces vertical mixing (Alexander and Niebauer 1981; Sakshaug 1989). Persistent cloud cover reduces incident solar radiation available for photosynthesis to a variable degree depending on the nature of the cloud cover. Solar heating and surface temperatures follow a gradual seasonal pattern, and phytoplankton growth is normally acclimated to ambient temperatures. Water column stratification, whether from freshening or solar heating, impedes further vertical transport of nutrients, however in open waters wind mixing can more readily promote nutrient resupply. Therefore, regional patterns of wind stress that can affect the redistribution of nutrients through upwelling or horizontal advection are of interest. While iron has been observed to be limiting phytoplankton growth in the subarctic North Pacific (Martin and Fitzwater, 1988), most phytoplankton production in the Arctic occurs over the wide, relatively shallow shelves with high runoff and abundant crustal sources. Iron limitation is presumably restricted to deeper waters well removed from continental shelves in the North Pacific and Atlantic sectors.

Similar relationships between chlorophyll derived from ocean color with various environmental parameters have been studied in the Antarctic using spatially and temporally sparse data from Nimbus-7/Coastal Zone Color Scanner (CZCS) from 1978 to 1986 as well as limited in situ data (Smith et al., 1988; Comiso et al., 1993; Sullivan et al., 1993). The CZCS data were also used in a similar manner in the Arctic (Muller Karger et al. 1990, Mitchell et al., 1991), but the data coverage was even more limited. No ocean color data was available for several years until the launch of the Ocean Color Temperature Sensor (OCTS) aboard ADEOS-1 which provided comprehensive global data but unfortunately lasted less than a year (fall 1996 to summer 1997). However, with the Sea-viewing Wide Field-of-view Sensor (SeaWiFS), has provided unprecedented global views and continuous ocean color data since fall 1997. With these data, spatially detailed distributions of phytoplankton chlorophyll concentrations in the Arctic region can be observed. The principal purpose of this study is to improve our understanding of the spatial and temporal variability of ocean color distributions in the Arctic region as a whole. Although the data record length is still relatively short with only 5 growth seasons (1998-2002), seasonal and interannual variability are analyzed and evaluated with respect to a changing Arctic environment. While not used in this study, we note that the capabilities will even be better in the future with the recent launches of new systems such as two MODIS sensors on board EOS-Terra and EOS-Aqua, respectively, GLI on board ADEOS-2 and MERIS on board ENVISAT. These sensors are expected to provide improved accuracy in the observations as well as improved spatial and temporal coverage.

2. Satellite Data and Data Fusion Issues

Ocean Color: The main source of ocean color data has been the recently reprocessed version 4 of SeaWiFS (Patt et al., 2003). The SeaWiFS data have been more carefully calibrated and widely validated than any other ocean color satellite (Hooker and McClain, 2000). The data have been used in many studies, and have been shown to be spatially and temporally coherent (McClain et al., 1993, Gregg and Conkright 2002). Comparative studies of chlorophyll concentrations derived from SeaWiFS with those measured in situ in the Arctic have indicated that the latter diverge significantly from global retrievals (Cota et al., 2003, accepted; Wang et al., 2003). Retrievals from SeaWiFS' global OC4v4 algorithm (O'Reilly et al., 2000) overestimate low chlorophyll concentrations (~0.7 mg m^{-3}), but underestimate higher concentrations almost twofold (Cota et al., 2003, accepted). Given typical bloom concentrations of about 3-10 mg m^{-3} this underestimation is highly significant. These results are consistent with and extend previous observations by Mitchell (1992) showing that the optical properties of polar waters are different from those in lower latitudes. The chlorophyll retrievals used in this study have been transformed to be consistent with an arctic algorithm (OC4L) based on in situ observations (n = 686) of chlorophyll and remote sensing reflectance collected over the last several years (i.e., Cota et al., 2003, accepted).

The differences between global (version 4.0) and transformed retrievals of the SeaWiFS data are quantitatively illustrated in Figure 1. The transformed Arctic chlorophyll data, presented in color coded format in Figure 1b, reveal significantly higher values for chlorophyll concentrations than the global version (Figure 1a) with the largest discrepancies (Figure 1c) occurring in the Eastern Arctic, Bering, Labrador, and Greenland Seas. It should be stressed that the spatial coverage of our in situ data is limited to the Canadian Archipelago, and the Labrador, Beaufort, Chukchi and Bering Seas. There seems to be very good agreement between similar bio-optical data sets collected in the Barents and Greenland Seas (Mitchell 1992; Stramski et al., 2003). However, there is a major void for in situ data from the Eastern Arctic or Siberian waters, and much of this Siberian region is heavily influenced by riverine runoff on quite shallow (<50 m) shelves. The degree of interference of colored dissolved organic material (CDOM) with chlorophyll retrievals can be substantial (e.g. Carder et al., 1991, Sathyendranath et al., 2001), but has not been properly evaluated in many regions, especially the Eurasian Arctic. The use of a single chlorophyll algorithm for the entire panarctic region may produce bias in some regions. Moreover, extrapolation of an arctic algorithm to far south may suffer in a similar way to applications of a global algorithm in polar regions. The differences between the generic global and transformed arctic values are almost twofold in blooms, indicating that the latter can provide significant improvements in the estimates of productivity in the Arctic where seasonal production is often highly pulsed. Also, since the spatial distributions of the phytoplankton blooms are the same in both data sets, the transformation should yield comparable results from correlation analyses with other geophysical parameters.

Since ocean color data are available only during clear sky conditions, it is useful to know what kind of bias this could cause in the statistical analysis. In the Arctic the cloud cover can be very persistent, and can be difficult to discriminate from the sea ice cover. Some ocean color retrievals were evident inside the perennial ice pack zone, but were eliminated from analyses by using sea ice passive microwave data for masking the ice covered areas. Another problem associated with the process of cloud masking is the other extreme in which more clouds were masked than is necessary. Some areas in the Arctic were identified during the processing of the SeaWiFS data as either sea ice or cloud covered area. Our study shows evidence that cloud masking in ice free areas in the Arctic during the summer is sometimes overdone, and may cause bias in the statistics. Unfortunately for this case, the only way to correct this problem is to reprocess the entire SeaWiFS data set with a much improved cloud mask. Such an endeavor is not within the scope of this study, but deserves further attention. Also, along the same lines, averaging for ocean color data is done only for pixels with data. Such an averaging procedure is employed for lack of a better technique and also causes a bias with respect to the true average that could affect the accuracy of variability and trend studies. Criticisms applicable to cloud masking and averaging are endemic to most ocean color investigations.

Sea Ice: The sea ice cover is the most documented parameter derived from satellites in the Arctic (Parkinson et al., 1987; Gloersen et al., 1992). The seasonal and interannual variability is well known from analysis of passive microwave data. However, the passive microwave sea ice data is relatively coarse (25 by 25 km) compared to the ocean color data (i.e., 1 km by 1 km that has been remapped to 6.25 by 6.25 km), and it is possible that some of the interesting spatial changes in ocean color data near ice edges require the availability of a higher resolution sea ice data. For mesoscale studies of blooms along oceanographic fronts, in eddies, bays, or polynyas beyond the ice edge during clear sky conditions, a visible channel from SeaWiFS can be used for improved spatial characterization of the ice cover. Also, continuous microwave sea ice data at a similar resolution (6 km) have become available with the advent of AMSR-E data starting in May 2002. However, for larger scale variability studies, such as the present case, the current resolution of 25 by 25 km is generally adequate. The data provide good averages for locations of the ice edge that would be useful (among other things) in obtaining first order estimates of the amount of meltwater that is introduced within a given period.

SST, SIT, and Clouds: Sea surface temperature (SST) and Surface Ice Temperature (SIT) been derived successfully from infrared thermal channels from AVHRR (Comiso, 2001, Comiso, 2003) in the Arctic. SST and SIT are part of the panarctic surface temperatures derived and are classified with the aid of co-registered sea ice data from passive microwave sensors which can detect the two distinct surfaces even in the presence of clouds. As with the ocean color and ice data these temperature data are mapped in a polar stereographic format at a grid resolution of 6.25 by 6.25 km. Clouds statistics and albedo have also been derived from AVHRR sensors (Comiso, 2001). The cloud cover statistics data are used in the correlation analysis but not albedo since the effect of the latter is more indirect.

Winds: ECMWF (European Centre for Medium-Range Weather Forcasting) winds are currently used to quantify the effects of wind vectors on the ocean color distributions. The data set is the only one available that could provide a complete picture about the overall behavior of wind as it changes directions over ocean, land and ice surfaces. Winds over land are also needed to study the transport of dust or iron to the Arctic region. Future studies will include the use of satellite observations over ice free ocean regions such as those from QuickSCAT and Adeos-2/SeaWinds. The latter will also be compared with ECMWF winds to assess consistency.

Data fusion: Data fusion is facilitated through the processing of data from different sensors onto a common grid. The polar stereographic grid used in the processing of SSM/I gridded sea ice data was used as the standard but for some data, the grid resolution was adjusted to take advantage of their finer resolution. The time averaging is made as is practicable and nighttime data are separated from daytime data to enable investigation of diurnal effects. The common grid also facilitates analyses, and allows pixel-by-pixel correlation studies for the various parameters.

Analyses of the relationships of different parameters require careful consideration of the general characteristics of the different data sets, which are generated at different spatial and temporal resolutions. This is especially important in the evaluation of environmental effects that leads to variations in ocean color since the latter is derived only during daylight and clear sky conditions only. When comparing ocean color with surface temperature derived from infrared data, it is important to note that although the latter is also obtained for clear sky conditions both night and day data are available and correlation analysis might provide better results if analysis is done separately for day time and night time data. On the other hand, melting of sea ice in warm waters or wind-induced upwelling can occur during both day and night, and therefore, these data can be conveniently combined. Moreover, with continuous daylight in summer cloudiness is most important in relation to photosynthetic activities around solar noon, but the diurnal impact of clouds varies with season in the Arctic. Careful consideration of these factors is therefore necessary in the preparation of data sets used in correlation analyses.

The power of having co-registered satellite data of different but related biological and geophysical parameters for the Arctic is illustrated in Figure 2. Monthly averages are shown for chlorophyll, sea ice concentration, surface temperature, and cloud fraction in August 2002 when the ice cover is near its minimum. The multi-parameter data set provides a quick assessment of the spatial distribution of the different parameters for this period. The data show panarctic distributions of chlorophyll (Figure 2a) that is strongly asymmetric for the eastern and western regions in the Arctic basin during the peak of summer. The corresponding sea ice data (Figure 2b) indicate that while the eastern region appears nearly ice free, the western region is still in the process of ice melt. But as shown later, the low values in the western region are persistent even in a later period when open water areas are more extensive. The surface temperature data in Figure 2c reveal that the eastern region and the western region have comparable values during the period. Such data could be used to evaluate temperature preferences, if any, for ecosystem models in global warming scenarios. Figure 2d shows cloud statistics and indicate comparable percentage of cloudiness in the eastern and the western regions. Thus, even before detailed analysis is made one can infer that temperature and clouds may not be the key factors affecting the asymmetry observed in the ocean color data. Having co-registered data sets from different parameters provide the convenience of finding apparent relationships of the different variables before a thorough statistical analysis is done.

3. Spatial and Temporal Variability

As the ice retreats in the Arctic basin it is interesting to discover, as indicate earlier, that the prevalence of blooms in the eastern region of the Arctic (Siberian, Laptev and Kara Seas) is markedly different from those in the western region (Beaufort and Chukchi Seas) (Figure 2b). The large difference in the retrieved chlorophyll concentrations in the two regions suggests disparate environmental conditions between the two regions and/or the bio-optical properties in the East are distinct from those in the West. Such a disparity in chlorophyll concentrations between the two regions was not apparent in earlier global (McClain et al., 1993) or regional studies of the Arctic (e.g., Muller-Karger et al., 1990, Mitchell et al., 1991), but is persistent during the SeaWiFS era (1998 to the present). This may, in part, be caused by very sparse satellite data collections in the Arctic before SeaWiFS was launched (McClain et al., 1993).

In the peripheral or surrounding seas of the Arctic, large regional variability of blooms is apparent in Figure 3. Phytoplankton blooms in the peripheral seas of the Arctic are usually located in the Bering Sea, the Sea of Okhotsk, the Labrador Sea, Baffin and Hudson Bays and the Greenland and Barents Seas following the onset of the melt of sea ice in late spring or early summer. However, some areas in the North Atlantic and North Pacific, which are located hundreds of kilometers away from ice pack, also show significant blooms.

The large seasonality of phytoplankton blooms is also illustrated by the set of monthly images (April through November 1998) in Figure 3. The large scale distribution of the chlorophyll in the monthly data indicates significantly different patterns in the development of blooms between the North Pacific Ocean and the North Atlantic Ocean. In the spring, there are intense blooms in the North Pacific, but they are generally confined to the relatively shallow Bering and Okhotsk Seas. On the other hand, the spring blooms in the Atlantic are much more widespread and basically extend over most of the region north of 45°N. In the summer, both regions show lower chlorophyll concentrations. But in the following autumn, blooms are more evident and widespread in the Pacific Ocean while concentrations remain low in the Atlantic Ocean. The seasonality of the two adjoining oceans is thus very different.

The evolution of the patterns of blooms from one month to the next in the peripheral seas is illustrated using 1998 data in Figure 3, and the changes are seen to progress rapidly over the growth season. For example, the western side in the Bering Sea (near 180E) shows very intense blooms in May, but the pattern basically disappeared in June. Also, very intense blooms appeared at the Sea of Okhotsk (about 140E) in June, but the extent was drastically reduced in July. Thus, month-to-month variations can be very large. On the other hand, there are regions like the James and Hudson Bays (around 90W) in which the bloom patterns were nearly constant from June through October.

The seasonality of biological activity in the Central Arctic basin can not be confirmed because of perennial pack ice cover. The peak of the bloom in the peripheral seas appears to be in May-June, while that of the marginal seas of the Arctic basin is approximately August. The large asymmetry in the bloom distributions between the eastern and western region is again apparent and it is interesting to note that the effect is persistent throughout the summer period and early autumn. In October, the Arctic basin is virtually covered by sea ice.

As a consistency check, the images in Figure 4 are monthly data similar to those of Figure 3 but for 2002. They illustrate that the timing and location of blooms are generally the same. However, large changes in the spatial distributions from one year to another in these regions are apparent. For example, the blooms are more intense in the Okhotsk Sea and Bering Sea in May 2002 than in May 1998, while the opposite is true for the same month in the Greenland Sea and Baffin Bay regions. In September, a reversal in the patterns of the latter two regions for the two years is apparent. In the central Arctic basin, however, the patterns are almost identical for the two years when the ice distributions are very similar.

The interannual variability of the chlorophyll concentrations for each month in each data element was estimated as the standard deviation of each pixel over the 5-year study period, and the results are presented in Figure 5. Low values of standard deviation are in blue while high values are in purple. It is apparent that high standard deviations are most prominent in May during the height of the spring bloom and mainly in the vicinity of the ice edges at the peripheral seas. The standard deviations are also high in Siberian waters of the Eastern Arctic during the summer ice minima in August and September. This phenomenon further illustrates that sea ice has a key role in the interannual variability of the chlorophyll concentration.

To better understand the high standard deviations and quantify interannual variations during the peak of bloom activity in May, anomaly maps of chlorophyll concentration are presented in Figure 6 for each month of May from 1998 to 2002. The anomaly maps are generated by subtracting the May climatology presented in Figure 6f from each of the monthly values. Large positive anomalies are indicated in the color code as red, while large negative anomalies are indicated as blue. The images shown in Figure 6 represent the anomalies during the peak of the spring bloom, which is primarily restricted to peripheral seas during May, when the impact of sea ice melt is expected to be particularly prominent. Most of the large areas of positive and negative anomalies are indeed adjacent to the sea ice cover indicating the significant influence of the latter. Figure 6f also indicates that the regions of highest chlorophyll concentrations are in the general vicinity of winter sea ice cover. In 1998, negative anomalies are prevalent in the Pacific sector while positive anomalies are common in the Atlantic sector. In May 1999, there is a good balance of positive and negative anomalies in the Pacific side with the negatives usually closer to coastal areas, while in the Atlantic side the anomalies are predominantly negative. In May 2000, there is also a relatively even balance between positive and negative anomalies in both Pacific and Atlantic regions. In May 2001 and 2002, there is a predominance of positive and negative anomalies in the Pacific and Atlantic regions, respectively. It is evident that some areas such as the Greenland and Bering Seas are characterized by large interannual variability with unusually high chlorophyll concentrations one year but unusually low in other years. Moreover, most of these biomass anomalies occur in the vicinity of the seasonal sea ice.

To evaluate the role of sea ice in the observed interannual environmental variability difference maps of monthly sea ice cover between May and February are presented for each year from 1998 to 2002 in Figure 7. Areas with high negative values (blue) basically indicate those areas covered by sea ice during winter but not in May. It is interesting to note that the difference maps show that when the sea ice cover was most extensive (Figure 7d) in the area around the Kamchatka Peninsula and the Sea of Okhotsk in 2001, the chlorophyll concentration anomalies have relatively high positive values (Figure 6d, purple). Similarly an unusually expansive winter ice cover (Figure 7a) in the Greenland Sea in 1998 also coincided with positive chlorophyll anomalies in the same region (Figure 6a). Also, the more extensive winter ice cover in the Bering Sea during 1998 is nearly coherent with high positive anomalies in chlorophyll concentration in the region.

Chlorophyll anomaly images similar to those of Figure 6 but for August, representing the summer season, are presented in Figure 8. The images indicate that extreme values of the anomalies are restricted spatially to the high Arctic, and values are much smaller than those for May in the peripheral seas suggesting that interannual variability is much less pronounced by summer. There is basically a better balance of positive and negative anomalies practically everywhere except at the Bering Sea in August 1999. In the Arctic basin, however, interannual variations are more dramatic. In the eastern region where the chlorophyll concentrations are consistently high, positive anomalies are prominent in the August 2002 data while negative anomalies are evident in August 2000. In August 1999, there is a good mixture of positive and negative anomalies in the same region. In the Western region, the year-to-year changes are more subtle, and are confined mainly to the coastal regions of Alaska and Canada.

In the Arctic Basin, the August climatology (Figure 8f) again shows the large contrast in the chlorophyll concentrations between the Eastern and Western regions. This indicates that the contrast is persistent in both seasonal and interannual data. Comparing the patterns of blooms in the climatology for May (Figure 6) and August (Figure 8) also illustrates the dramatic latitudinal changes in the spatial distribution of bloom activity. By contrast, in areas that are not covered by sea ice in winter such as between 40° N and 50° N, the chlorophyll concentrations are often actually higher in August than in May.

Interannual variability of the growth seasons as indicated by biomass accumulation in the Arctic and peripheral seas have been characterized for each year from 1998 to 2002. To better quantify seasonal and interannual fluctuations of chlorophyll concentrations, nine productive but highly variable areas were identified as distinct study areas, with boundaries as indicated by different colors in Figure 9, and were analyzed separately and together. The study areas include peripheral seas such as the Bering, Okhotsk, Barents, Greenland and Labrador Seas and bays such as Hudson Bay and Baffin Bay, all with some sea ice cover during the winter. Two sub-areas in the Arctic basin are also included, namely: the Eastern region that includes the Siberian Sea, Laptev Sea and Kara Sea, and the Western region that includes the Chukchi and Beaufort Seas and the Canadian Archipelago. These study areas were between 65 to 80 °N and from 70 to 180 °E for the Eastern Arctic Region and 180 to 280 °E for the Western Arctic region. For comparison with results from other seas, a North Atlantic study area is also chosen as indicated.

To obtain a general overview of the seasonal patterns, monthly averages of chlorophyll concentrations within the boundaries of the nine study areas were calculated, and the results from February through November were combined for each of the five years are shown in Figure 10a. It is apparent that there is one dominant peak in spring and a much smaller one in late summer/early autumn period. Large interannual variability in spring blooms is also evident with 2002 having the highest value during the 5-year period, followed by 2001 and 1999. In late summer and early autumn, the highest value also occurred in 2002, with the other years having very similar values. For comparison, a similar plot is shown in Figure 10b but only for the six peripheral sea study areas as mentioned above with ice during the winter and excluding the North Atlantic, Eastern and Western Arctic study areas. Again, the highest values occur in 2002 for both spring and late summer but the difference between 2002 and the other years is not as large as in Figure 10a during the latter period. The two sets of plots show basically similar patterns with the peak during the late summer/early autumn period more suppressed in Figure 10b. The key reason is the absence of contributions from the Arctic basin in the latter. In both plots, data from the last two years shows higher values than the previous three years suggesting what can be expected in the Arctic if the perennial sea ice cover continues to retreat as has been recently observed (Comiso, 2002). A much longer record of the data is, however, needed before a meaningful trend analysis can be conducted.

4. Correlation with Environmental Variables

To gain insights into the large spatial and temporal variability of the plankton distributions weekly maps of ocean color, sea ice, surface temperature, cloud, and wind data were generated. The weekly composites provide a means to better understand the regional, seasonal as well as interannual fluctuations in chlorophyll concentrations described above. Although data with time resolutions better than weekly are available, they are not practical for time series studies because of large data gaps caused by extensive cloud cover. Averages of plankton distributions from the nine study areas in Figure 9 were calculated for the entire time series and are presented in Figure 11. The plots are color coded seasonally with blues, yellows, reds and black for spring, summer, fall and winter, respectively. There are no large gaps in the time series in some regions, like the Sea of Okhotsk, the Labrador Sea, and the North Atlantic, where ocean color data are available nearly all year. However, in other regions, like the Eastern, Western Arctic and Hudson Bay, there are substantial gaps in winter when the entire regions are effectively dark or covered with continuous sea ice.

The temporal variability can be pronounced at seasonal and interannual scales. The Eastern Arctic and the Greenland Sea showed markedly higher chlorophyll concentrations in 1998, when the opposite was true in the Bering Sea. The Barents Sea was also most productive in 2002. In the Eastern Arctic (Figure 11a), the seasonal development for each year looks different partly because of interannual differences in the onset of ice melt for some areas and differences in statistical coverage as sea ice retreats to its minimum extent. However, during the ice minima in late summer (yellows), the average values are consistently high at about 10 to 15 mg/m^3. These values are much higher than those in the Western Arctic during the same period (yellows) (Figure 11b). The main phytoplankton blooms in the high Arctic areas occur when the ice cover starts to break up and both light and nutrients are near seasonal maxima. Increases in biomass during late summer in the Arctic Ocean, when the ice cover starts to increase and nutrients are low, may be artifacts caused by frazil ice scavenging of cells with accumulation in grease ice or poor corrections of subpixel bright targets. All of the peripheral seas display similar patterns (Figures 11c-11h) with large blooms in spring, and in many cases, much smaller ones in late summer or fall. The Barents Sea and Hudson Bay regions show large gaps in their records due to darkness or prevalent ice cover. The North Atlantic region (Figure 11i), which is ice free for all seasons, also displays strong seasonality similar to other regions but more modest biomass accumulation in blooms.

Sample weekly averages of phytoplankton concentrations and the other environmental variables for the nine study areas are presented in Figures 12, 13 and 14; these plots are for 1998 and have an expanded seasonal scale compared to those of Figure 11. The weekly data starts during onset of the retreat of sea ice about 10 April (Julian day 100) and ends around 27 October (Julian day 300) when ice cover is advancing at higher latitudes. The upper panels are for chlorophyll concentrations, sea ice area (second row in Figures 12-14), surface temperature (third row in Figure 12-14), cloud statistics (fourth row in Figures 12-14) and the scalar wind with its vector components (bottom row in Figures 12-14). In the high Arctic (Figure 12d) sea ice cover can be nearly continuous for up to 10 months per year. The chlorophyll concentrations in the peripheral seas and bays (Figures 13 and 14 and part of Figure 12) show that the major peaks occur at similar times during the spring due to some melt-induced stratification along receding ice edges (e.g. Cota et al. 2003). Early in the growth season, vernal blooms occur when net gains in phytoplankton biomass exceed losses as suggested by Sverdrup's (1953) critical depth hypothesis (Platt et al. 1994). The sea surface temperatures (SST) show similar patterns, but attain different maxima at distinct times in the nine areas. In the high Arctic SST peaks at ~ 276 to 277° K (3-4° C) about mid-July shortly after the summer solstice (Figure 12), whereas the other areas all have higher (~280° to 285° K) maxima around mid-August except for the even warmer (~290° K) and ice-free North Atlantic study area (Figures 13 and 14). Sea ice melt buffers the seasonal SST gain in the Arctic Ocean basins, while ice-free waters at lower latitudes continue to warm further in summer. For regions partly covered by sea ice, the areal averages are done for both the entire region that includes sea ice (SST+SIT) and for open waters devoid of sea ice cover (SST). The cloud statistics show a number of different levels and different patterns. The ice-free North Atlantic and partially ice-covered Bering Sea areas have the highest fractions of cloud cover and the most persistent (Figures 13j and 14l). These are followed by the Greenland and Labrador Seas and Baffin Bay. By contrast, the high Arctic regions with the most ice cover have the fewest clouds (Figure 12). Most regions have maximal cloud cover seasonally during maximum open water. Winds are represented by the u and v components, and also by the magnitude of the vector sum. Wind speeds were highly variable, but were of comparable magnitude and seasonal minima in most areas followed the maximum SST. Seasonal patterns for the wind were observed in some areas, but in others interannual variations are more distinct.

During spring (April-June), chlorophyll concentration versus either ice area or average temperature exhibits two linear clusters of data: one for the first half of spring and the other for the second half of spring. Examples of these data clusters for Okhotsk and Bering Seas are presented in Figure 15 and for Baffin Bay/Labrador Sea and Greenland Sea in Figure 16. The clusters of points (squares) along the line BA in the plots shows that chorophyll concentration increases as the sea ice retreats and the SST warms up. After SST reaches a threshold value, the average chlorophyll concentration starts to decline as illustrated in data points (closed circles) along AC. It appears that this threshold value is about 276 to 277° K for practically all study sectors except the North Atlantic area which has a higher threshold value of about 285° K. This phenomenon is an indication that SST may be a more informative than initially anticipated, and could be an indicator of the magnitude of blooms. It is also consistent with nutrient drawdown during spring blooms, and may be indicative of nitrate-depletion temperatures (Carder et al. 1999). However, nitrate-depletion temperatures have been found to be highly variable and largely unreliable for the Labrador, Chukchi, and Beaufort Seas (Cota et al., unpublished). This may be generally true for high northern latitudes (D. Kamikowski, pers. comm. 2001), where property profiles are relatively scarce and nutrient concentrations are often not closely related to SST. Phytoplanktons are normally well acclimated or adjusted to their ambient environmental temperature of growth, but typically have optimal temperatures for growth and photosynthesis above these values (Li 1980). The difference in the observed threshold values for polar and temperate assemblages may reflect a genotypic adaptation their natural environments; the North Atlantic area was warmest (~283 to 291° K) (Figure 14).

Because of the split of the spring data points into two data clusters, one with a positive slope and the other with a negative slope, the correlation coefficients from the regression analysis of all data points combined would suggest relatively weak coupling. On the other hand, separating the data into an early and late spring components, represented by Sp1 and Sp2, respectively, results in much higher correlations for each period. In this study, early spring is defined as the time period of chlorophyll growth in spring (as shown in Figure 11) and include the maximum value while late spring correspond to the other side of the peak and also include the maximum value. Correlation analyses were done using simple linear regression techniques between two variables and for three periods, namely, Sp1, Sp2, and summer and results are presented in Table 1 for pigment concentrations versus sea ice, temperature and clouds and in Table 2 for pigment concentrations versus three wind variables. The strength of the relationship is represented by the correlation coefficient R which may be positive or negative. To interpret R, it should be noted that R^2 x 100% of the variation in the values of the abscissa can be accounted for by a linear relationship with the ordinate.

Table 1. Results of Correlation Analysis at the Various Study Regions for 1998-2002.

Study Region	R(Sea Ice) Sp1/Sp2/Summer	R(SST) Sp1/Sp2/Summer	R(Clouds) Sp1/Sp2/Summer
Eastern Arctic	now[1]/0.032/-0.088	now/0.481/-0.116	now/-0.642/-0.029
Western Arctic	now/-0.233/-0.035	now/-0.391/-0.612	now/-0.342/-0.013
Okhotsk Sea	-0.841/ 0.672/no ice	0.784/ -0.859/-0.601	-0.018/-0.505/-0.006
Bering Sea	-0.829/ 0.823 /no ice	0.685/-0.670/0.223	-0.094/-0.312/-0.261
Barents Sea	-0.407/ 0.502/-0.048	0.149/-0.588/-0.676	-0.077/-0.189/ 0.438
Greenland Sea	-0.313/ 0.599/-0.163	0.587/-0.811/0.435	-0.113/ 0.367/ 0.010
Hudson Bay	-0.785/ 0.641/-0.225	0.418/-0.149/-0.519	0.293/-0.657/-0.519
Baffin Bay/Lab. Sea	-0.772/ 0.642/0.303	0.298/-0.624/-0.335	-0.227/-0.129/-0.335
North Atlantic	No ice/no ice/no ice	0.770/-0.080/0.437	-0.416/-0.328/-0.453

now[1] represents "no open water"

Relationships with Sea Ice/Open Water Area

The strong coherence of the location of plankton blooms with the location of ice melt in spring, as discussed earlier, confirms previously postulated relationships between these two variables in marginal ice zones (Alexander and Niebauer 1981, Smith and Nelson, 1985, Sakshaug 1989). As sea ice retreats in spring, the surface waters are uncovered and slightly stratified by melt water providing a nearly ideal environment for phytoplankton growth. The strength of the relationship between melt water and chlorophyll concentrations is discussed quantitatively in this section. The correlation coefficients (R) between the two variables, as derived from regression analyses, are presented in Table 1 for early spring (SP1), late spring (SP2) and the summer. The value of R, as shown in Table 1, indicates substantial variability from region to region and from one time period to another.

Sea ice cover precludes chlorophyll from being observed in the Arctic basin until the late spring and summer period. In the Eastern Arctic sector, the correlation of chlorophyll concentration with sea ice retreat in the summer is rather weak, the correlation coefficients being 0.032 and

-0.088 in late spring and summer, respectively. There is an abundance of runoff and substantial meltwater every year in this region, and the variability of phytoplankton is likely dominated by other environmental variables. The weak correlations with ice cover are likely associated with the rapid increase in chlorophyll concentration (Figure 12a) for the different years that may be more closely associated with river discharge than the changes in open water area (Figure 12c). Interference of CDOM with chlorophyll retrievals is most likely in this area, and detailed in situ observations are needed to validate chlorophyll algorithms the Eastern Arctic. In terms of discharge, the Yenisey, Lena and Ob are three of the largest rivers in the world and the volume of discharge from these rivers has been increasing (Peterson et al. 2002). In the Western Arctic, the relationship of chlorophyll concentration with sea ice retreat is a little stronger with the correlation coefficient being -0.233 in late spring but in the summer, it is quite weak with the correlation coefficient being about -0.035. During spring melt, the retreat of sea ice had some effects on the phytoplankton growth but again other factors are likely more influential and the release of more meltwater or freshwater runoff may promote nutrient limitation in the highly stratified arctic waters.

The impact of the retreat of sea ice in spring on the plankton concentration is more apparent in the peripheral seas. During early spring (SP1), the correlation of the two variables are shown to be high at the Okhotsk Sea, Bering Sea, Hudson Bay, and Baffin Bay/Labrador Sea regions, the correlation coefficients being -0.841, -0.829, -0.785, and -0.772 respectively. These are areas where the sea ice cover is dominated by relatively thin first year ice, which retreats rapidly and completely disappears during the summer. Similar correlations are weaker in the Barents Sea and Greenland Sea with coefficients of -0.407 and -0.313, respectively. These later two areas are the major sites of discharge for thick multiyear ice floes from the Arctic, particularly in the Fram Strait region.

As indicated in Figures 15 and 16, the correlations are also relatively high in late spring (SP2) but with a different sign. The corresponding values were 0.672, 0.823, 0.641, and 0.642, respectively, for the Okhotsk Sea, Bering Sea, Hudson Bay and Baffin Bay/Labrador Sea regions. The implied relationships appear to be counter-intuitive, but suggest that after the initial impact of meltwater, other factors or combinations of factors become more important. For example, the continued increases in temperature and meltwater certainly would impede further nutrient resupply. The relatively high positive correlations occur after the largest decrease in ice cover and increase in biomass when nutrients are largely exhausted in surface layers. It is partly for the same reasons that in the summer, the correlation coefficients show weak relationships with ice (Table 1). In some regions, correlation analysis cannot be done, as in the Okhotsk and Bering Seas, because they are completely free of ice before the summer.

Relationships with Changes in SST

As discussed earlier, the scatter plots in Figures 15 and 16 show that phytoplankton biomass increases early in spring up to certain temperatures and beyond this, it starts to decline. The results of correlation analysis of plankton concentration versus SST also done separately for early and late spring are presented in Table 1 for all nine study areas. The values indicate strong positive correlations in early spring for Okhotsk Sea, Bering Sea, and North Atlantic with correlation coefficients of 0.784, 0.685, and 0.770, respectively. Similar correlations are reasonably good for the Greenland Sea and Hudson Bay with respective values of 0.587 and 0.418, but are fairly weak in Baffin Bay/Labrador Sea (0.298) and Barents Sea (0.149). The strong correlations indicate that SST is an important factor affecting the initial rates of accumulation of phytoplankton biomass and may reflect the initial nutrient supply. The correlations are not any better, because of the influence of other parameters like sea ice melt as indicated earlier.

Further warming in the SST beyond a threshold value corresponds to decreases in the biomass of phytoplankton concentration as indicated by the results for late spring (Table 1). The negative relationship is especially strong in the Sea of Okhotsk and Greenland Sea where the correlation coefficients are -0.859 and -0.811, respectively. The correlation is also significant at the Bering Sea, Barents Sea and Baffin Bay/Labrador Sea regions where the correlation coefficients are -0.670, -0.588, and -0.624, respectively. It appears that SST is not as reliable an indicator for Hudson Bay and the North Atlantic during this period since the correlation coefficients are relatively low at -0,149 and -0.180, respectively.

During the summer, the correlation coefficients are generally negative and significant averaging about -0.48 except in the Bering Sea where R = 0.223 and the North Atlantic where R is 0.437. During this period, chlorophyll concentrations generally increase as SST declines which may be a manifestation of mixing events with cooler, nutrient rich subsurface waters being entrained into surface waters. Moreover, fall blooms observed in some regions.

The relatively high correlations both in early and late spring are indications that temperature can be a valuable proxy for the observed variability in chlorophyll distributions. While depletion of nutrients is presumably the major factor, as indicated earlier, the strong correspondence with temperature suggests that physiological acclimation may be operative. It was interesting to note that the highest average chlorophyll concentrations occur at about the same temperature (~ 276 to 277K) in the Arctic basin, peripheral seas and major bays.

Relationships with Clouds

The influence of clouds is primarily to reduce shortwave radiation needed for photosynthesis while trapping longwave radiation that promotes warming. Cloud cover in the Arctic ranges from 60% to 85% on average with considerable interannual variability. Cloud cover was slightly higher in the Western Arctic than the Eastern region which may in part be related to the amount of open water.

The regional correlations between pigment concentration and clouds are summarized in the last column of Table 1. The correlations are more variable and generally weaker than those with sea ice and temperature. In all but four cases there is a negative correlation with cloud cover as might be expected. In early spring (SP1), the only regions in which data show possible relationships of pigment concentration with clouds are the Hudson Bay, Baffin Bay/Labrador Sea and North Atlantic regions where the correlation coefficients are 0.293, -0.227, and -0.416, respectively. In late spring, the effect of clouds are shown to be little bit stronger with R values of -0.642, -0.505, and -0.657 for the Eastern Arctic, Okhotsk Sea, and Hudson Bay. The correlations are slightly lower but still significant at the Western Arctic, Bering Sea, Greenland

Sea and the North Atlantic, with R values of -0.342, -0.312, -0.367, and -0.328, respectively. In the summer, the correlations are again mainly weak except in the Barents Sea, Hudson Bay, Baffin Bay/Labrador Sea, and the North Atlantic where the R values are -0.261, -0.519, -0.335, and -0.453, respectively. For Barents Sea, the correlation is positive at 0.438 which may mean that more cloudiness is associated with more storms that cause upwelling of nutrients. Overall, the only region where there were fairly strong relationships observed between phytoplankton concentration with clouds was in Hudson Bay, which is a relatively shallow and almost totally enclosed environment. The initial positive correlation in early spring may be related to clouds associated with storms that promote ice break up, while in late spring and summer they result in dispersion of biomass. A distinction between clouds types (e.g. heavy fog or low clouds associated with open waters versus those associated with storms) may help elucidate the role of cloud cover in the Arctic.

Lag correlation analyses were also implemented and show only slight improvements at all regions, except for a few, with a 4-week lag providing optimum results. The exceptions are increases in the correlation coefficient from -0.094 to -0.344 for the Bering Sea Sea, and -0.113 to -0.353 for Greenland Sea in early spring. Lag correlation analysis for the entire spring period was also performed but the improvements were again mainly marginal. The general lack of strong correlations may be associated with results from previous studies indicating that phytoplankton at high latitudes are usually acclimated to the low ambient light conditions. Photoacclimation to high light in natural assemblages is on the order of hours to days, while it can take weeks to acclimate to low light (Gallegos et al. 1983). Storm events with persistent clouds are also indicative of high winds that can mix populations vertically and entrain nutrients. Such events can reduce production temporarily but could enhance subsequent growth.

Relationships with Wind

Regression analyses were done with wind speed and the u- and v-components, and the results for all nine study areas are shown in Table 2. There are generally weak correlations between pigment concentrations with the three wind variables. Part of the reason maybe the high variability of wind as illustrated in Figures 12, 13, and 14. But low correlations may not necessarily mean negligible impact for wind since the key effects of the latter are twofold, one of which is positive and the other negative. The positive effect is when it injects nutrients from deeper layers to the surface through entrainment or upwelling. The vertical transport of nutrients is significant only if they are nearly depleted in the surface layer. Also, once the nutrients become available, there is a lag time before they are consumed. The potentially negative effect is that strong winds may cause mixing that disperses the phytoplankton, decreases ambient light, and destroys the stability of surface layers. This would reduce chlorophyll concentrations detectable by satellite in the near surface layer.

In the Eastern Arctic there appears to be a positive correlation (R = 0.429) with wind speed, a negative correlation (-0.402) with the v-component and practically no correlation with the u-component of the wind in late spring. This indicates a preference for a southerly wind during this period. In the summer, the correlation results are all very weak but part of the reason is that the chlorophyll concentration is consistently high during the period practically everywhere in the study region. In the Western Arctic, the correlations are both negative for u- and v-components of the wind while it is very weak and positive for wind speed in late spring. The lack of correlation with wind speed is consistent with low values and lack of variability in the pigment concentrations in the region. The negative values are likely associated with the drop in pigment concentrations after the onset of the retreat of the ice in the region in late spring (see Figure 12).

Table 2. Correlation coefficients for the nine study areas for 1998-2002.

Study Region	Wind speed Sp1/Sp2/Summer	u-component Sp1/Sp2/Summer	v-component Sp1/Sp2/Summer
Eastern Arctic	Ice Cov/0.429/0.060	Ice Cov/0.040/0.162	Ice Cov/-0.402/-0.107
Western Arctic	Ice Cov/0.034/0.154	Ice Cov/-0.332/-0.045	Ice Cov/-0.239/-0.224
Okhotsk Sea	0.011/-0.001/0.028	-0.305/0.091/0.091	0.045/-0.157/-0.325
Bering Sea	-0.533/-0.218/-0.115	-0.475/-0.332/-0.350	-0.017/-0.192/-0.130
Barents Sea	0.036/ 0.296/-0.257	0.066/-0.130/0.089	0.122/ 0.016/ 0.138
Greenland Sea	-0.323/ 0.133/-0.257	0.182/ 0.129/ 0.184	0.285/-0.037/ 0.284
Hudson Bay	-0.034/ 0.341/-0.031	0.079/ 0.385/-0.022	0.013/ 0.408/ 0.145
Baffin Bay/Lab. Sea	-0.034/ 0.290/-0.049	-0.072/-0.111/-.098	0.013/-0.034/-0.167
North Atlantic	-0.287/-0.381/-0.422	-0.324/-0.457/-0.327	0.080/-0.024/ 0.198

The effect of wind at the Sea of Okhotsk is significant only in early spring where the correlation with the u-component is negative (-0.305) while that with the v-component is positive (0.448). The contrasting effects of the u and v-components are likely the reason why the effect with wind speed is quite weak (R=0.011). The Bering Sea is the region where wind effect is persistent for both early and late spring. The correlation coefficients are negative for all three wind variables with R being -0.533, -0.475, and -0.017 for wind speed and the u- and v-components, respectively. They are also negative with R being slightly less at -0.218, -0.332, and -0.192 for the respective wind variables. In the summer, the correlation is even weaker except with the u-component in which R=-0.350.

The correlations of pigment concentration with wind at the Barents Sea and Greenland Sea are generally very weak for all time periods. The only exceptions are late spring in the Barents Sea where R=0.296 for wind speed and early spring in Greenland where R=-0.323 for wind speed and 0.285 for the v-component of wind. At Hudson Bay, it appears that wind facilitate growth in late spring in that the correlations are positive at 0.341, 0.385, and 0.408 for the wind speed, u- and v-components respectively. At Baffin Bay/Labrador Sea region, the only significant correlation is for the late spring period where R=0.290 in late spring. In the North Atlantic, the effect of wind is mainly negative for all season. In early spring R= -0.287 and -0.324 for wind speed and u-component respectively while in late spring, the corresponding values are -0.381 and -0.457. In the summer, R= -0.433 and -0.327 for wind speed and u-components, respectively. The effect of the v-component in the North Atlantic is basically negligible which means that the u-component of the wind is the key factor.

Lag correlation analyses were performed but the results did not show significant improvements except for some exceptions. One exception is in the Sea of Okhotsk where R changed from 0.011 to -0.594 for the wind speed and from 0.045 to 0.716 for the v-component in early spring.

Also, in the Barents Sea, R changed fro 0.036 to -0.403 in early spring. However, the correlation could get worse with lag analysis as in the case of the Bering Sea where R changed from -0.475 to 0.142 for the u-component of the wind and a 4-month lag.

5. Conclusions

Five years of SeaWiFS ocean color data have been analyzed in conjunction with ancillary environmental data that includes sea ice concentration, surface temperature, and cloud statistics and wind from ECMWF reanalysis data to study the large scale seasonal distribution and interannual variability of phytoplankton blooms in the Arctic and peripheral seas. In the Arctic basin, there is a large asymmetry in the chlorophyll concentrations during the summer, with the Eastern Region having average intensity of about fivefold higher that that of the Western Region. Large monthly and yearly variability is also observed in the peripheral seas with the largest blooms normally occurring in the Bering Sea, Sea of Okhotsk, and the Barents Sea during spring.

The latitudinal and seasonal distribution of blooms was shown to be similar during the 1998 to 2002 period. However, the magnitude of blooms varies from one year to another with the highest averages occurring in 2002 and 2001 in spring during the 5-year period. Also, during the summer, the highest concentrations occurred in 2002 with the other years having very similar values. Seasonality is very different in the northern Pacific and Atlantic sectors in that the Atlantic side is usually most expansive in spring while the Pacific side is more so in autumn.

In the Arctic basin, the weak correlations with sea ice cover are likely caused by the influence of meltwater and runoff persisting throughout the growth season. Moreover, while a little stratification can be advantageous for bloom development to limit vertical motion, further increases in stability may promote nutrient limitation by reducing vertical exchange. The correlations with SST, clouds and wind are also generally weak. The reasons for the asymmetry in the high Arctic are not well understood, but the difference may, in part, be related to shallower shelves, nutrient availability, and runoff. CDOM may interfere with chlorophyll retrievals more in one region than the other. The influence of the prodigious river runoff in the Eastern Arctic has not been characterized optically.

In the peripheral seas, the relationship of phytoplankton growth with the retreat of sea ice and sea surface temperature appears very strong in early spring and late spring but with opposite signs. This suggests that chlorophyll concentrations increase with SST up to a threshold value of about 276 to 277 K in early spring and beyond this, the concentration starts to decline. That biomass decreases despite the continued retreat of sea ice indicates nutrient limitation or that the threshold value is near optimal for phytoplankton growth in situ. The threshold appears consistent in all peripheral seas, but is about 285 K in the ice-free North Atlantic study area. This phenomenon is viewed as an evidence of the importance of SST as indicator or a key factor in the formation and demise of phytoplankton blooms. It could also help explain observed decadal changes in global primary production as reported recently (Gregg, et al., 2003)

The correlations with clouds are significant in some areas, but negligible in others. Correlations with wind are also very weak in practically all study regions except for a few regions and during some time periods. While clouds tend to reduce light, the correlation with clouds may not be strong because of other indirect effects. For example, storms and strong winds that cause upwelling of nutrients usually occur in cloudy regions, and this may obscure the effect of reduced cloud cover at other times in these same locations. The effect of wind is also hard to quantify, especially when dealing with weekly averages because the latter may not reflect event scales with highly variable wind direction and strength.

This study provides new insights into the spatial and temporal variability of chlorophyll concentrations at high northern latitudes. However, it is by no means complete, and more in depth regional studies are in progress to better understand oceanographic forcing. For lack of data, our ability to fully evaluate the asymmetry in the chlorophyll distributions between the Eastern and Western Arctic was limited. With only a short, five year ocean color data record it seems premature to infer biological responses to climate forcing over the entire Arctic.

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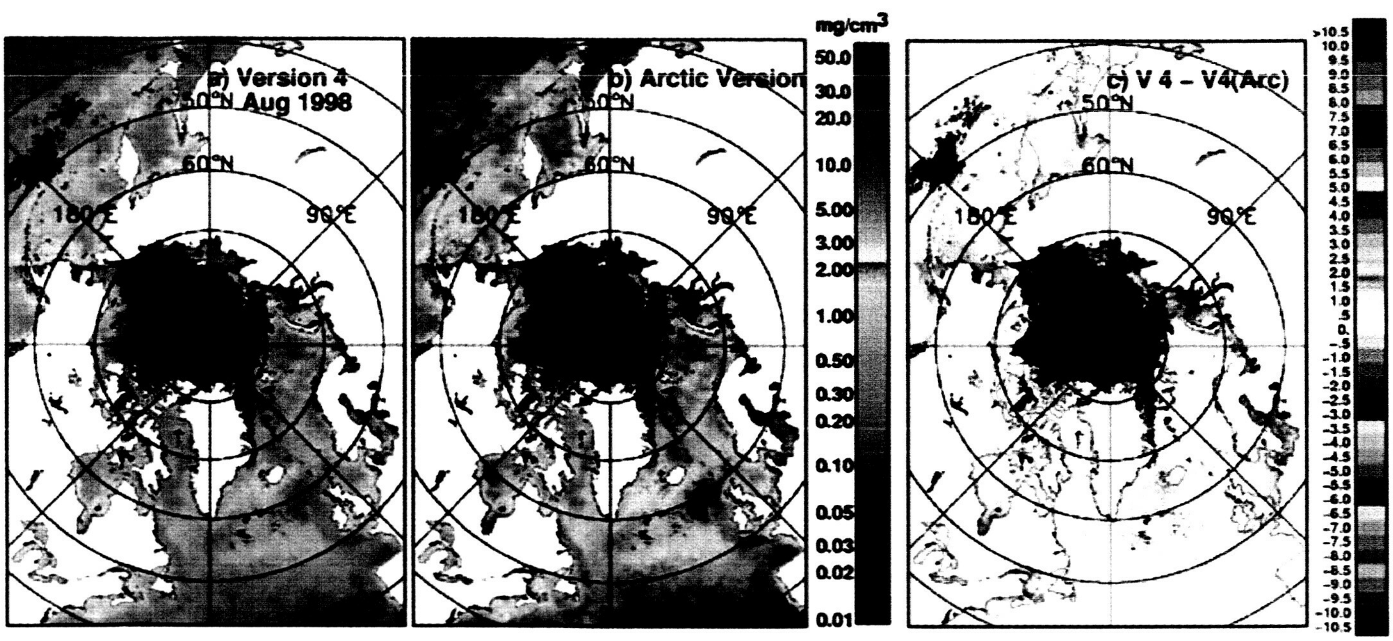
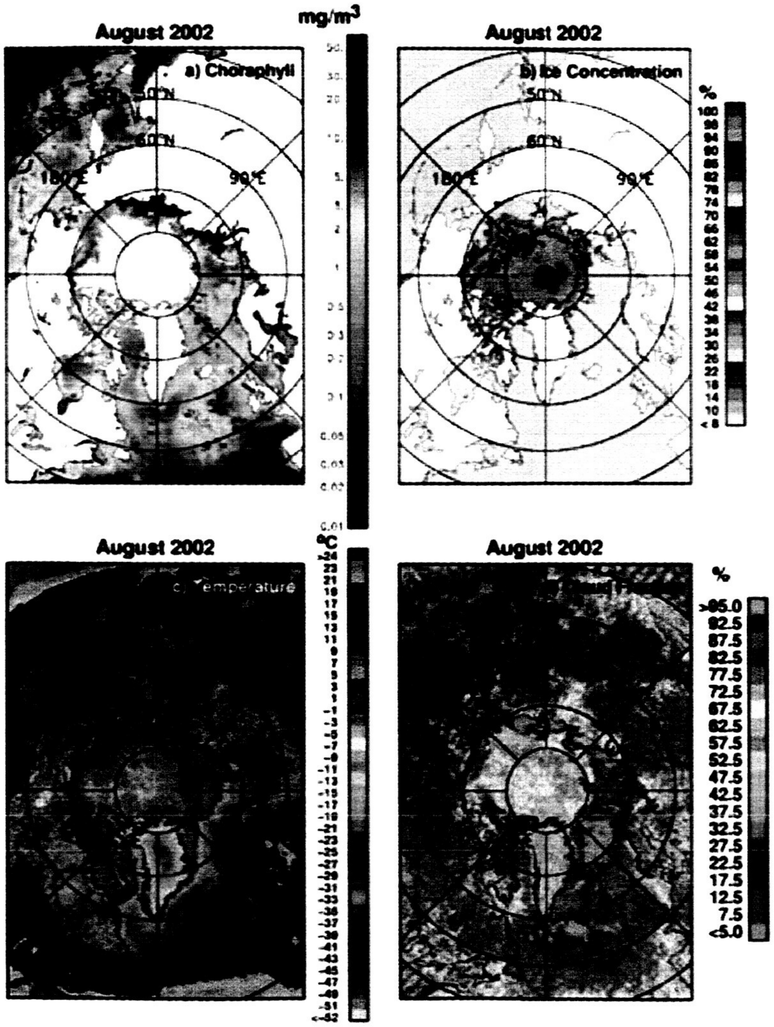


Figure 1.



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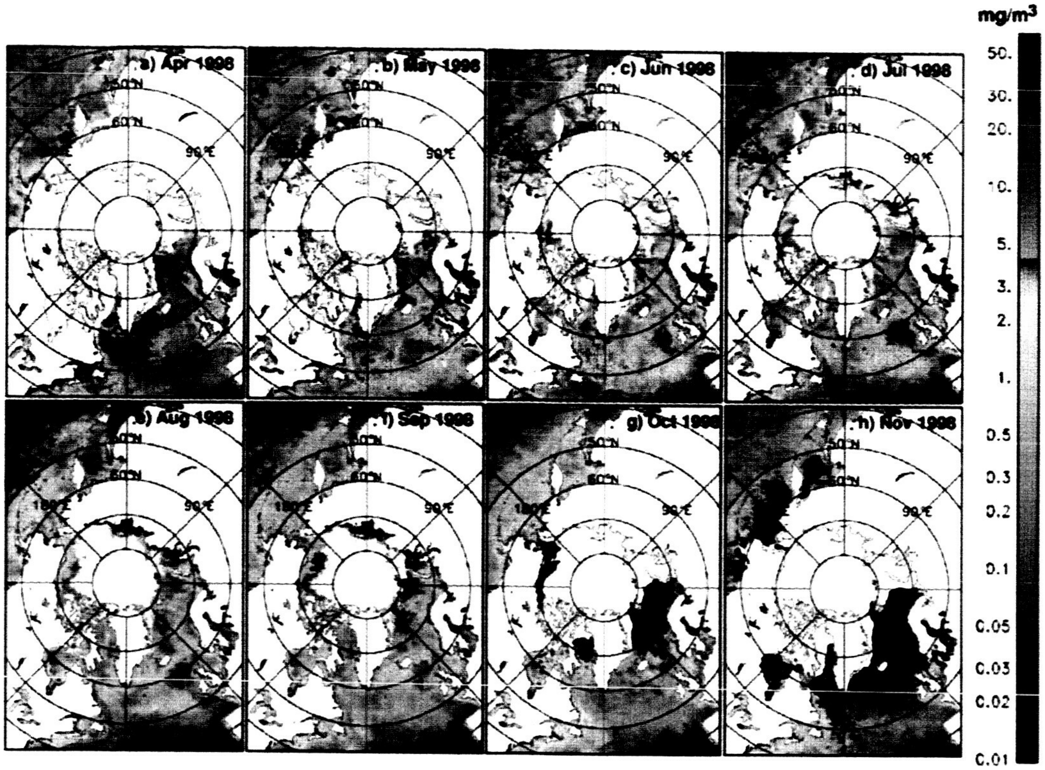

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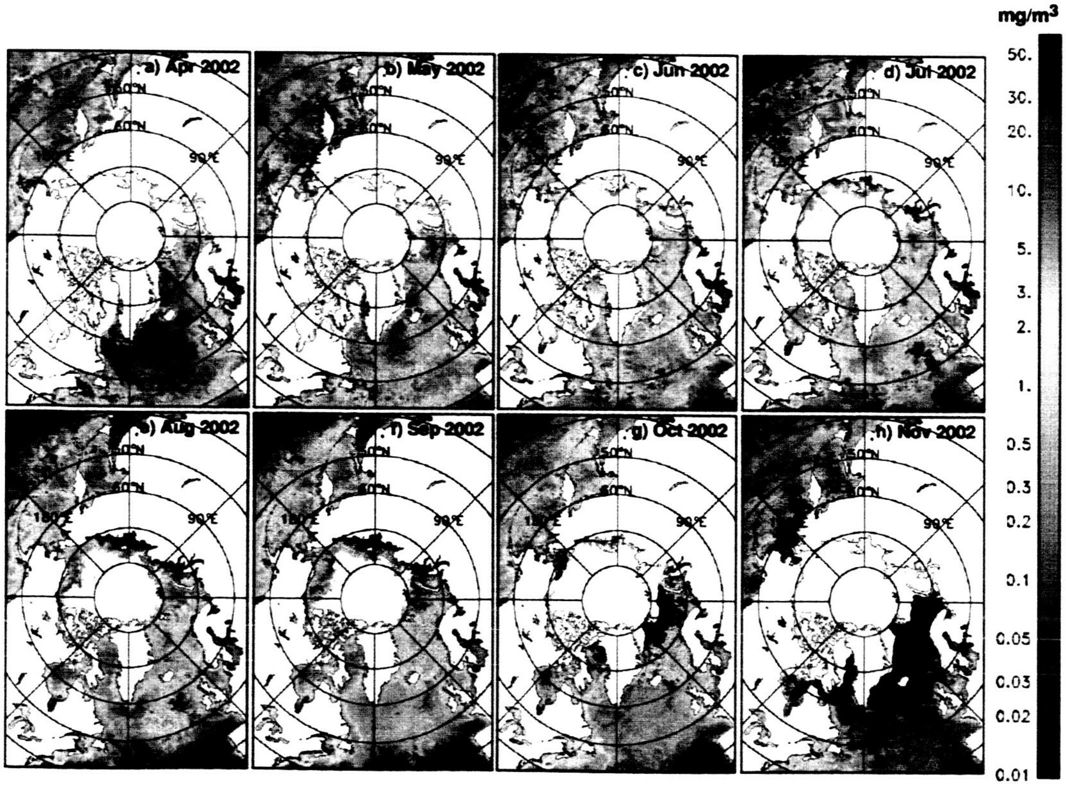

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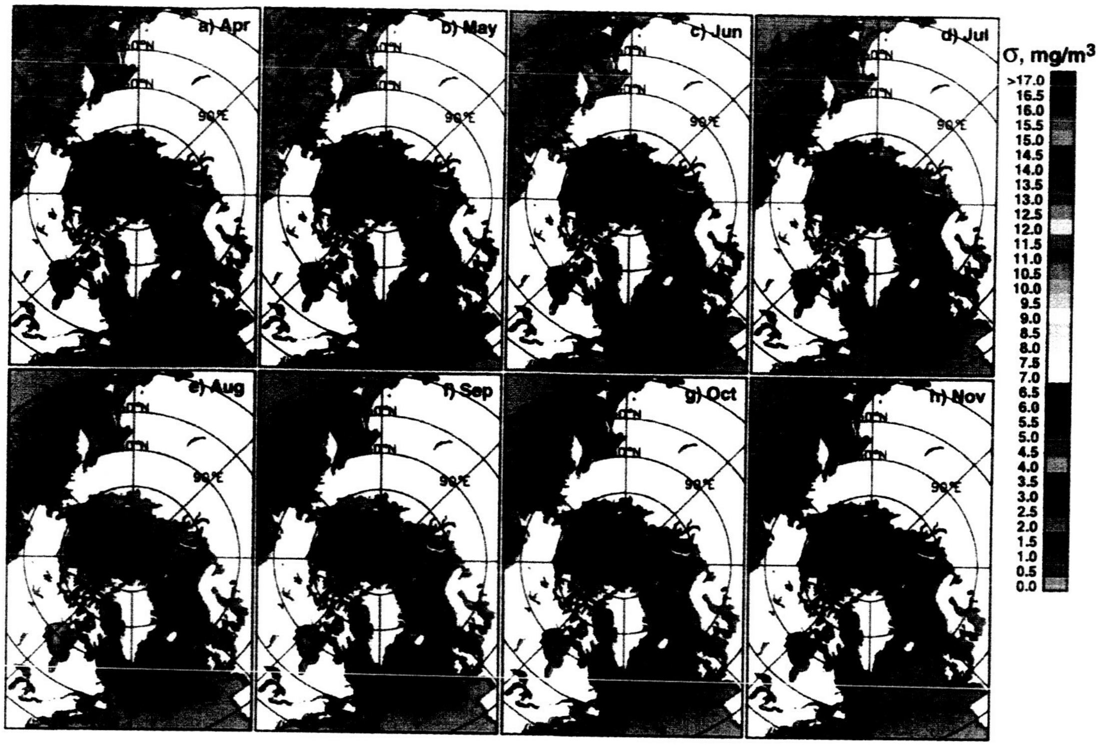

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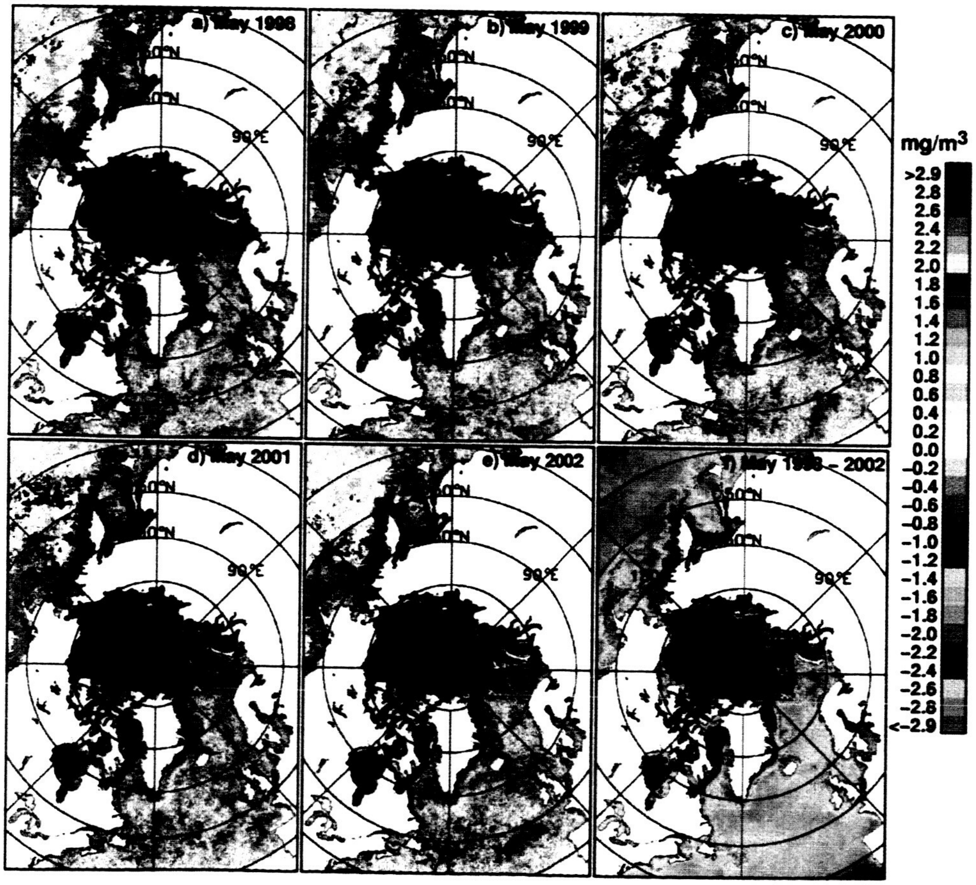

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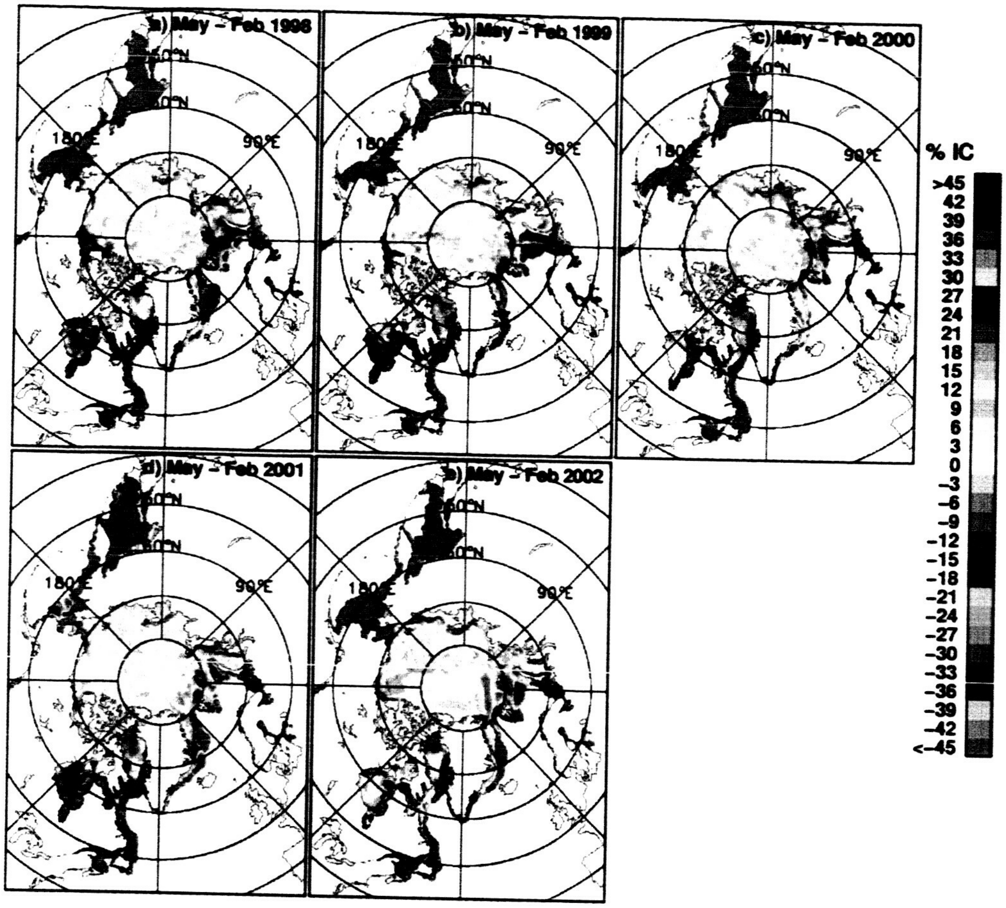

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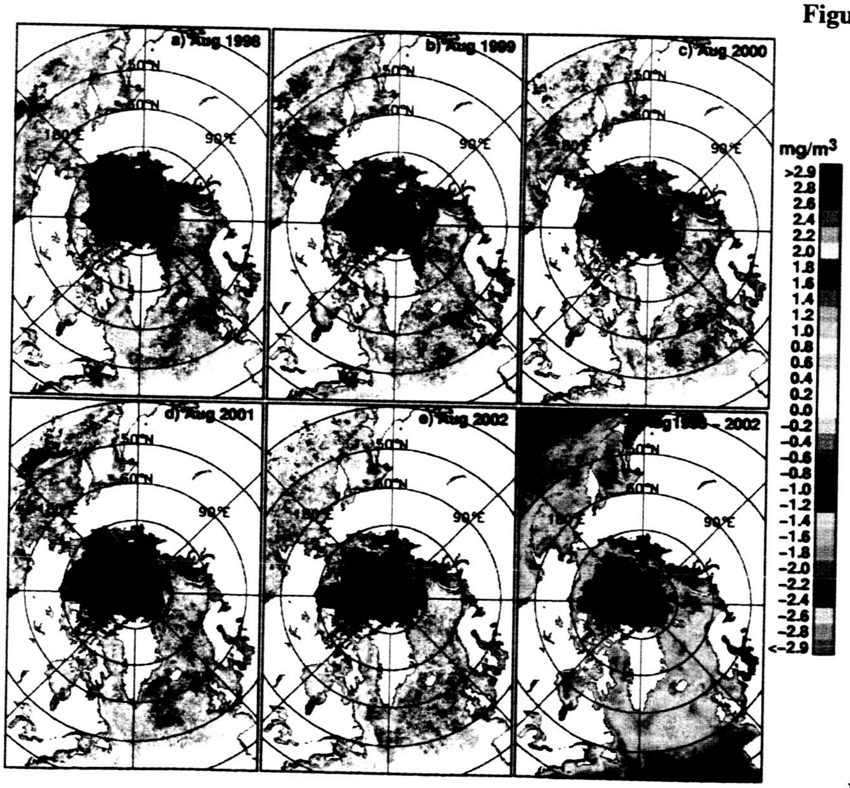

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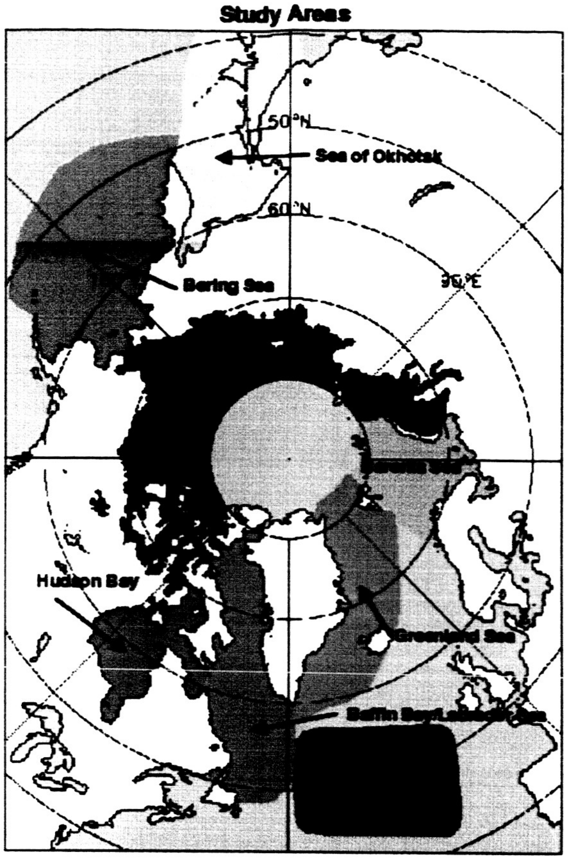

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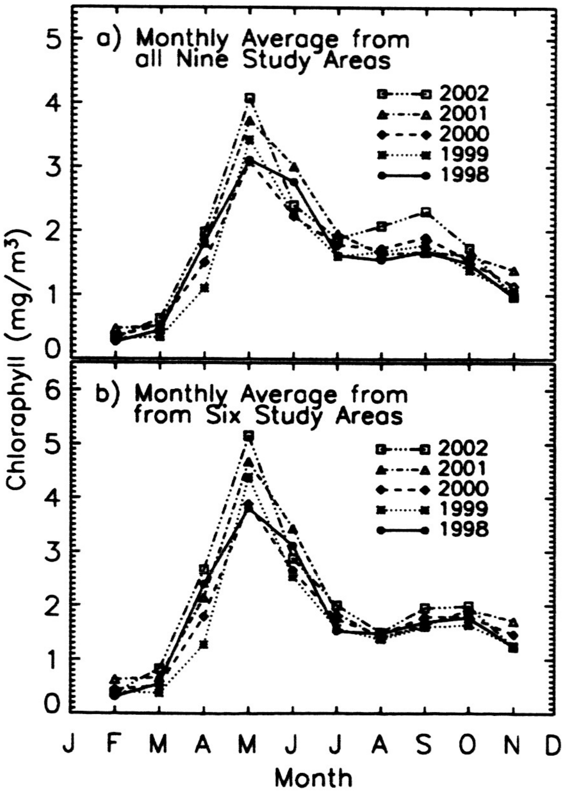

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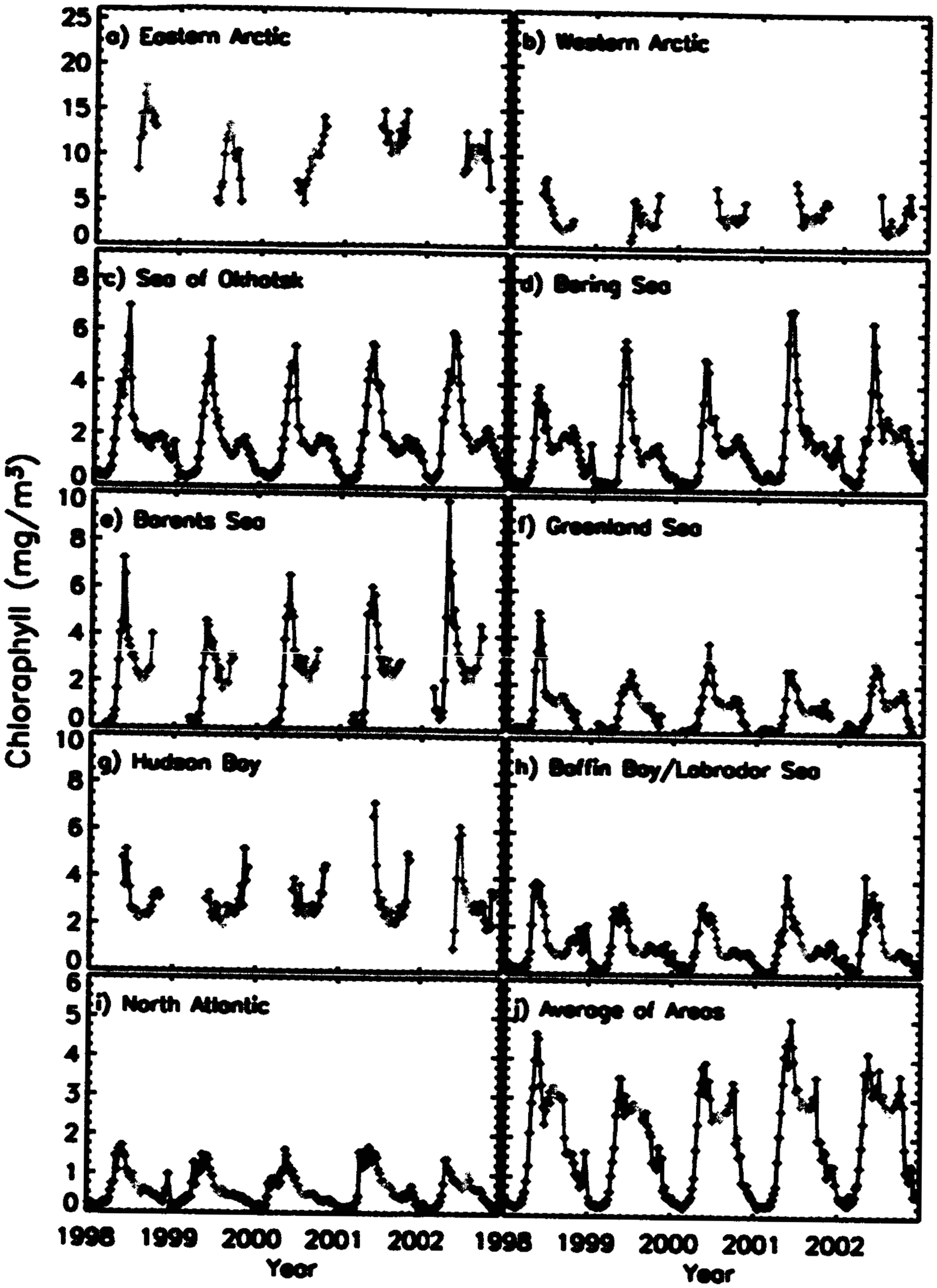

a) Eastern Arctic
b) Western Arctic
c) Sea of Okhotsk
d) Bering Sea
e) Barents Sea
f) Greenland Sea
g) Hudson Bay
h) Baffin Bay/Labrador Sea
i) North Atlantic
j) Average of Areas
Chloraphyll (mg/m³)
25
20
15
10
5
0
8
6
4
2
0
10
8
6
4
2
0
10
8
6
4
2
0
6
5
4
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1
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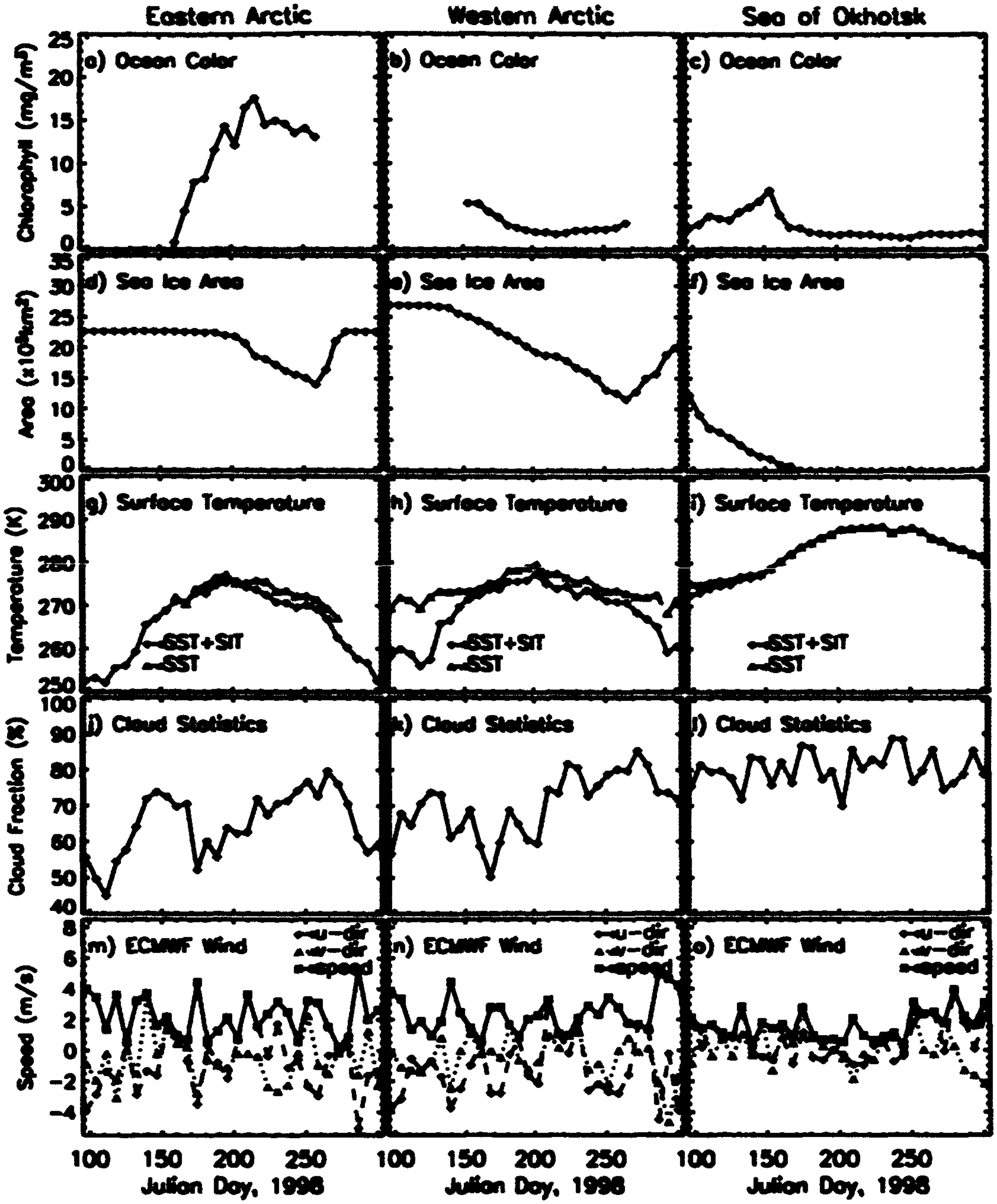
1998
1999
2000
2001
2002
1998
1999
2000
2001
2002
Year
Year

Figure 11



Eastern Arctic
Western Arctic
Sea of Okhotsk
a) Ocean Color
b) Ocean Color
c) Ocean Color
Chlorophyll (mg/m³)
0
5
10
15
20
25
d) Sea Ice Area
e) Sea Ice Area
f) Sea Ice Area
Area (x10⁵km²)
0
5
10
15
20
25
30
35
g) Surface Temperature
h) Surface Temperature
i) Surface Temperature
Temperature (K)
250
260
270
280
290
300
SST+SIT
SST
j) Cloud Statistics
k) Cloud Statistics
l) Cloud Statistics
Cloud Fraction (%)
40
50
60
70
80
90
100
m) ECMWF Wind
n) ECMWF Wind
o) ECMWF Wind
u-dir
v-dir
speed
Speed (m/s)
-4
-2
0
2
4
6
8
100
150
200
250
Julian Day, 1998

Figure 12

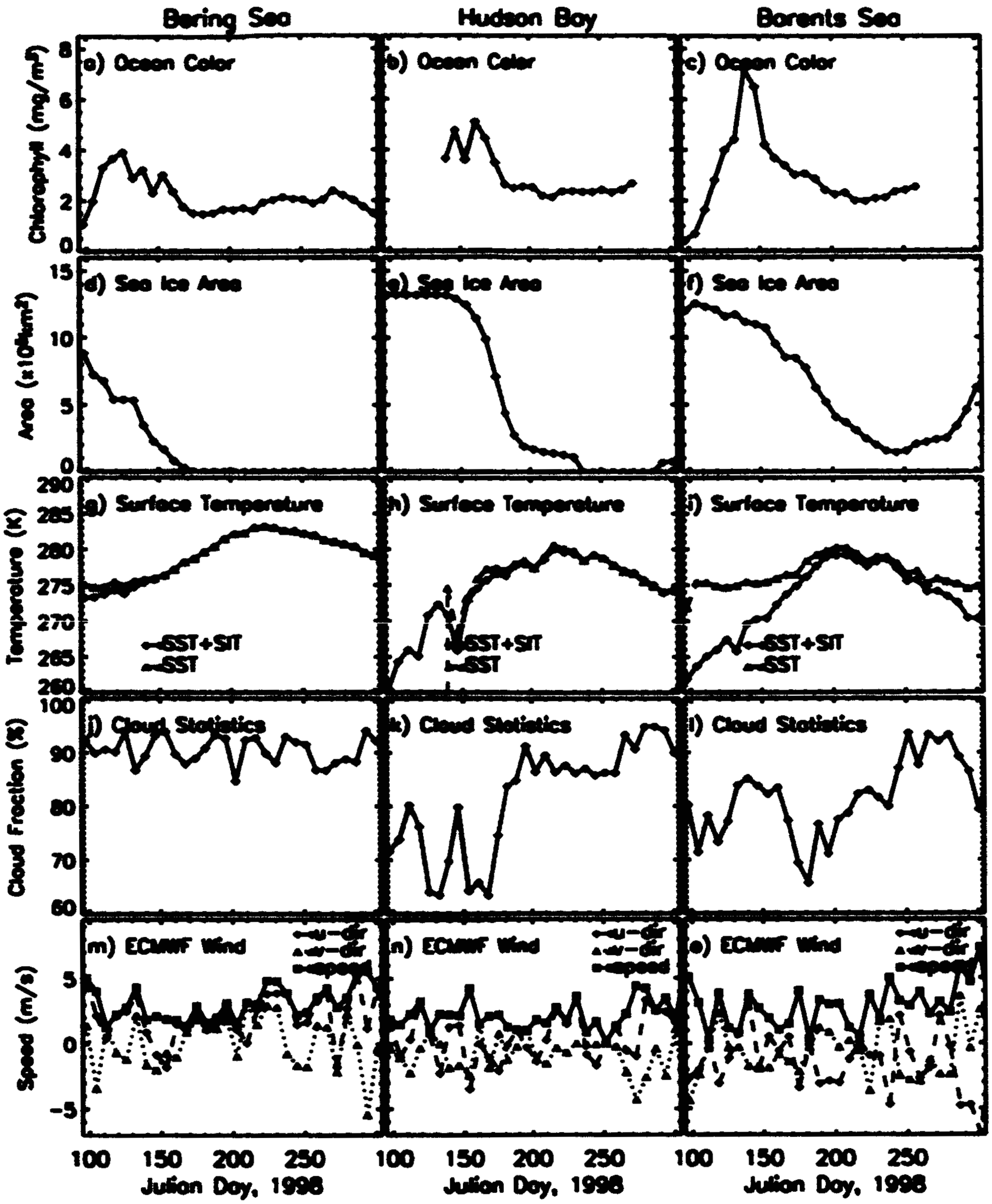
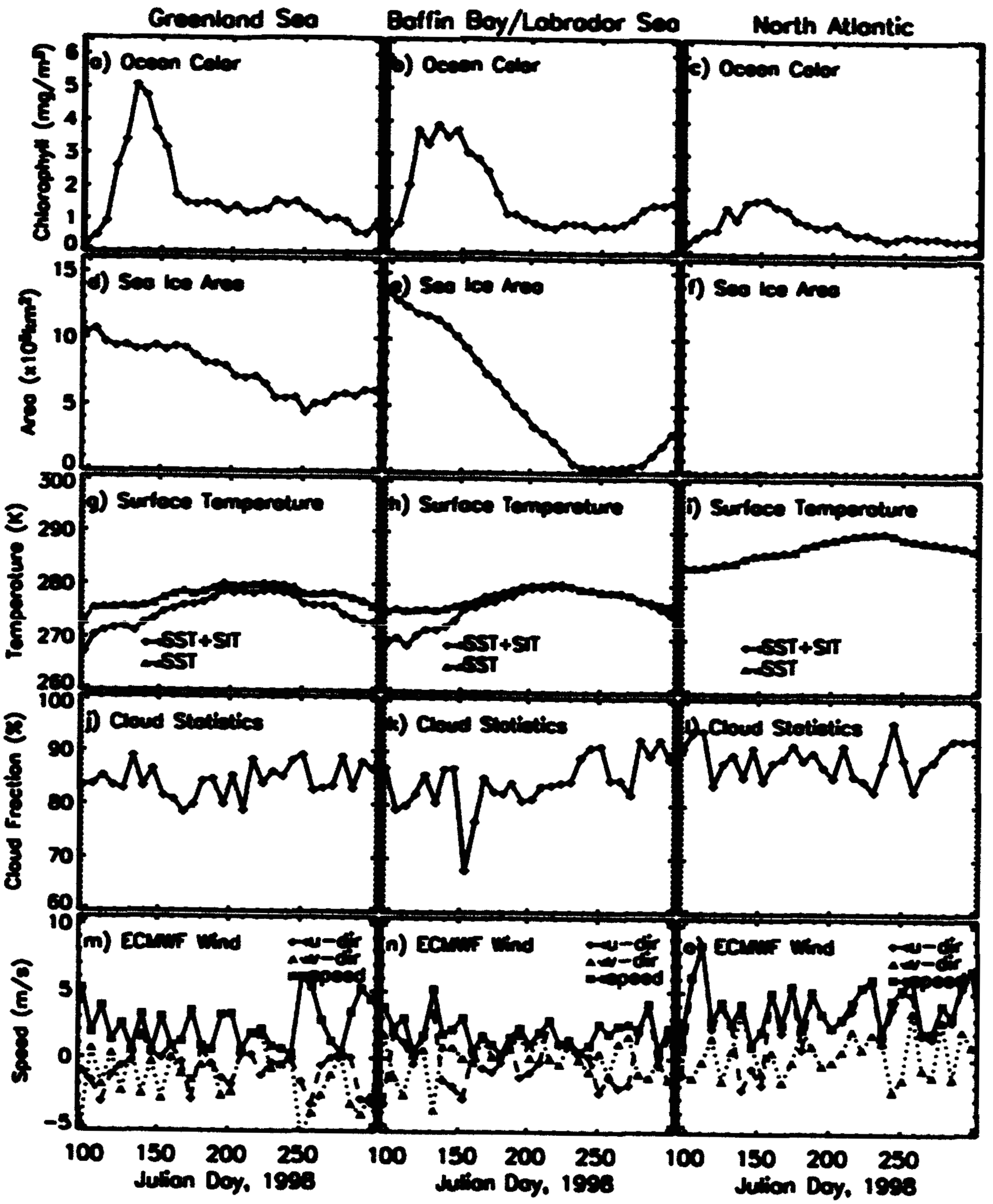
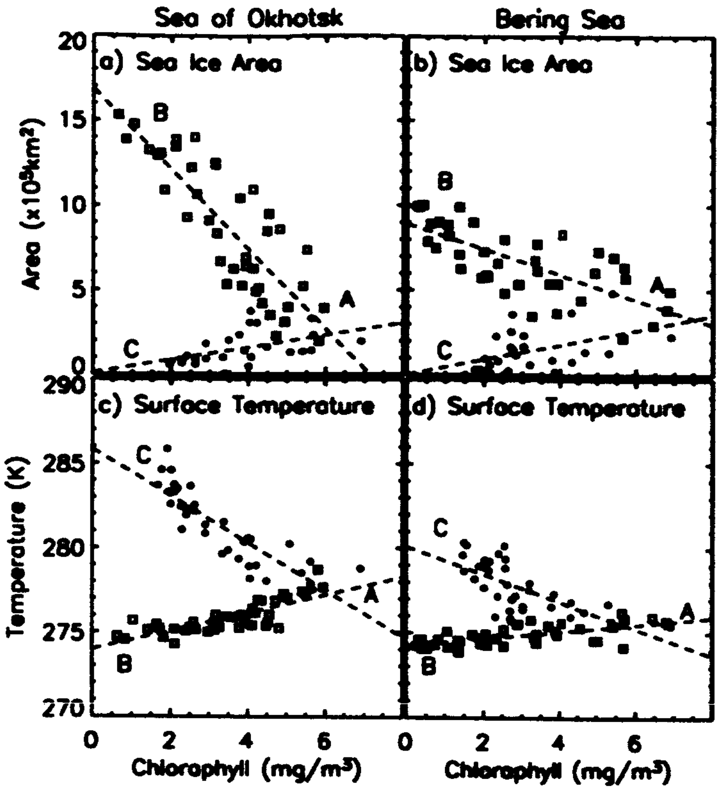

Bering Sea
Hudson Bay
Barents Sea
a) Ocean Color
b) Ocean Color
c) Ocean Color
Chlorophyll (mg/m³)
d) Sea Ice Area
e) Sea Ice Area
f) Sea Ice Area
Area (x10⁴km²)
g) Surface Temperature
h) Surface Temperature
i) Surface Temperature
Temperature (K)
SST+SIT
SST
j) Cloud Statistics
k) Cloud Statistics
l) Cloud Statistics
Cloud Fraction (%)
m) ECMWF Wind
n) ECMWF Wind
o) ECMWF Wind
u-dir
v-dir
speed
Speed (m/s)
Julian Day, 1998
100
150
200
250

Figure 13



Greenland Sea
Baffin Bay/Labrador Sea
North Atlantic
a) Ocean Color
b) Ocean Color
c) Ocean Color
Chlorophyll (mg/m³)
0
1
2
3
4
5
6
d) Sea Ice Area
e) Sea Ice Area
f) Sea Ice Area
Area (x10⁴km²)
0
5
10
15
g) Surface Temperature
h) Surface Temperature
i) Surface Temperature
Temperature (K)
260
270
280
290
300
SST+SIT
SST
j) Cloud Statistics
k) Cloud Statistics
l) Cloud Statistics
Cloud Fraction (%)
60
70
80
90
100
m) ECMWF Wind
n) ECMWF Wind
o) ECMWF Wind
u-dir
v-dir
speed
Speed (m/s)
-5
0
5
10
100
150
200
250
Julian Day, 1998

Figure 14



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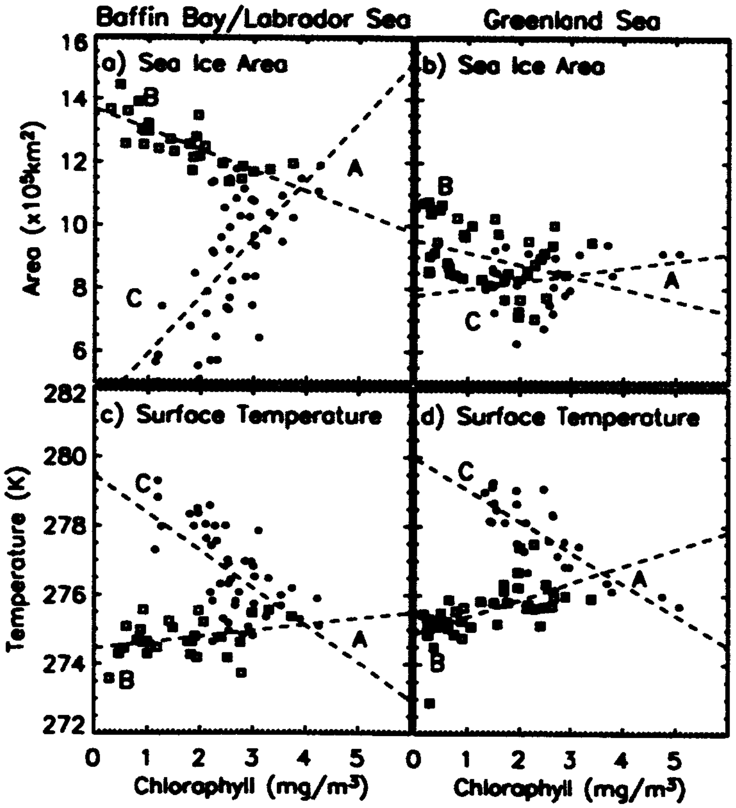

Figure 16