

REMOTELY SENSED STUDIES OF PHYTOPLANKTON DYNAMICS UNDER PHYSICAL FORCING IN DIFFERENT OCEAN REGIONS

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ABSTRACT

The information obtained from the modern Earth-observing satellites, enables comprehensive studies of seasonal dynamics of ecosystems in different regions of the World Ocean. The properties of physical environment (sea surface temperature, measured by AVHRR radiometers; currents estimated from altimetry data; wind and precipitation measured by meteorological satellites) combined with biological data derived from ocean optics, reveal principle features of phytoplankton seasonal cycles in diverse ocean environments. The peculiarities of these cycles depend on local bottom topography, hydrological regime, wind forcing, etc; in coastal regions river discharge is of great importance. The examples of different types of seasonal cycles of phytoplankton are presented, and the mechanisms influencing the phytoplankton growth are discussed. The peculiar region is the Northwest Atlantic near Newfoundland Rise, where abrupt environmental contrasts (the cold Labrador Current flowing from the north and the warm Gulf Stream from the southwest) result in different types of seasonal cycles over rather narrow area. Another illustrative example is the Black Sea where extremely high water stratification results in seasonal cycle similar to subtropical regions rather than to temperate ones. The general regularities of seasonal phytoplankton cycles depend on physical factors influencing water stratification.

The analysis of remotely sensed information is at present a powerful tool of oceanographic studies in all regions of the World Ocean. The data collected by satellites since late 70's provide oceanographers with a large volume of information on the state of the ocean surface although these data are not always accurate enough. The remotely sensed information is available to scientists either directly from the satellites being received by the local stations and processed directly by users, or disseminated via Internet after processing at large centers. The most important centers are DAAC (Distributed Active Archive Center) in GSFC (Goddard Space Flight Center), PODAAC (Physical Oceanography Distributed Active Archive Center) in JPL (Jet Propulsion Laboratory), SAA (Satellite Active Archive). The most important remote sensing instruments are infrared sensors collecting data on Sea Surface Temperature (*SST*), altimeters obtaining anomalies of Sea Surface Height (*SSH*), and the sensors working within the visible light band. The information collected by the visible light sensors is especially valuable for biologists, because it characterizes the concentration of plant pigments (*Chl*) in the most productive surface ocean layer. The surface chlorophyll concentration is, in its turn, an important quantity, which can be used for predictions of the properties of pelagic community (Vinogradov *et al.*, 1997), including primary production rate and biomass of different trophic groups of plankton.

The most important instrument collecting bio-optical information on ocean color is SeaWiFS (Sea-viewing Wide Field-of-view Sensor) radiometer, operating from September 1997. By summer 2000 as much as almost three seasonal cycles of phytoplankton development were observed; these data enable scientists to reveal general regularities of seasonal variations of phytoplankton biomass. Previous studies of seasonal cycles of remotely sensed phytoplankton in many regions of the World Ocean (Banse and English, 1994; Longhurst, 1995, and many others) were based on the data of CZCS radiometer, collected during 1978-1986. However, after launch of the *OrbView-2* platform with SeaWiFS radiometer the amount of remotely sensed bio-optical data significantly increased. Moreover, nowadays we can combine the remotely sensed *Chl* data with simultaneously measured satellite data on physical environment (*SST*, *SSH*, meteorological information, etc.).

The goal of the present paper is the analysis of basic mechanisms of influence of hydrological and meteorological factors on phytoplankton, using for this purpose remotely sensed data. The first point of this analysis is to distinguish between, on the one hand, the process of passive transport of phytoplankton by water currents, and, on the other hand, the hydrological conditions influencing phytoplankton growth. In the first case we analyze horizontal water movements. The remotely sensed information used for this purpose is *SST* distribution derived from high-resolution infrared images and the anomalies of water circulation derived from *SSH* data. On the contrast, phytoplankton growth seems to depend on vertical stratification of the upper part of water column. Unfortunately, remote sensing does not provide information on vertical distribution of hydrological parameters. However, the analysis of hydrological and meteorological information (heat flux, wind, precipitation) can reveal general features, which either enhance or disturb water column stratification.

To illustrate the mechanism of influence of stratification on phytoplankton development we selected two ocean regions: the Northwestern Atlantic near Newfoundland Rise and the Black Sea. The first region is peculiar with its abrupt environmental contrasts. The cold Labrador Current flowing from the north and warm Gulf Stream flowing from the southwest result in different types of seasonal cycles observed over rather small area. The Black Sea is peculiar due to extremely high water stratification resulting from increased (as compared with other regions) input of freshwater with river discharge. Both seasonal cycles observed in these regions and the local variations of these cycles reveal the role of water stratification in the process of phytoplankton development.

REMOTELY SENSED DATA USED FOR ANALYSIS

All the remotely sensed data used in this study were obtained via Internet from the centers of processing and dissemination. The following data were used:

CZCS (Coastal Zone Color Scanner). The data were collected during 1978–1986 with CZCS radiometer (Hovis *et al.*, 1980) on *Nimbus-7* satellite. It was collecting information from November 1978 to June 1986. The color of water surface layer was measured at the bands 443, 520, 550, 670, and 750 nm. More than 60,000 images were processed at Goddard Space Flight Center (GSFC, NASA) and summarized as climatic monthly data averaged over the entire period of observations. These data were stored on CD's in the form of regular grids of resolution 2048 pixels /360°, equivalent to ~18.5 km on equator. The structure of this archive is described in (Feldman *et al.*, 1989). We used these monthly climatological data to analyze the general regularities of the dynamics of plant pigments concentration in the regions under study.

SeaWiFS (Sea-viewing Wide Field-of-view Sensor). The ocean color data (1997–2000) used in this study were produced by the SeaWiFS Project at GSFC. The data were obtained from the Goddard DAAC under the auspices of NASA. Use of this data is in accord with the SeaWiFS Research Data Use Terms and Conditions Agreement. SeaWiFS radiometer measures ocean color at the bands 412, 443, 490, 510,

555, 670, 765, and 865 nm. In this study the Level 3 Standard Mapped data were used (global grids of the resolution 4096 pixels/360 degrees (~9.28 km). We used for analysis both chlorophyll *a* and CZCS-like pigment concentrations. The first ones were used during time-series analysis; the latter values were used when we compared the spatial distribution of SeaWiFS data with CZCS observations.

MCSST (Sea Surface Temperature). The data were collected by AVHRR (Advanced Very High Resolution Radiometers) aboard the NOAA-7, -9, -11 and -14 polar orbiting satellites and processed using the Multi-Channel Sea-Surface Temperature algorithm (McClain *et al.*, 1985) in the Physical Oceanography Distributed Active Archive Center at the Jet Propulsion Laboratory (JPL PODAAC Product 016). The data have been collected since November 1981, averaged weekly and interpolated (without missing values) over global equal-angle grids of spatial resolution of 2048/360° pixels (~18.5 km) per degree of longitude and latitude (similar to CZCS). The nominal accuracy is 0.3°C. We used only the data collected during nighttime (descending pass) to avoid the short-period *SST* variations resulting from heating of thin surface layer.

TOPEX/POSEIDON Sea Surface Height. We used the gridded sea level anomalies, which have been observed by TOPEX/POSEIDON satellite altimeter since 1992. The data were processed in the University of Texas at Austin Center for Space Research (UT/CSR). The sea level anomaly is the deviation of the sea surface away from the 4-year (1992–1996) averaged mean surface. The altimeter observations were averaged into grids of 1° by 1° resolution. The topography has an estimated accuracy of 15–20 cm. The data processing and the error analysis are described in detail in (Tapley *et al.*, 1994). We used these data to evaluate anomalies of the main currents in the Newfoundland region.

NCEP Wind data. We used zonal and meridional components of wind speed at 10 m from SeaWiFS near-real time ancillary data set. The data were obtained from the National Center for Environmental Prediction (NCEP) and processed in GSFC SeaWiFS Data Processing Center. The data were interpolated to Equidistant Cylindrical images of 1° latitude/longitude resolution. The temporal coverage is from March 1997, temporal resolution 6–12 hours. The zonal and meridional wind speed components were monthly averaged to estimate the differences between winds dominating during the period under study (1997–2000) and climatological winds (averaged over 1946–1990) obtained from the same source.

GPCP (Global Precipitation Climatology Project) data. The data on atmospheric precipitation were processed in GSFC NASA from satellite measurements of precipitable water content in the atmosphere and rain gauge data, monthly averaged and interpolated on regular grids of 2.5° latitude/longitude resolution. From these data we calculated the mean intensity of precipitation over the Black Sea area.

Meteorological data were obtained from the archive of World Meteorological Organization (WMO). The temperature anomalies for both *SST* and air temperature were calculated by subtracting from actual values climatic means calculated for the period 1982–2000.

SEASONAL CYCLES OF PHYTOPLANKTON IN THE NEWFOUNDLAND AREA

The zone of Newfoundland Rise (Figure 1) is under strong influence of both the cold Labrador Current flowing from the north and the warm Gulf Stream flowing from the southwest. The physical and biological gradients are extremely pronounced in this region, and distinct features typical to different geographical zones occur over the small area. The sharp frontal zone separates cold and fresh Labrador water from warm and saline Atlantic water of the Gulf Stream extension area. Therefore, we expect the great difference between phytoplankton seasonal cycles in the northern and southern parts of the region. To discover the difference, we selected three small regions (2° latitude x 3° longitude), which were considered to be typical to the main natural zones, located from north to south (Figure 1). Region 1 was

selected in the zone of influence of the Labrador Current, region 3 was in the zone of influence of the Gulf Stream. Region 2 was selected in the zone of the Grand Bank (in the deepest area of the Flemish Pass).

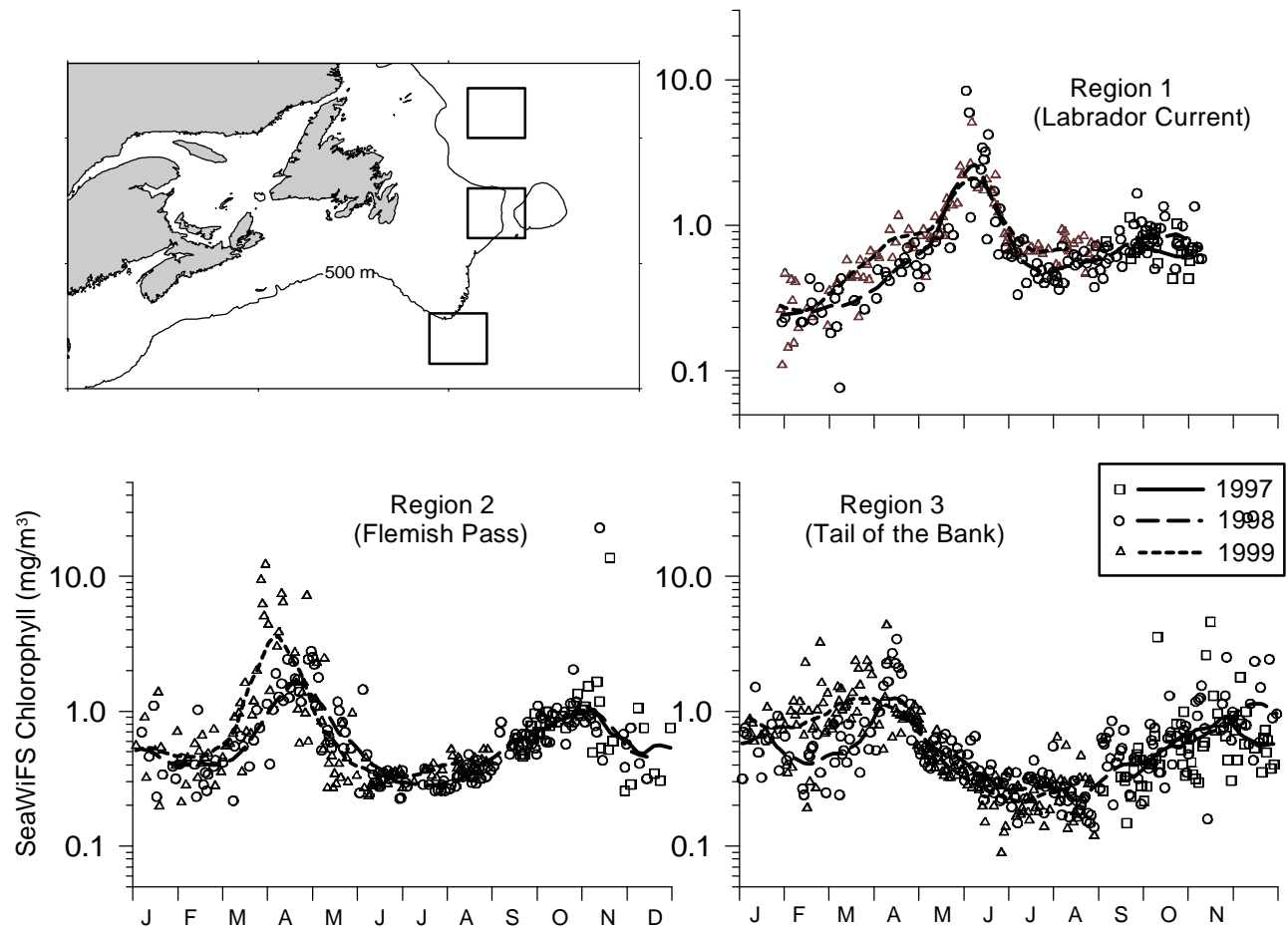


Fig. 1. The boundaries of the regions (1–3) in the Newfoundland area used for time-series analysis and seasonal variations of surface chlorophyll concentration in the regions.

The patterns of seasonal variations in three small regions (Figure 1) correspond well to the seasonal patterns typical to Arctic, mid-latitude, and subtropical zones of the World Ocean (Longhurst, 1995). In region 1 (the Labrador Current) the chlorophyll concentration increased from January until June, then it decreased, and from August to December remained stable. In region 2 (the Flemish Pass at the edge of the Grand Bank) the spring maximum in March–April was pronounced. It was followed by decrease in chlorophyll concentration with minimum in summer. Then *Chl* gradually increased by November and then decreased again. In the southern region 3 (Tail of the Bank) the surface chlorophyll concentration was of minimum in summer and increased during the cold season (from November till April). The seasonal variations during 1997, 1998, and 1999 didn't differ significantly, but the spring maximum in 1999, however, was more pronounced in region 2.

Water Stratification Influencing Phytoplankton Growth. The general mechanism of influence of hydrometeorological factors on phytoplankton growth was formulated in 40–50's during the analysis of the reasons of spring bloom (Riley, 1947; Sverdrup, 1953). We consider two main limiting factors: illumination and nutrients. Light limitation is crucial under low water stratification (e. g., winter

convection in high latitudes), because algae cells are dispersed by turbulent mixing within deep dark layers, where photosynthesis is impossible. Nutrient limitation is crucial under enhanced stratification (e. g., seasonal thermocline in summer), because nutrients do not penetrate from deep layers into the euphotic (i. e., well illuminated) upper mixed layer where phytoplankton is concentrated. The hydrometeorological factors (air temperature, wind, input of freshwater with precipitation and river discharge) either increase or decrease stratification within the euphotic layer. These physical factors perform regular seasonal oscillations; hence, typical seasonal cycles of phytoplankton result from the combined effect of seasonal cycles of hydrometeorological factors influencing water stratification within the euphotic layer. The most illustrative is the phytoplankton seasonal cycle in mid-latitudes with two maximums in spring and autumn (see Figure 1). During winter both wind mixing and cooling of upper layer are of maximum and result in deep convection, which can be as deep as several hundreds meters; phytoplankton during winter is of minimum resulting from light limitation. During spring wind mixing weakens and heating of the upper layer increases, which result in formation of seasonal thermocline. Nutrient concentration remains still high; therefore, both light and nutrient limitations are absent and this period is most favorable for phytoplankton growth; hence, the spring bloom occurs. In summer due to maximum heating of the upper layer and minimum wind mixing the seasonal thermocline is pronounced and water stratification is of maximum. During this period phytoplankton is of summer minimum resulting from nutrient limitation. In autumn both cooling of the sea surface and wind mixing increase; these processes result in erosion of seasonal thermocline, decrease of nutrient limitation, and autumn bloom.

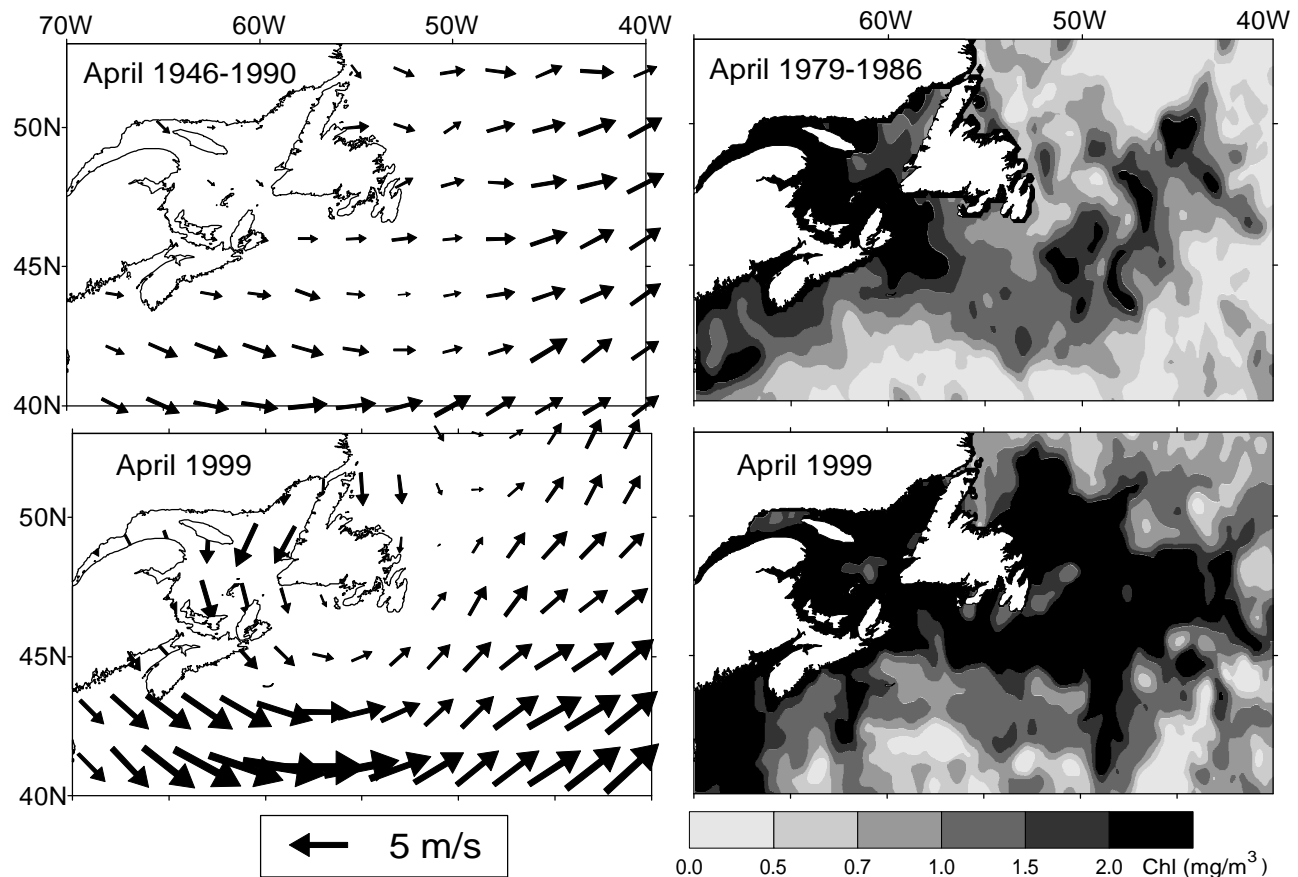


Fig. 2. Wind speed (left) and surface plant pigment concentration (right) in April in the Newfoundland area: climatically averaged (above) and 1999 (below). Chlorophyll data are CZCS (climatically averaged) and SeaWiFS (1999).

In 1998 and especially in 1999 the spring bloom in April was more pronounced as compared with the period of CZCS observations in 1978–1986 (Figure 2). To reveal the reason of this phenomenon we first of all check the hypothesis that it resulted from variations of water circulation. In waters of the flowing from the north Labrador Current *Chl* concentration in April was rather low, in contrast to the Gulf Stream waters near the Tail of the Bank (Figure 1, region 1 and 3, respectively). However, both *SST* and *SSH* data indicate, that in April 1999 the strength of the Labrador Current exceeded climatic mean. Therefore, we cannot explain extensive spring bloom in April 1999 with advection of rich in chlorophyll waters.

It is more reasonable to assume that it is the combination of wind forcing and heat flux that resulted in the enhanced phytoplankton bloom during spring 1999. The main reason seems to be the atypical pattern of wind forcing together with warmer air temperature (in February–March 1999 it exceeded climatic mean as much as +4°C). The wind pattern in April 1999 was peculiar (Figure 2): the westerly winds were strong in the southern part of the region and weak in the north. We can speculate that the weak winds favored the formation of seasonal thermocline to the north of the Gulf Stream Frontal Zone. To the south of the frontal zone strong westerly winds disturbed the stratification of the upper mixed layer (the effect similar to autumn/winter mixing in temperate and subtropical regions), enabling transport of nutrients to the euphotic zone. Both reverse processes resulted in similar effect: enhanced development of phytoplankton. As a result, the spring bloom over the Newfoundland Region was much stronger than usually.

SEASONAL CYCLES OF PHYTOPLANKTON IN THE OPEN BLACK SEA

The peculiar feature of vertical hydrological structure of the Black Sea is its pronounced two-layer haline stratification (Murray *et al.*, 1991), resulting from intensive input of fresh water with river discharge into the partially isolated semi-enclosed basin. The upper layer of the Black Sea is formed by a mixing of the resident water mass and the fresh river water inflow; this layer usually extends down to 150 m. The salinity in the 30–40-m surface layer is typically 18.0 ppt and varies seasonally as much as 0.5–1.9 ppt as a result of changes of evaporation, precipitation, runoff, etc. (Oguz *et al.*, 1992). At the depth of 150 m the salinity reaches 21.0 ppt; below 150 m the water masses are remarkably stable.

The seasonal variation of plant pigments concentration in the surface waters of the open part of the Black Sea from September 1997 (the beginning of SeaWiFS observations) by March 2000 is given at Figure 3. Each seasonal cycle manifests two periods: the warm season with low plant pigments concentrations and the cold season with high values of this index. Similar seasonal pattern of phytoplankton biomass is typical to subtropical ocean regions (Longhurst, 1995); this pattern of seasonal variations in the Black Sea was revealed on the basis of both remotely sensed (Nezlin, 1997) and field observations of chlorophyll concentration (Yilmaz *et al.*, 1998). The most important is that both 20 year ago on CZCS data (Nezlin, 1997) and nowadays on SeaWiFS data we never observed the spring bloom of phytoplankton typical to temperate waters of the World Ocean. The reason seems to be extremely pronounced stratification of the Black Sea (the increase of salinity within the upper 150 m about 3 ppt). This stratification results in that winter convection never penetrates deeper 100 m. At the same time, at similar latitudes in the North Atlantic, where typical seasonal phytoplankton cycle with two maximums was described, winter convection reaches the depth of several hundreds meters (Longhurst, 1995). Therefore, in the Black Sea the atmospheric impacts decreasing stratification (wind, heat and salt fluxes) should be treated as factors favoring phytoplankton growth.

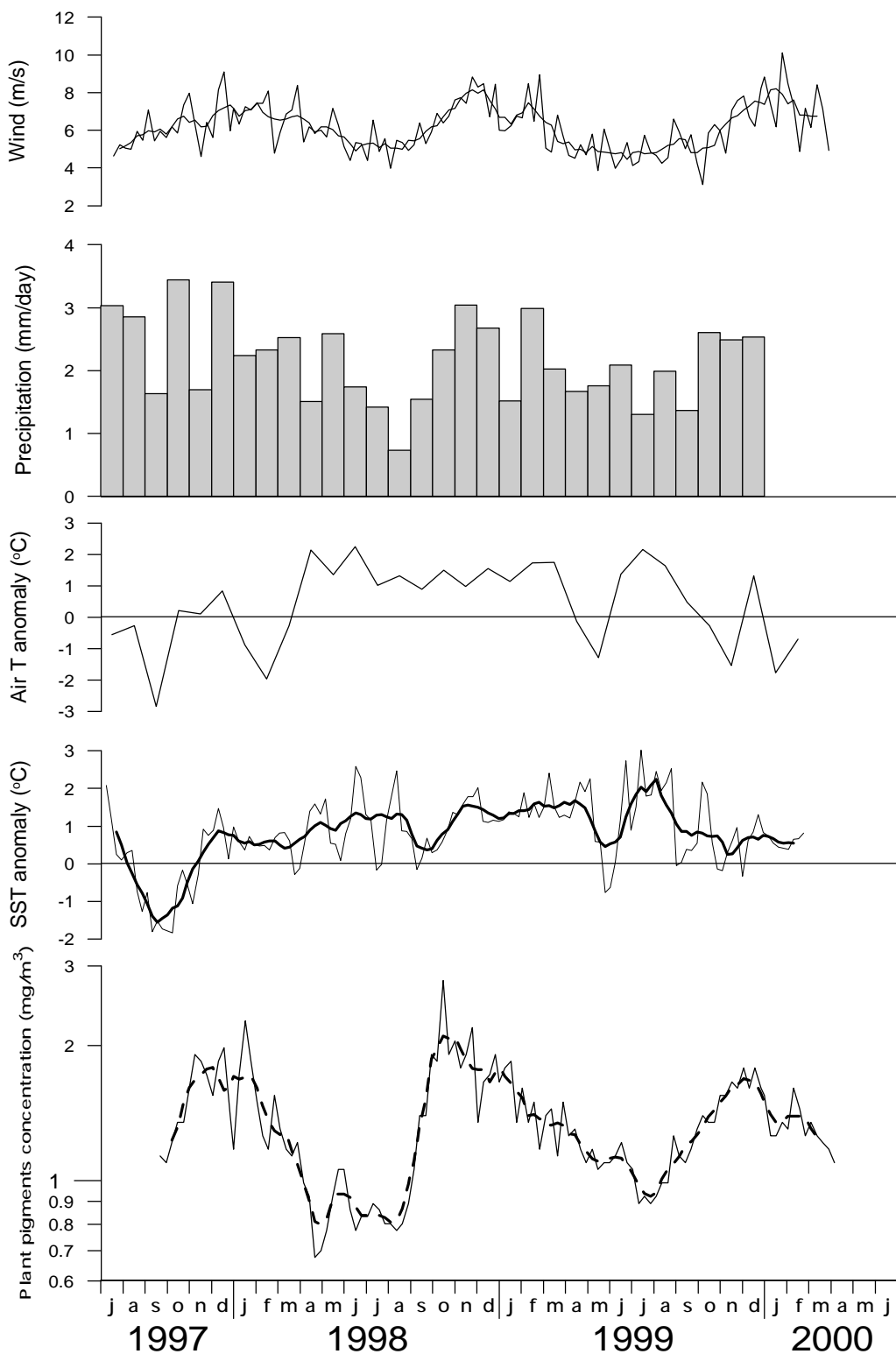


Fig. 3. Variations of wind speed (m/s), precipitation (mm/day), air temperature and SST anomalies (°C), and plant pigments concentration (mg/m³) over the open part of the Black Sea during July 1997–March 2000.

It is evident from Figure 3 that the cold season of 1998–1999 differed from both the previous and the next seasons by both higher values of plant pigments concentration and longer period of winter bloom. In autumn 1998 the growth of phytoplankton started as soon as in late August. In October 1998 the plant pigments concentration was of maximum over the entire period of observations. In summer 1999 the concentration of plant pigments was also significantly higher than in summer 1998, it gradually decreased by July–August, when new autumn increase started; the latter was evidently weaker as compared with the previous year.

Three periods of decreasing *SST* were evident: in September–October 1997, in September 1998, and in May 1999 (Figure 3). The first and the last ones coincided with the decreases of air temperature, and the *SST* decrease in September 1998 follows the period of abnormally low precipitation in August 1998. The precipitation was lower by a factor of 2–3 as compared with other summer seasons. The decrease of precipitation seemed to result in salinity increase at the sea surface and more intense convective mixing within the upper layer just during the period of maximum nutrient limitation of phytoplankton growth. The increased convective mixing manifested itself in about 1°C decrease of *SST*; the intensification of nutrient flux from the zone below seasonal thermocline resulted in the start of autumn bloom as early as in September. The vertical mixing of water column was also enhanced by wind, the latter being of maximum in October–November 1998 (Figure 3).

The significant decrease of *SST* was observed also during autumn 1997, resulting from abrupt cooling of the air in the Black Sea region (Figure 3). However, during that period the atmospheric precipitation was increased, and wind speed decreased as compared with the values typical to that season. Moreover, the discharge of Danube River is usually of minimum in autumn, but in autumn 1997 it significantly increased (Nezlin, 2000). Therefore, it is reasonable to consider that in autumn 1997 the abrupt cooling of the upper layer was partly counterbalanced by its desalination due to freshwater input, and the influence of autumn convection was not as strong as in autumn 1998.

The bloom period from autumn 1998 till spring 1999 was longer than the previous bloom. In April 1998 the concentration of plant pigments decreased down to typical summer values; on the contrast, during spring 1999 it remained rather high and gradually decreased by the end of July. The decrease of phytoplankton biomass in the beginning of warm season is explained by the formation of seasonal thermocline and the start of limitation of phytoplankton growth by lack of nutrients. In April 1999 the air temperature sharply decreased (Figure 3), that seemed to delay the formation of seasonal thermocline. This phenomenon evidently manifested itself in significant decrease of *SST* in May 1999. Hence, the period of summer limitation of phytoplankton growth by nutrients began in 1999 later than usually, and high concentrations of plant pigments in the upper layer remained as long as by July.

Thus, the peculiar complex of meteorological conditions occurred in the Black Sea region during the second half of 1998 and the first half of 1999. These conditions favored the growth of phytoplankton, the basic chain of the pelagic food web. An important point is that the high level of phytoplankton development occurred from the late summer of 1998 till the first half of the summer of 1999; i. e., high phytoplankton biomass coincided with the period of high biomass of herbivorous zooplankton (Vinogradov *et al.*, 1998). It is reasonable to consider that this long period of conditions favorable for feeding of planktonic animals resulted in the increase of the biodiversity of the Black Sea ecosystem, especially its high trophic levels. The most important result of the biodiversity increase appeared to be the development in autumn 1999 of the carnivore ctenophore *Beroe ovata*. This species is the predator of the ctenophore *Mnemiopsis leidyi*, the latter being treated as the destroyer of the entire ecosystem of the Black Sea since late 1980's (Kideys, 1994). The recent changes of the Black Sea pelagic community seemed to improve to some extent the consequences of natural catastrophe observed in this region during the last decade.

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