

Continental Shelf Research 22 (2002) 1477-1492

CONTINENTAL SHELF RESEARCH

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The role of mesoscale processes controlling biological variability in the Black Sea coastal waters: inferences from SeaWIFS-derived surface chlorophyll field

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Received 11 August 2000; received in revised form 27 July 2001; accepted 7 February 2002

Abstract

Several different time series of chlorophyll images from the 1997–2000 Seaviewing Wide Field-of-view Sensor data set have been analysed to gain a perspective on the dynamical and biological variability in the Black Sea, particularly on its northwestern shelf region and along the Anatolian coastal zone. The images are interpreted in terms of documenting the close link between biological production and physical dynamics of the boundary system, and of emphasizing the role of eddy processes on controlling mesoscale chlorophyll distributions. It is shown that western coastal waters of the Black Sea are characterized by permanently high chlorophyll concentrations of more than $4.0 \,\mathrm{mg}\,\mathrm{m}^{-3}$, often subject to considerable dynamical transformations, and modulated by mesoscale structures including southward elongated filament-like features extending up to 100 km offshore with a lifetime of up to a month. Filaments, meanders, offshore jets and other forms of mesoscale and sub-mesoscale structures appear as a common signature of the system along the Anatolian coast. They play an important role in the cross-stream transport of biota and chemical constituents, and thus supporting productivity within the interior parts of the basin. The images reveal phytoplankton blooms lasting several months in all three autumn seasons. During autumn 1999 to winter 2000, the phytoplankton biomass declines in December, and then increases to form another bloom in February–March 2000, albeit somewhat weaker. For the previous 2 years (1997, 1998), the autumn bloom is extended towards the first half of the winter but the late winter–early spring bloom is absent. \mathbb{C} 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Black Sea; Circulation; Biological production; Mesoscale variability; SeaWIFS chlorophyll data

1. Introduction

The Black Sea is regarded as one of the most interesting water bodies of the global oceans from a physical and biological standpoint (Fig. 1). It has an extremely dynamic, mesoscale-dominated circulation and a highly eutrophic ecosystem both of which favour the detection of the structurally rich chlorophyll patterns by the Sea-viewing Wide Field-of-view Sensor (SeaWIFS), for most of the year.

The dynamic circulation patterns have been shown in various studies dealing with satellite data (Oguz et al., 1992; Sur et al., 1994, 1996; Sur and

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Fig. 1. Bathymetry and location map of the Black Sea. A set of geographical names used in the text as well as locations of the rivers discharging into the Black Sea is indicated. The bathymetric contours are depicted between 200 and 2000 m at an interval of 200 m.

Ilyin, 1997; Oguz and Besiktepe, 1999; Ginzburg et al., 2000; Nezlin, 2000; Korotaev et al., 2001) and hydrographic data (Oguz et al., 1994, 1998; Oguz and Besiktepe, 1999; Gawarkiewicz et al., 1999). These studies have identified the importance of the Rim Current in this region: a cyclonic, unstable system with baroclinic and frontal instabilities generating considerable mesoscale and short-term variability, superimposed on its sub-basin and gyral scale, seasonal varying structures. The presence of highly convoluted Rim Current frontal zone around the periphery of the basin, in general, and onshore-offshore interactions between low-salinity (<17.0 psu) waters of shelf the northwestern and more saline (>18.0 psu) waters of the western basin, in particular, is shown in Fig. 2.



Fig. 2. Surface (5 m) salinity distribution obtained during the July 1992 hydrographic survey. The major hydrographic features of the basin are shown as well as the inner shelf front induced by the river outflows along the northwestern coast. The contours are drawn at an interval of 0.5 up to 17.0 psu, and of 0.2 afterwards; 17.8 and 18.0 psu contours representing offshore limit of the Rim Current frontal zone are shown in bold (redrawn from the original figure in Oguz et al., 1998).

The Black Sea planktonic ecosystem is regulated strongly by physical processes, which allows the possibility of using SeaWIFS imagery to study spatial and temporal biological structures in relation to the dynamics of this region. Prior to this study, the CZCS imagery (Sur et al., 1994, 1996), which was rather limited in number, has already demonstrated the potential use of the surface chlorophyll data for exploring mesoscale dynamics of the Rim Current system, interactions between the shelf and interior regions, etc. Since the 1970s, severe eutrophication in the western coastal waters, due to enormous amounts of anthropogenic load, enables biological productivity to occur throughout the year. The phytoplankton biomass was found to increase from an average (wet weight) value of 1.0 gm^{-2} in the 1960s to 18 gm^{-2} in the 1970s and 30.0 gm^{-2} in the 1980s and 1990s in the northwestern shelf waters (Zaitsev and Mamaev, 1997). Similarly, high values of surface chlorophyll concentrations of around $5-10 \text{ mg m}^{-3}$ were measured consistently within the western coastal waters during the 1990s (Yilmaz et al., 1998). This distinct characteristic feature of the western Black Sea allows the use of the SeaWIFS chlorophyll data set as a tracer to infer regional flow structure controlling biological variability.

In the present work, several different time series of the SeaWIFS images is utilized to present a descriptive analysis of the dynamical and biological variability in the Black Sea during 1997-2000. Our main objectives are to study the structure of the boundary current system, and to document the role of eddy processes on the control of mesoscale chlorophyll distributions, particularly along the western and southern coastal waters of the Black Sea. It will be shown that the SeaWIFS images provide a remarkably good time series to monitor the evolution of the flow structure in these regions of the Black Sea. These images turn out to be instrumental in understanding the regional flow dynamics, frontal instabilities and their interactions with the adjacent interior basin.

The paper is structured as follows. After a short description of the data processing in Section 2, we explore the dynamically distinct flow characteristics on the Northwestern shelf (NWS), and their influence on the regional phytoplankton production in Section 3. Following a brief description of the general characteristics of the NWS, to aid in the interpretation of the images, we focus specifically on the spring-summer periods of 1998 and 1999, and infer different types of flow regimes regulated by a combination of river plume, local wind field, as well as the basin-wide general circulation system. In Section 4, we use chlorophyll concentration distributions to describe the Rim Current instabilities and subsequent eddy-induced changes along the Anatolian coast (also referred to as southern or Turkish coast). Section 5 is devoted to the basin scale phytoplankton production during the autumn and winter months of three consecutive years of the data, where some year-to-year variability can be seen. Our major findings and main conclusions are presented in Section 6.

2. Data processing

The $9 \text{ km} \times 9 \text{ km}$ gridded chlorophyll concentration data set, provided by the Distributed Active Archive Center at the Goddard Space Flight Center at a period of 1 day, 8 days, and a calendar month, are used in our analyses. The SeaWIFS algorithms are known to be more appropriate for the case 1 waters, and may contain some errors for case 2 waters, such as the Black Sea, due to the problems of atmospheric correction and the high level of turbidity. We consider that interpretations of images, in a qualitative sense, will not be altered by these possible error sources.

The lack of good coverage on most of the daily products appears as a problem in the Black Sea SeaWIFS data set. The 8-day average products solve this problem to a large extent, but they may not be entirely appropriate to study details of bloom structures since the averaging period corresponds roughly to half of the typical duration of a phytoplankton bloom event (cf. Oguz et al., 2001). Therefore, by using daily data files, a 4-day running average data set was created as a compromise, in terms of resolution of bloom events and of their mesoscale spatial structures. On days where the data value was available for a given location, it was included in the average. Otherwise, it was left empty. This strategy filled many data gaps to make the analysis more feasible. The noise present in the data was filtered by applying a Wiener Filter (Deshpande, 2000).

3. Biological and circulation characteristics of the NWS during spring-summer periods of 1998 and 1999

3.1. General characteristics of the northwestern shelf relevant for this study

The Northwestern Shelf (NWS) is a triangular basin bordered by a northeast-southwest oriented coastline on its continental side and the Crimean peninsula on the east (Fig. 1). It has a smooth topography which is an important characteristic feature. The 50 m contour divides the shelf approximately into two equal portions. A broad topographic slope zone, also extending in a northeast-southwest direction, separates the shelf from the deep interior basin. The maximum width of the slope is almost comparable with that of the NWS. Just to the south of the Crimean peninsula, the slope steepens, forming an almost vertical wall, and the shelf narrows. This wall feature runs parallel to the orientation of the Crimean coastline in the northwest direction, and exerts a strong topographic control on the Rim Current. The particular orientation of the slope causes a gradual reduction in the shelf width towards the Cape Kali-Akra, where the shelf retains only a narrow opening towards the south. Along the Bulgarian and Turkish coast, the shelf is characterized by a narrow coastal strip up to about 31°E longitude. Beyond this point, the shelf practically terminates at the coastline, and the adjacent shelf/slope topography is tilted abruptly towards the northeast. Near the Cape Kali-Akra, the Rim Current of the basin-wide circulation system merges with the downstream coastal current system. Together they give rise to a stronger topographically controlled current along the southern coast. The ADCP measurements (Oguz and Besiktepe, 1999) indicated a current speed that changes between 50 and $100 \,\mathrm{cm \, s^{-1}}$ within the core of the Rim Current jet near the surface.

The NWS receives considerable fresh water input, particularly from the River Danube (see Fig. 1 for locations of the rivers). The discharge from the Danube varies seasonally between 4000 and $9000 \,\mathrm{m}^{3}\mathrm{s}^{-1}$ with a long-term average estimated as about $6500 \text{ m}^3 \text{ s}^{-1}$ (or equivalent to about $200 \text{ km}^3 \text{ yr}^{-1}$). The seasonal changes account approximately for 30% of the annual mean. There are two other rivers, the Dniester and the Dnieper that discharge slightly to the north of the Danube. The annual mean estimate of the Dniester discharge is about $50 \text{ km}^3 \text{ yr}^{-1}$, which is approximately five times stronger than the Dnieper outflow. Thus, the contribution of these two rivers to the total discharge is about 30% of the Danube. As expected, they all provide their peak outflows during the spring months (Cociasu et al., 1997).

The salinity pattern (Fig. 2) at the surface (5 m)obtained from the July 1992 field survey (Oguz et al., 1998) shows a typical fresh-water-induced inner shelf frontal structure and onshore-offshore interactions between the shelf and interior waters. The inner shelf front exhibits a difference in salinity of more than 3.0 psu over an $\sim 50 \text{ km}$ zone along the coast. On the offshore side of the front, the Rim Current penetrates up to the frontal zone, carrying relatively more saline ($S \sim 18 \text{ psu}$) waters of interior origin onto the shelf. Immediately to the southwest, there is an offshore transport of the lower salinity frontal waters over the slope zone. Similar structures are reported consistently in other hydrographic surveys, as well as in the satellite imageries (e.g. Oguz et al., 1994; Sur and Ilyin, 1997; Oguz and Besiktepe, 1999; Ginzburg et al., 2000).

3.2. Spring-summer 1998 chlorophyll distributions

Figs. 3 and 4 provide a series of 4-day composite SeaWIFS chlorophyll fields during June–September 1998. The most distinguishing features of these images are the presence of a sharp boundary separating the high chlorophyll coastal (or inner shelf) waters from the less productive waters further offshore, and its transformation to different forms during this period. Such a dramatic contrast in concentrations within a few tens of kilometres



Fig. 3. The 4-day composite images of the surface chlorophyll concentration (in mg m⁻³) within the northwestern part of the basin at six particular 4-day periods between the days 152–155 (1–4 June) and 206–209 (25–28 July) of the year 1998. The shelf break and continental margin topographies, represented by the 100 and 2000 m contours, are indicated by red lines in each of these figures. The chlorophyll concentration contours are plotted with different colours and intervals for a better visualization of frontal features. For concentrations of 0.8 and 1.0 mg m⁻³ contours shown in orange; between 1.2 and 1.8 mg m⁻³ (using an interval of 0.1) contours shown in white; and >2.0 mg m⁻³ (using an interval of 0.5), contours shown in black.

suggests the presence of a strong dynamic front associated with the fresh water discharges. The red lines shown in these figures represent the 100 and 2000 m depth contours to mark the positions of the shelf break and slope zone.

All the images from June 1998 reveal three distinct zones of different productivities identified by chlorophyll concentrations. As inferred from the images for days 152–155 (beginning of June) in Fig. 3(a), the narrow coastal zone has concentrations higher than 4.0 mg m^{-3} . The rest of the shelf, however, attains chlorophyll concentrations of about $1-2 \text{ mg m}^{-3}$. The adjacent offshore waters of the western interior, on the other hand, are identified by even lower concentrations of about

 $0.5 \,\mathrm{mg}\,\mathrm{m}^{-3}$. The Danube River plume seems to flow downstream in the form of a coastally attached density current during this period. Not much frontal activity exists except small amplitude perturbations.

By the end of June, two specific changes are noted in the regional flow structure. Firstly, there is a growth of the perturbations into larger amplitude meanders. Secondly, the southward coastal flow gradually weakens and a more dominant upstream deflection occurs. These changes are indicated by the gradual increase of chlorophyll concentrations on the northern side of the shelf, and a decrease in the Bulgarian and southwestern Turkish coastal waters (see



Fig. 4. The 4-day composite images of the surface chlorophyll concentration (in mg m⁻³) within the northwestern part of the basin at six particular 4-day periods between the days 212–215 (31 July–3 August) and 251–254 (8–11 September) of the year 1998. The shelf break and continental margin topographies, represented by the 100 and 2000 m contours, are indicated by red lines in each of these figures. The chlorophyll concentration contours are plotted with different colours and intervals for a better visualization of frontal features. For concentrations of 0.8 and 1.0 mg m⁻³ contours shown in orange; between 1.2 and 1.8 mg m⁻³ (using an interval of 0.1) contours shown in white; and >2.0 mg m⁻³(using an interval of 0.5), contours shown in black.

Figs. 3(b)–(d)). Fig. 3(b) provides an example for an early stage of frontal instability development. The frontal wave structure is disturbed by the formation of a trough (i.e. inshore displacement of the wave pattern) in the northern part and a crest (i.e. offshore position of the wave pattern) in the southern part of the shelf. The crest nearly extends to the shelf break. Superimposed on this wave is a more convoluted frontal structure as compared with the one in the previous images. Deformation of the front becomes more pronounced a week later (Fig. 3(c)). The wave crest and trough undergo further steepening. The flow system associated with this frontal activity transports high chlorophyll waters offshore (i.e. into the outer shelf) near the crest, and low chlorophyll slope waters inward near the trough. An early stage of a filament formation is also evident along the crest. The fresh-water-induced coastal current system penetrates southwestward along the western Crimean coast, and also contributes to the steepening of this frontal system.

A week later, the filament intensifies and extends all the way across the wide slope zone (Fig. 3(d)). The relatively higher chlorophyll concentrations inside the filament, with respect to the previous image, suggest its efficiency in transporting shelf waters offshore. Its clockwise swirl and "hook" shape formation distributes shelf waters to other parts of the slope zone. Moreover, currents along

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the Crimean coast extend further south within the outer shelf and surround the low chlorophyll waters near the trough from the southeast. At the same time, a small-scale meander spawned at the downstream flank of the trough (Fig. 3(d)) distributes some chlorophyll-rich frontal waters from the crest into the nearby low chlorophyll region. These processes are shown to be completed within a week (Fig. 3(e), for days 203-206), as by then the trough zone disappears. The entire central and northern portions of the NWS are totally occupied by high chlorophyll waters within a large anticyclonic cell. Moreover, because the filament continues to transport shelf waters into the slope region, the chlorophyll content of the area to the west of the filament increases by about 1.0 mg m^{-3} within a month (cf. Fig. 3(e) with Figs. 3(a) and (b)). The filament, during this phase, is transformed gradually from a sub-mesoscale feature to a mesoscale eddy-like feature of the shelf circulation system. Another filament is spawned near the Crimean coast (Fig. 3(e)), but only lasts for a week, and then is pinched off from the main system (see Fig. 3(f)).

General features of the coastal flow system during the next few days remain more or less unchanged, except that the main filament weakens, gradually looses its intensity, and spawns two more filaments from its stem (Fig. 3(f)). They are transformed later to a new hook type formation (Fig. 4(a)), and the whole filament system finally looses its identity with only a very weak signature left, after a week (Fig. 4(b)).

The images shown in Figs 4(a)–(f) exhibit another phase in which the fully developed shelf circulation, during July 1998 (see Fig. 3), is deformed. It is difficult to determine whether the relatively low chlorophyll concentrations is a consequence of local biological processes (such as zooplankton grazing) or caused by the horizontal transport (intrusions) of low chlorophyll outer shelf waters towards the coast (Fig. 4(a) and (b)). A high chlorophyll area remains only in the eastern part of the NWS, along the Crimean peninsula. Near the tip of the Crimea, a new filament formation (Fig. 4(c)) transports a considerable amount of high chlorophyll shelf waters southward into the upper slope zone (Figs. 4(d) and (e)). In common with the other filament structures described above, it also swirls clockwise to form an anticyclonic eddy into which shelf waters are supplied by the filament. This system persists for the next two weeks (see Fig. 4(d), days 242–245), and becomes a major component of the NWS structure (Fig. 4(e), days 245–248). At the same time, mesoscale frontal activities transport chlorophyll-rich shelf waters laterally into the low chlorophyll zone, and the entire shelf is covered once again by relatively high chlorophyll waters a week later (Fig. 4(f)).

3.3. Spring-summer 1999 chlorophyll distributions

The spring 1999 shows conditions similar to the previous summer in terms of spreading of waters with high chlorophyll content over the entire shelf (Figs. 5(a)-(c)). The front lies along the shelf break, identified by the 100 m bathymetric contour (see the red line in the figures), and exhibits small amplitude meanders as in the previous year (Figs. 5(a) and (b)). Once again, these perturbations grow in time and turn into larger amplitude offshore meanders protruding into the slope waters (Figs. 5(c) and (d)). Two major filament formations are noted in these images. One of the filaments, within the vicinity of the Crimean peninsula, keeps its position stable in time while the other one, which originated between 30°E and 31°E longitude, migrates southwestward along the front. As shown in the images for days 162-165 and 177-180 (Figs. 5(d) and (e)), both filaments reach their mature states during June, and then weaken and disappear in July (see Fig. 5(f) for days 192-195). The images show clearly how these offshore jets transport high chlorophyll waters of shelf origin into the slope zone during their active lifetimes.

The front retreats back to the inner shelf zone and lies approximately along the 50 m bathymetric contour by the end of June (Fig. 5(e)). It then maintains this position during the rest of the summer season (see Figs. 6(a)–(f) for selected July and August 1999 images). This situation reflects totally different conditions with respect to the previous summer, which was characterized by the highly dynamic frontal activities. The shelf circulation is not driven any more by the northward



Fig. 5. Same as in Fig. 3, except between the days 121–128 (1–8 May) and 192–195 (11–14 July) of the year 1999. The first three images are based on the 8-day composite data.

deflection of the Danube outflow and associated anticyclonic shelf circulation. Instead, the river outflows proceed in the downstream (i.e. southward) direction along the coast. The chlorophyll concentration within the outer shelf constitutes only about one-third of that available in the coastal zone. Weak frontal activities are present but they do not lead to development of any notable mesoscale or sub-mesoscale structures.

4. Rim current instabilities and biological production along the anatolian coast

Several forms of mesoscale features, Rim Current meanders and their impacts on the local productivity can be traced from the monthly

chlorophyll patterns. Here, we deal particularly with the spring and summer images. Similar features observed in autumn and winter months will be pointed out in the next section. The April 1999 monthly composite image (Fig. 7(a)) indicates relatively weak meander activity of the Rim Current throughout the basin, whereas the subsequent images of May, June and August (Figs. 7(b)-(d)) describe their modification to larger meanders and persistence on the seasonal scale. The May image (Fig. 7(b)) displays two filaments along the NWS, and two additional ones along the Turkish coast; one in the vicinity of the Bosphorus region and the other one near the Cape Kerempe ($\sim 33^{\circ}E$ along the Turkish coast). The offshore transport associated with the Bosphorus filament is particularly strong. These filaments

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Fig. 6. Same as in Fig. 3, except between the days 202-205 (21-24 July) and 242-245 (30 August-2 September) of the year 1999.

persist for the entire summer (1999) period in the form of two well-developed meander crests in the western Anatolian coastal zone, and export a large proportion of coastal production towards the central parts of the interior basin. A similar offshore transport, albeit weaker, is shown also to take place along the Caucasian coast of the eastern basin.

The other interesting feature, which can be noted in the spring–summer 1999 monthly images, is the linkage between biological production along the Anatolian coast and nutrient supply from the NWS (Figs. 7(a) and (b)). In other words, downstream transport of the NWS nutrients appears to be a crucial factor for maintaining local production along the southern coast, as evidenced by the high chlorophyll content of the entire western coastal waters. Here, the occasional coastal upwelling events last only for a few days (cf., Sur et al., 1994), and, therefore, cannot support such a season-long phytoplankton production.

The 1998 spring–summer monthly images (Fig. 8), on the other hand, possess a counter situation. In this case, the southward coastal flow from the NWS is quite weak because of the presence of an anticyclonic gyral circulation in the northern part of the shelf and, therefore, nutrient supply is limited. The May 1998 image (Fig. 8a) displays some evidence of linkage between productions in the NWS and the Turkish coast waters. As the nutrient supply is cut off gradually (see the June, July and August images in Figs 8(b)–(d)) by the change in the NWS circulation system, the Anatolian coastal zone can no longer sustain its phytoplankton productivity. The absence of coastal production, however, does not necessarily imply



Fig. 7. The monthly composite images for the basin-wide distributions of surface chlorophyll concentration (in $mg m^{-3}$) for (a) April, (b) May, (c) June and (d) August 1999.



Fig. 8. The monthly composite images for the basin-wide distributions of surface chlorophyll concentration (in $mg m^{-3}$) for (a) May, (b) June, (c) July and (d) August 1998.

the lack of mesoscale activity along the coastal waters. It simply suggests that the images cannot resolve them due to the insufficient meridional gradients in the chlorophyll fields.

5. Autumn-winter chlorophyll patterns during 1997-2000

The monthly composite patterns for the October–March periods of the three consecutive years (Figs. 9–11) provide a synthetic way of illustrating the seasonal and year-to-year variability, and indicate the monthly-to-seasonal scale persistence of biological production at the basin scale. Although the analysis described here is based on the monthly composite images, a similar analysis performed using 8-day composites (but not shown here for brevity) fully confirms these results. The 1997–1998 images (Fig. 9) suggest that the autumn 1997 bloom started in October in the western basin and later, intensified and spread over the entire sea in November. The chlorophyll concentrations vary between $1.5-2.0 \text{ mg m}^{-3}$ in the western basin and $1.0-1.5 \,\mathrm{mg}\,\mathrm{m}^{-3}$ in the eastern basin in November. The December image shows the declining phase of this bloom event, especially in the western part of the sea, characterized by concentrations of less than 1.0 mg m^{-3} . The January image shows some sign of recovery of the biological production over the western and central basins, even though it does not reach the level observed in October. The typical chlorophyll concentrations change between $1.0-1.25 \text{ mg m}^{-3}$ over the sea. In February and March, chlorophyll concentrations tend to decrease; the interior parts of the sea attain chlorophyll values of around $0.75 \,\mathrm{mg}\,\mathrm{m}^{-3}$ in February and less than 0.5 mg m^{-3} in March. The Turkish coastal waters, however, remain productive during these 2 months.

The 1998–1999 images (Fig. 10) exhibit almost similar structures to the autumn and winter bloom



Fig. 9. The monthly composite images for the basin-wide distributions of surface chlorophyll concentration (in mgm^{-3}) for October, November, December 1997, and January, February, March 1998.



Fig. 10. The monthly composite images for the basin-wide distributions of surface chlorophyll concentration (in $mg m^{-3}$) for October, November, December 1998, and January, February, March 1999.

events, with the exception of higher chlorophyll concentrations. The monthly chlorophyll concentrations in October are typically more than 2.0 mg m^{-3} . This autumn bloom persists throughout the basin in November and then declines in December, starting from the western basin. In January, the chlorophyll concentrations remain at the same level of the previous month. The concentrations then drop below 1.0 mg m^{-3} within the interior basin, during February and March. The phytoplankton production, on the other hand, continues actively within the Rim Current zone along the Turkish coast.

The distribution of chlorophyll during the October–December period of the following year (1999, Fig. 11) also resembles the previous autumnal conditions. The strong bloom activity occurs in October–November with concentrations around $1.5-2.0 \text{ mg m}^{-3}$. This level of production is sustained in December, and then followed by a declining phase in January almost everywhere,

except along the periphery of the eastern basin and on the NWS. The biological activity recovers to some extent in February and early March, once again reflecting typical conditions of the late winter-early spring bloom episode. Moreover, we note that the January, February, March 1998 and 1999 images (Figs. 9 and 10), and October, November, December 1999 images (Fig. 11) provide further examples of the NWS supported productivity within the Anatolian coastal waters. They possess sufficiently strong coastal-offshore gradients to distinguish ongoing biological activity along the coast as compared to the post-bloom waters of the interior basin.

6. Discussion and conclusions

The composite of the monthly images for summer 1998 and 1999 (Fig. 12) synthesizes all the major features of the Black Sea circulation and



Fig. 11. The monthly composite images for the basin-wide distributions of surface chlorophyll concentration (in $mg m^{-3}$) for October, November, December 1999, and January, February, March 2000.



Fig. 12. A composite image of the surface chlorophyll concentration (in mgm^{-3}) derived from May–August monthly images of 1998 and 1999.

associated biological characteristics studied here. The meanders, offshore jets, filaments of the boundary current system, and the way in which they disintegrate the interior cyclonic cell into a series of large mesoscale eddies (typically 100 km in size) are represented remarkably well in this image. It further emphasizes high productivity in the NWS, its southward transport along the Anatolian coast and intrusions into the interior basin by means of offshore jets. The filaments extending up to 100 km offshore from the shelf may persist for up to a month, during which the outer edges (i.e. the "hook") transform gradually into larger anticyclonic eddies. Munk et al. (2000) offer a quantitative description for generation of such frontal features. They are shown to be a distinct signature of horizontal shear instability developed along a frontal zone provided that it has an unstable ambient horizontal shear and associated vorticity field. As the unstable perturbations grow, and the shear becomes comparable with the Coriolis acceleration, the cross-frontal flow generated promotes the spiralling process on the weak gradient side of the front. The images shown in Figs. 3-6 exhibit examples for all these stages of the filament formation process.

Biological production persists along the western part of the Anatolian coast throughout the year, as long as it receives sufficient nutrient supply from the NWS via the coastal current system. Persistency of offshore mesoscale structures during the April-to-August 1999 period suggests that they can efficiently transport considerable amounts of biota to the interior parts of the basin. The interior basin production, therefore, does not solely depend on the vertical processes (i.e. new production supported by sub-surface nutrient supply), which occur only at certain distinct periods of the year. The eddy-induced lateral transports, especially from the southern coast, may take place over the entire year, and emerge as a highly efficient mechanism for supporting the interior basin productivity. At times, the coastal flow is trapped inside the NWS, then, productivity within the Anatolian coastal zone, and consequently the supply into the interior of the western basin, rapidly ceases. These periods correspond to

potentially unproductive spring/summer seasons of the Black Sea surface waters.

The spring-summer 1998 and 1999 images reveal striking examples of different states of the NWS circulation depending on various combinations of river outflow, wind forcing, Rim Current structure and frontal mesoscale activities. Generally, coastal flows bend to the right (downstream; facing seaward) in the northern hemisphere. However, it has been shown that they can also turn to the left and move in the upstream direction. There are a considerable number of modelling studies that investigate the dynamics of fresh water outflows and attempt to identify the mechanisms leading to their right- or left-hand attachment (Beardsley and Hart, 1978; Nof, 1978; Chao and Boicourt, 1986; Garvine, 1987; Zhang et al., 1987; Chao, 1988; Kubakawa, 1991; Oey and Mellor, 1993; Kourafalou et al., 1996; McCreary et al., 1997; Fong and Geyer, 2001). On the basis of these modelling studies, the summer 1998 and spring 1999 chlorophyll images may suggest a coastally attached flow system directed downstream (i.e. southward) along the west coast, decoupled from the outer shelf by an inner shelf front. On the other hand, the spring 1998 and summer 1999 images imply an alternative circulation structure involving a circulation cell confined to the northern part of the NWS.

The SeaWIFS chlorophyll data set suggests a year long, high-level productivity in the NWS characterized by chlorophyll concentrations of greater than 4.0 mg m^{-3} as observed in the 1980s (Vedernikov and Demidov, 1993) and the first half of the 1990s (Yilmaz et al., 1998). On the basin scale, the autumn bloom emerges as the most pronounced signal for all the 3 years. Starting by early September, it persists until the end of November, and for the years 1998 and 1999 it may even be extended to the first half of the subsequent winter season (i.e. December and a part of January). In such cases, it is not followed by the classical late winter-early spring bloom shown in the earlier data sets (e.g. Vedernikov and Demidov, 1993; Yilmaz et al., 1998; Nezlin et al., 1999). The autumn 1999-winter 2000 period, on the other hand, reveals a different pattern of evolution, in which the late winter-early spring

phytoplankton bloom takes place after termination of the autumn bloom episode at the end of November. It remains to explore the possible mechanisms generating and maintaining such strong and longer lasting mixed layer phytoplankton production during autumn months. Because of its persistency during the last 3 years, it may well be a robust feature of the 1990s Black Sea ecosystem modified by the dominant role of gelatinous carnivores, but it was not recognised before due to the lack of sufficient sampling in autumn–winter months.

Acknowledgements

This work is supported by NSF Grant OCE-9906656, and is a contribution to the Black Sea-ODBMS Project sponsored by the NATO Science for Peace Program. T. Oguz acknowledges the NATO linkage Grant EST.CLG975821. The authors thank Stephanie Duckiewicz for her help in retrieval and analysis of the SeaWIFS data. They also thank the SeaWiFS Project and the Distributed Active Archive Center at the Goddard Space Flight Center for the production and distribution of the data. Suggestions from two anonymous reviewers are greatly appreciated.

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