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Research Article

Critical regions: A GIS-based model of marine productivity hotspots

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Abstract. Marine productivity hotspots can be defined as areas of high chlorophyll concentration and low temperature distribution. Here we demonstrate how Geographic Information Systems (GIS) can be used to define areas of high productivity and we use fishery data to verify model results and reveal areas of potential fishery locations. We develop a GIS model based on spatial data integration between monthly satellite imagery of Advanced Very High Resolution Radiometer (AVHRR) sea surface temperature (SST) and Sea-viewing Wide Field-of-view Sensor (SeaWiFS) chlorophyll concentration (Chl-a) for Eastern Mediterranean waters. Data are analyzed for the production of climatology and mapping of anomaly distribution in these environmental parameters. The geographic distributions of anomalies are spatially integrated to map areas of combined persistent environmental anomaly of below average SST and above average Chl-a (lowSST/highChl-a) indicating marine productivity hotspots and potential fish feeding aggregation regions. A preliminary comparison of surveyed fisheries production data for small pelagic fish and pelagic cephalopods to lowSST/highChl-a areas is performed for the period from December 1997 to November 2001, revealing potential spatial associations among fishery resources and productivity hotspots in terms of unexploited regions as well as overexploited fishing grounds that could be characterized as candidate marine protected areas.

Key words. Environmental anomalies; remote sensing; AVHRR; SeaWiFS; oceanography; fisheries.

Introduction

Marine ecosystems are supplied by nutrients that are recycled within the euphotic surface zone by influx from intermediate and deep waters. Productivity hotspots in the marine environment are considered areas of increased sea surface chlorophyll (Chl-a) concentration resulting from certain oceanographic processes such as upwelling, cyclonic gyres, fronts and eddies (Agostini and Bakun, 2002). Marine productivity hotspots are usually associated with low sea surface temperature (SST) distribution due to the surfacing of deep water masses. These waters, previously located below the pycnocline, are nutrient-rich and promote the bloom of microscopic plants of phytoplankton that use the nutrients as food. Bakun (1998) and Agostini and Bakun (2002) described marine productivity hotspots as the "fundamental ocean triad" of: a) enrichment (upwelling and mixing), b) concentration (convergence and frontal formation) and c) retention (favoring drift toward appropriate habitat) processes providing marine species favorable living and reproductive habitat. It was found that because of the increase in productivity of upwelling areas, which constitute about 0.1 percent of the ocean surface, such regions account for around 50 percent of the world's fisheries production (Summerhayes, 1996). Marine productivity hotspots are critical areas for

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fish aggregation for mating, spawning and feeding as well as for fish production through regional and local fishing operations.

Several studies have used Geographic Information Systems (GIS) and Remote Sensing (RS) technologies to model regions of increased marine productivity (Li and Shao, 1998; Valavanis, 2002). Such studies included the modeling of upwelling (Solanki et al., 1998; Demarcq, 1999; Su and Sheng, 1999; Demarcq and Faure, 2000), SST fronts (Drinkwater, 1996; Mesick et al., 1998; Moore et al., 1999; Waluda et al., 2001), and cyclonic gyre formation (Menon, 1998; Valavanis et al., 1999).

Many studies have analyzed monitored fisheries production data to verify relations among marine productivity hotspots and pelagic fisheries resources, e. g., on anchovy stocks (Olivar, 1990; Le Clus, 1991; Cole, 1999) and squid stocks (Pierce, 1995; Yatsu and Watanabe, 1996; Bakun and Csirke, 1998; Waluda et al., 1999; Xavier et al., 1999; Faure et al., 2000; Anderson and Rodhouse, 2001; Arguelles et al., 2001). Du et al. (2000) used GIS to analyze a time series of mean weekly SST images and corresponding purse net statistic productivity for the period 1987–1997 in East China Sea. They found that SST data had high correlation with purse net productivity, and their relationship varied steadily in certain ranges over time and area. Santos et al. (2001) computed monthly SST upwelling indices along the Portuguese west coast using satellite images. Indices were related to data on sardine and horse mackerel recruitment dynamics, revealing that winter upwelling in the area corresponds to the spawning season for the species. This has a negative impact on species recruitment due to an increase in those conditions that are favorable to the offshore transport of larvae and, consequently, an increase in their mortality. Mokrin et al. (1999) studied the spatial distribution of flying squid in NW Japan Sea. Distribution, abundance and movements of the species were related to temperature, thremocline gradient and, generally, to water masses of different types of water structures. Schwartzlose et al. (1999) and Chavez et al. (2003) allocated the collapsing and reappearing of sardine and anchovy fisheries in the Pacific Ocean to long-term changing environmental anomalies induced by naturally occurring variations of El Nino Southern Oscillation. Finally, Valavanis et al. (2002) mapped the spatiotemporal extent of SST and Chl-a anomalies in the Eastern Mediterranean for the period 1993–1997 and found that local cephalopod resources were linked to certain environmental variation regarding persistent offshore upwelling and frontal processes.

We propose a GIS-based satellite data-driven model for the spatiotemporal mapping of long-term marine productivity hotspots in the Eastern Mediterranean, and we use officially monitored fisheries production data for small pelagic fish and pelagic cephalopods to verify model results. The model is based on the combined integration of SST and Chl-a anomalies, revealing marine productivity hotspots that characterize regions of below average SST and above average Chl-a anomaly (lowSST/highChl-a).

Materials and methods

Study area

The study area is located in the Eastern Mediterranean Sea, including the Hellenic Seas (35°N, 19°E and 42°N, 30°E) comprising four main water bodies, the Aegean and Ionian Seas, and the northern parts of the Libyan and Levantine Seas (Fig. 1). The topography of the area is characterized by extreme changes in bathymetry, featuring extensive shallow continental shelves (North Aegean and Cyclades Plateau) interrupted by deep trenches (North Aegean trough, and Chios and Cretan basins). The oceanography of the area is influenced by nutrient-rich waters through river and Black Sea input (north part), and by the northward Asia Minor Current (south part). The whole area is influenced by strong northwesterly Etesian winds that blow during summer, causing productive upwelling and fronts along the east coast of the Aegean Sea and in the North Aegean and Cyclades Plateau areas that establish an east-to-west temperature gradient along the central Aegean Sea with colder temperatures in the east and warmer temperatures in the south. During winter (no Etesians), an overall cyclonic surface circulation is established with a northerly current along the Asia Minor coast and a southerly current along the Greek coast.

Data

The area is well monitored for environmental and fisheries production data (Table 1). For the initiation of the GIS model, a time series of monthly satellite images of SST distribution derived from the Advanced Very High Resolution Radiometer (AVHRR) was obtained from the German Aerospace Agency (DLR) satellite data archive using DLR's Graphical Interface to the Intelligent Satellite Data Information System (GISIS) for the period from March 1993 to December 2001 (1.6 km spatial resolution). In addition, a time series of monthly satellite images of Chl-a concentration derived from the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) was obtained from the National Aeronautics and Space Administration (NASA) SeaWiFS Project website and data archive for the period from September 1997 to December 2001 (4 km spatial resolution). Monthly fisheries production data (CPUE: catch-per-unit-effort) for European sardine (*Sardina pilchardus* Walbaum, 1792), European anchovy (*Engraulis encrasicolus* Linnaeus, 1758), long-finned

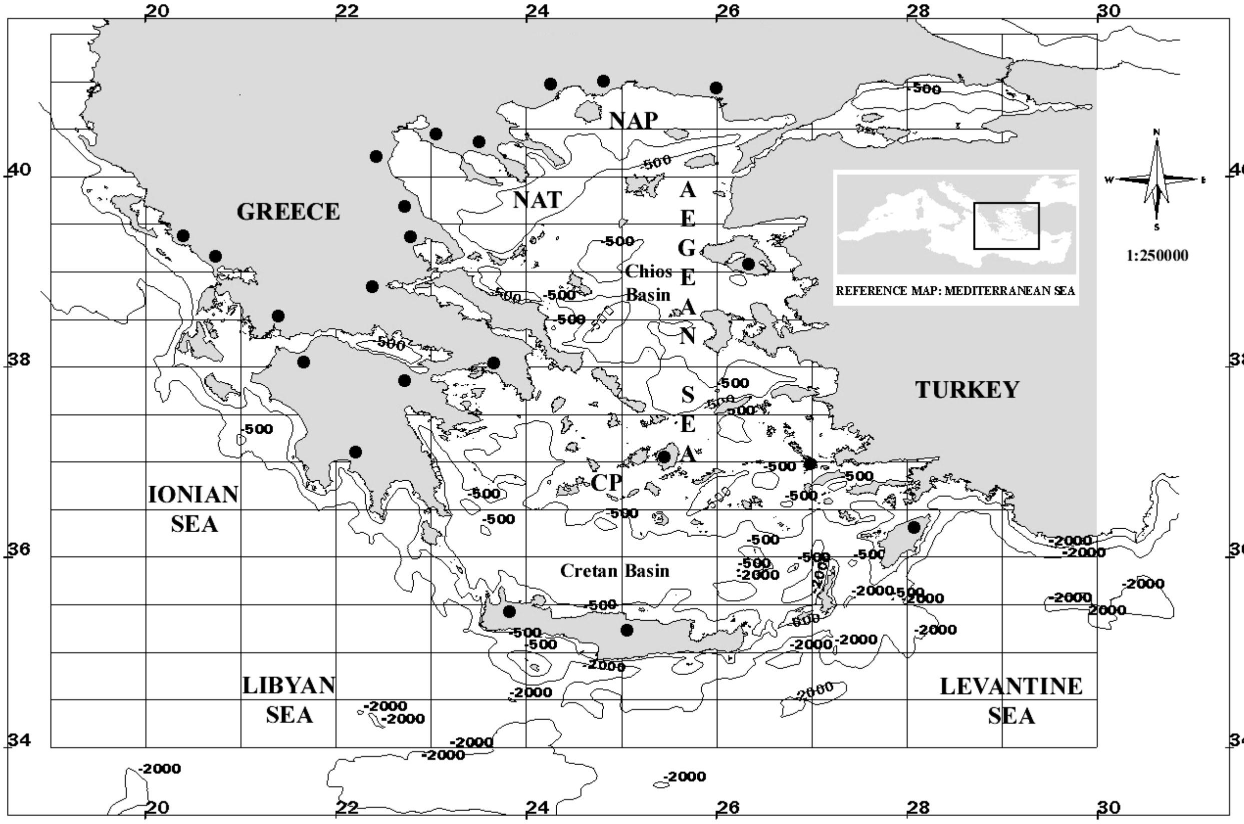

Figure 1. Hellenic Seas: the study area is located in the Eastern Mediterranean Sea, including the Aegean Sea and part of Ionian, Libyan and Levantine Seas as well as the North Aegean Plateau (NAP) and Cyclades Plateau (CP) where the main commercial fishing activity occurs. The location of fish market auctions (black dots) that report monthly fishery CPUE data, and fishery production statistical rectangles are shown. 500 m and 2000 m bathymetric contours are also shown.

Table 1. Characteristics and sources of remotely sensed environmental parameters and sampled biological data that were used for the modeling and verification of marine productivity hotspots in Hellenic Seas (Eastern Mediterranean) for the period 1998–2001.

Dataset	Characteristics	Source
Sea Surface Temperature satellite imagery (AVHRR SST)	Advanced Very High Resolution Radiometer (resolutions: 1.6 km, monthly images, 03/1993–12/2001)	German Aerospace Agency (website: www.dlr.de)
Sea Surface Chlorophyll satellite imagery (SeaWiFS Chl-a)	Sea viewing Wide Field of view Sensor (resolutions: 4 km, monthly images, 09/1997–12/2001)	National Aeronautics and Space Administration, SeaWiFS Project (website: seawifs.nasa.gov)
Fisheries CPUE for sardine, anchovy and squids fisheries in Hellenic Seas (Eastern Mediterranean)	Management System of Hellenic Fisheries Resources (resolutions: 45 × 30 km, monthly CPUE, 12/1997–11/2001)	Institute of Marine Biology of Crete, Greece, MSHFR database

squid (*Loligo vulgaris* Lamarck, 1798) and short-finned squid (*Illex coindetii* Verany, 1839) were obtained from the Management System of Hellenic Fisheries Resources (MSHFR). The system consists of a network of 22 official sampling stations scattered all over Greece (Fig. 1), gathering and storing monthly CPUE data in a central database maintained at the Institute of Marine Biology of Crete (IMBC), Greece. The spatial extent of monitored fisheries catch data is organized in 45 × 30 km (1° × 0.5°) statistical rectangles and covers the period from January 1995 to present. Environmental and production data used for the initiation and verification of the model outputs cover the period from December 1997 to November 2001, while environmental climatology was calculated from the available time series of AVHRR SST (03/1993–12/2001) and SeaWiFS Chl-a (09/97–12/2001).

Model description

The GIS model was based on Environmental Systems Research Institute's (ESRI) ARC/INFO GIS (ESRI, 1994) and it was developed with the use of the Arc Macro Language (AML). The model includes several marine data processing and georeferencing routines (Valavanis et al., 1998) and consists of four modeling modules:

1. The "Climatology Module", which includes averaging AML routines for the production of separate SST and Chl-a monthly climatologies. These routines produce average SST and Chl-a values for the 12 months of the year. For example, (Sep97 + Sep98 + … + Sep01)/5 produced Chl-a climatology for September (SepChl-a).
2. The "Anomaly Module", which includes calculation routines for the production of separate SST and CHL monthly anomalies. These routines perform subtraction of the actual monthly data from the corresponding monthly climatological data for both SST and CHL. For example, Sep97 – SepChl-a produced Chl-a anomaly for Sep97.
3. The "Integration Module", which includes spatial integration routines for the production of regions of combined SST and Chl-a monthly anomaly. These routines convert anomaly grid data to vector polygon data and spatially integrate anomaly data for SST and Chl-a in one vector dataset.
4. The "Output Module", which includes selection routines for the output of marine productivity hotspots. These routines perform spatial selection of polygons that describe areas of combined below average SST and above average Chl-a (lowSST/highChl-a patterns).

In addition, the model's "Output Module" includes routines for monthly and seasonal classification of lowSST/highChl-a patterns. Seasonal classification of these pairs of parameters is produced by the model through spatial intersection and selection of anomaly data for the four seasons of each of the years 1998–2001 (e.g., Dec97/Jan98/Feb98 used for Winter98).

Model output was verified by comparing the spatial extents of modeled marine productivity hotspots and fisheries CPUE data using cross tabulation (calculation of common area percentage indicators and spatial correlation between spatial extents of hotspots and CPUE).

Model results

The environmental characteristics of modeled marine productivity hotspots are presented in Figure 2, while

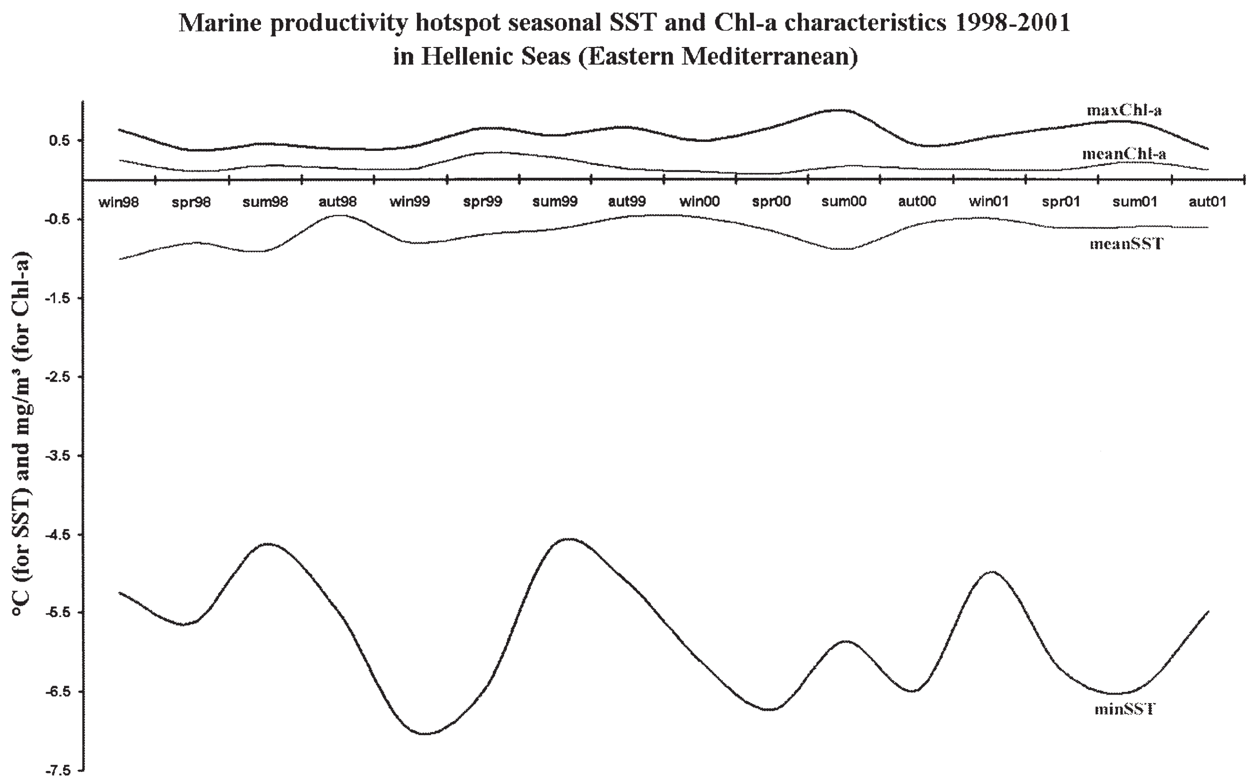

Figure 2. Minimum, maximum and averaged seasonal SST and Chl-a anomaly characteristics derived from monthly time series of nine years of AVHRR SST and four years of SeaWiFS Chl-a satellite imagery. Modeled marine productivity hotspots in Hellenic Seas (Eastern Mediterranean) for the period 1998–2001 describe areas of strong anomaly signatures in lowSST/highChl-a patterns.

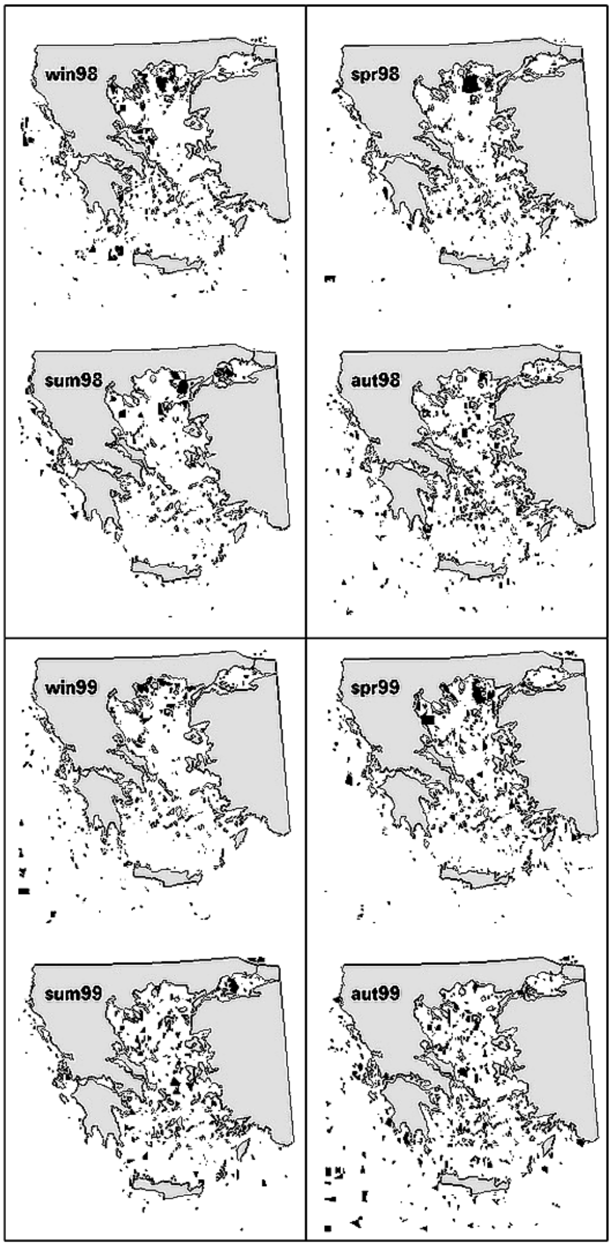

Figure 3. Seasonal marine productivity hotspots in Hellenic Seas (Eastern Mediterranean) for 1998 and 1999. These areas (in black) describe spatial relations of combined and persistent lowSST/high-Chl-a anomaly patterns in high productivity regions.

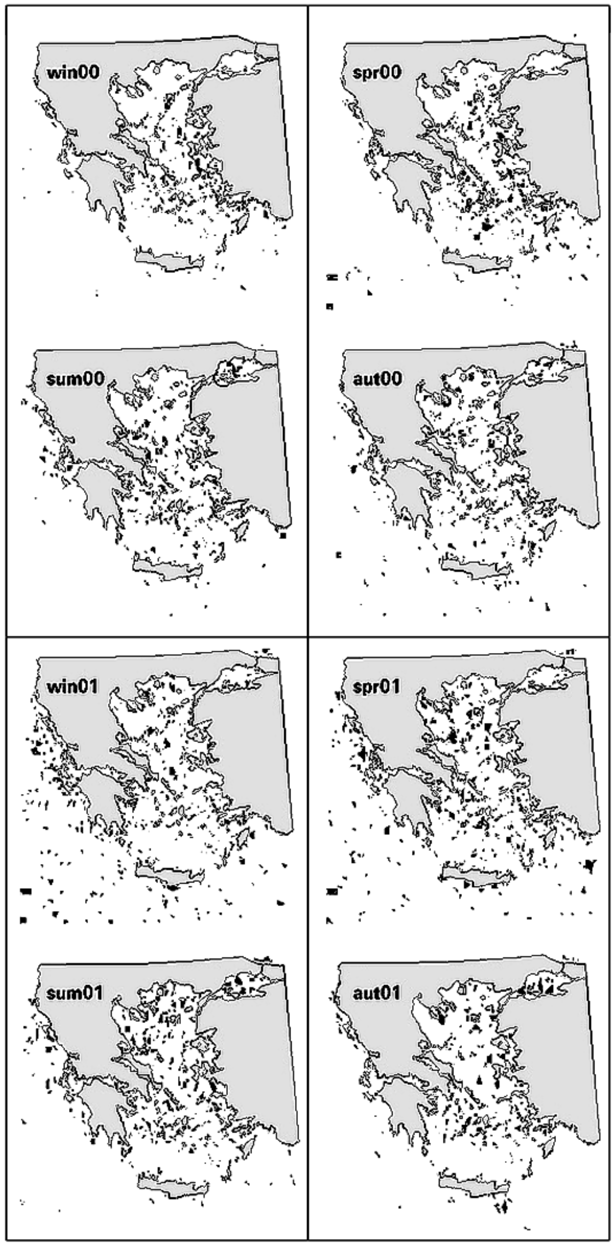

Figure 4. Seasonal marine productivity hotspots in Hellenic Seas (Eastern Mediterranean) for 2000 and 2001. These areas (in black) characterize high marine productivity regions and are considered as major feeding aggregation areas for pelagic fisheries resources.

their spatiotemporal distributions are presented in Figure 3 and Figure 4. These areas describe combined environmental anomaly of below average SST and above average Chl-a and indicate persistent oceanic productive processes (e.g., upwelling, gyre and frontal formations). During the study period, modeled hotspots were characterized by lowSST/highChl-a anomaly patterns of –5.8 °C SST minimum and 0.55 mg/m^3 Chl-a maximum.

The environmental and spatial characteristics of productivity hotspots in Hellenic Seas (Eastern Mediterranean) for the period 1998–2001 are presented in Table 2. During the study period covering an area of 424062 km^2, a mean hotspot size of 32.2 km^2 was observed while an average 10.3% of the region was characterized by persistent lowSST/highChl-a anomaly patterns.

A seasonal quantitative index among spatial extents of marine productivity hotspots, species catch and their common area (Table 3) showed that 38% of small pelagic fish catch and 35.5% of pelagic squids were associated with productivity hotspots. Further, correlation coeffi-

Table 2. Area characteristics of marine productivity hotspots in Hellenic Seas (Eastern Mediterranean) for the period 1998–2001. An annual mean spatial extent of approximately 10.3% of the whole study area (424062 km^2) is characterized by lowSST/highChl-a anomaly patterns with yearly fluctuations depending on the general meteorological and oceanographic patterns of the area.

Year	Max area (km^2)	Mean area (km^2)	Sum area (km^2)	Hotspot area (%)	Min SST anomaly (°C)	Mean SST anomaly (°C)	Max Chl-a anomaly (mg/m^3)	Mean Chl-a anomaly (mg/m^3)
1998	1229	27	40188	9.5	−5.2	−0.80	0.47	0.17
1999	1499	32	52272	12.3	−5.8	−0.65	0.57	0.21
2000	593	32	43909	10.4	−6.3	−0.65	0.61	0.11
2001	645	38	39531	9.3	−5.8	−0.58	0.58	0.14
MEAN 98-01	911	32.2	43975	10.3	−5.8	−0.67	0.55	0.16

Table 3. Quantitative index between spatial extents (in km^2) of species catch, modelled productivity hotspots and their common area (overlap) in Hellenic Seas (Eastern Mediterranean) for the period 1998–2001. In a total study area of 424062 km^2, a major part of the spatial extent of fisheries production is characterized by modeled marine productivity hotspots.

Areas in km^2	Productivity hotspot	Sardine catch	Sardine Overlap	Anchovy catch	Anchovy Overlap	Short-finned squid catch	Short-finned squid overlap	Long-finned squid catch	Long-finned squid overlap
Win98	19657	22906	2536	22859	3888	54854	4501	49644	4135
Spr98	15252	36725	4292	38120	4725	54854	4369	54876	5884
Aut98	14469	55362	3468	37482	2568	59360	3297	27109	1238
Win99	13695	40074	4058	20866	2995	55422	7047	30346	3653
Spr99	23892	44390	5488	27751	3065	39231	4308	18125	903
Aut99	29281	33077	3517	19287	2370	59809	5801	25856	2767
Win00	7999	35579	2264	17191	799	90874	5574	68548	4218
Spr00	16126	58080	2608	29981	2082	29300	1670	71298	5438
Aut00	16085	2227	4665	30128	3640	72843	5659	49646	4230
Win01	21897	48134	2435	16877	986	70884	4830	53215	3530
Spr01	24704	60844	5123	47901	4814	73809	4779	57923	5613
Aut01	11841	49935	1926	23856	1224	70893	2175	43536	1929
1998–2001	175900	116599	42380	81628	33156	151890	54010	121498	43538
Overlap (%)			36.35		40.61		35.55		35.83
Correlation coefficient (ρ)			0.23		0.72		0.40		0.80
Unexploited hotspots			133520		142744		121890		132362

cients between the spatial extents of species catch and that of common areas between species catch and productivity hotspots showed strong association links between fishery resources and marine productivity hotspots, especially for anchovy (= 0.72) and long-finned squid (= 0.80).

Discussion

The geographic distribution of marine productivity hotspots generally covers the whole study area in smaller and larger patches (observed average patch size 32.2 km^2). However, productivity hotspots follow the annual cycle of mixing and stratification of surface waters in the Aegean Sea caused primarily by the Etesians (Christopoulos, 1997). These are summer northernly strong dry winds triggered primarily by the Azores high-pressure system, which during summer, moves north and extends to southeastern Europe and the Balkans and the deep Asiatic low, which extends to the west and sometimes further into southeast Mediterranean. Etesians trigger upwelling along the north, central and eastern Aegean Sea, establishing an east-to-west temperature gradient in the central Aegean Sea. During summer (Etesians), productivity

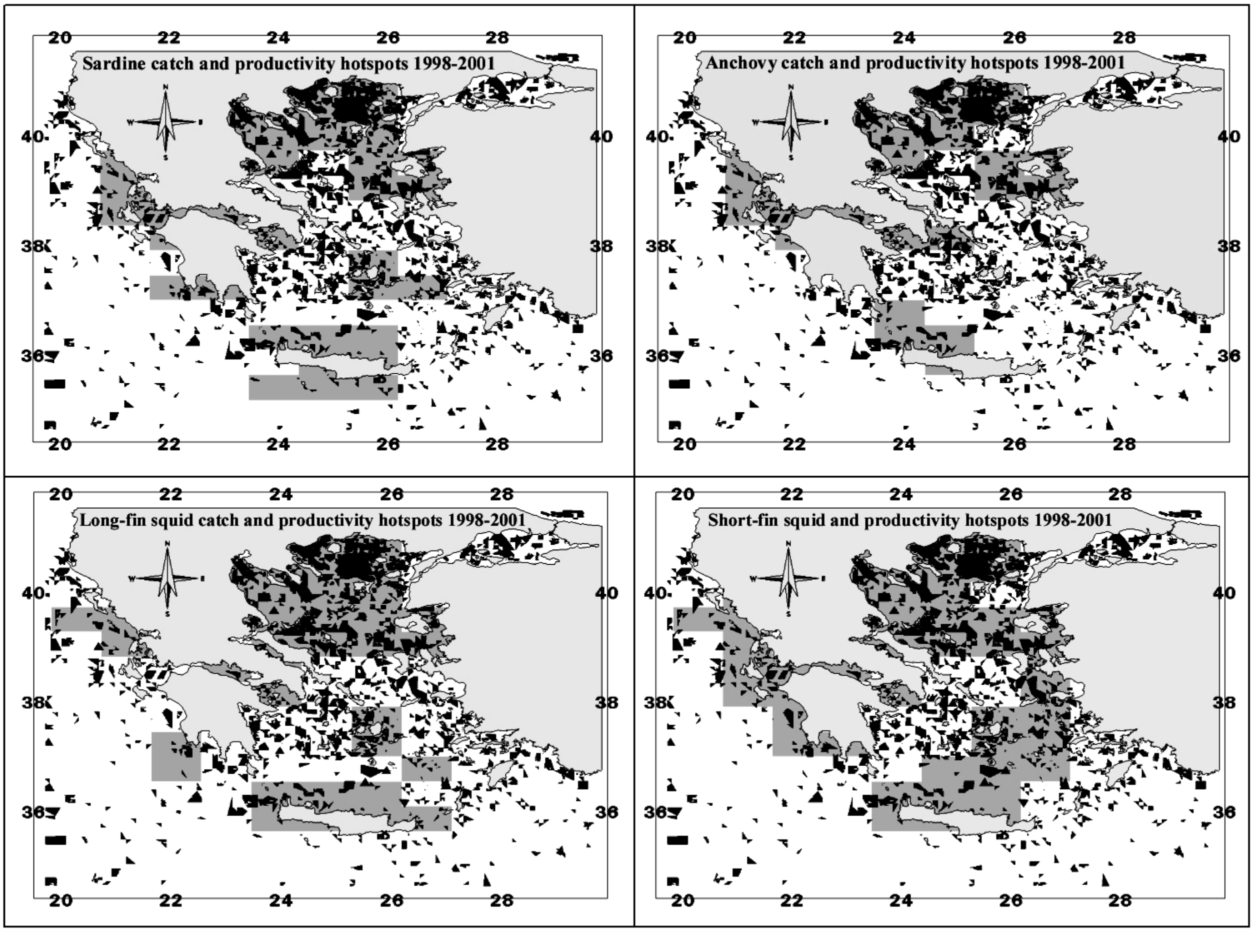

Figure 5. Coincident seasonal spatial relations between fisheries production data for pelagic fisheries resources (dark gray) and modeled marine productivity hotspots (black) in Hellenic Seas (Eastern Mediterranean) for the period 1998–2001. Modeled productivity hotspots describe major well-known fishing grounds for sardine, anchovy and squid resources while they reveal alternative unexploited regions.

hotspots are mainly observed in the north, central and eastern Aegean Sea. Etesian influence on the oceanography of the area may be considered as an indicator of summer hotspot distributions. Weak Etesians during summer 1998 (Zervakis et al., 2000; Xoplaki et al., 2003) resulted in decreased distribution of anomalies in central Aegean Sea along with narrow annual environmental extremes and small spatial extents, while this pattern is reversed during 1999–2001 (Table 2). However, throughout the study period, summer averaged environmental extremes of lowSST and highChl-a present a broader value range (stronger anomaly signature) as compared to other seasons (Fig. 2).

During autumn, winter and spring (no Etesians) when an overall cyclonic surface circulation is established in the area (Valioulis and Krestenitis, 1994), lowSST/highCHL anomaly patterns are more evident along the northernly current of the Asia Minor coast and less evident along the relatively weaker southernly current of the Greek coast (Metaxas, 1973; POEM Group, 1992). Also, larger hotspot patches dominate the north part of the study area (North Aegean Plateau) which is highly influenced by river plume and inflow of Black Sea water (Theocharis and Georgopoulos, 1993) as well as by coastal upwelling (Valavanis et al., 1999).

The geographic distribution of marine productivity hotspots in relation to that of fishery resources for the period 1998–2001 reveals the association between marine productivity and major species catch areas (Fig. 5). This spatial association shows areas of major fishing fleet activity, especially the well known Aegean Sea (North Aegean and Cyclades Plateau) and Ionian Sea fishing grounds. Monitored fishing areas for both pelagic fish and cephalopods present a significant overlap with the spatial extent of marine productivity hotspots (Table 3). Particularly, the high spatial correlations associated with anchovy and long-finned squid fisheries may be attributed to the high sensitivity of these species to temperature variations (e.g., Nakata et al., 2000; Lefkaditou et al., 1998) as well as to their high mobility in search of feeding grounds (e.g., Coelho et al., 1994; Tudela and Palomera, 1997).

The association between marine productivity and major species catch areas also reveals offshore and coastal marine productivity hotspots where no major fishing activity occurs. Marine productivity hotspots located outside species catch areas are good indicators of potential unexploited alternative fishing grounds. These hotspots are characterized by the same environmental factors that sustain fishery resources in known catch areas. The fact that they are not presently exploited may be attributed to their distant location from fishing ports (offshore productivity hotspots in the south part of the study area) or to their random distribution (coastal and mid-distant hotspots in central Aegean Sea, excluding Cyclades Plateau).

Known fishing grounds in the area are generally close to overexploitation (Kapantagakis et al., 2001). Modeled marine productivity hotspots that reveal known fishing grounds should be further studied and may be characterized as candidate marine protection areas (MPAs). In addition, modeled marine productivity hotspots that are not associated to known fishing grounds reveal unexploited regions that can sustain pelagic fishery resources and may be used as alternative fishing grounds. Stergiou (2002) underlined the need of discovering new unexploited fishing grounds in the study area under the broader concept of placing fisheries management into an ecosystem perspective (Cochrane, 2000; Pitcher, 2000). Further, Ludwig et al. (1993) and Fogarty (1999) proposed that the establishment of effectively large-sized marine protected areas (no-take zones) must proceed quickly under a precautionary approach in fisheries management around the world, thereby relieving pressure on existing fisheries and harvesting new stocks. The spatiotemporal mapping and monitoring of marine productivity hotspots in relation to fisheries production may facilitate these processes.

Conclusions

The proposed GIS-based satellite data-driven model of marine productivity hotspots features analytical modules for the processing and integration of time series of remotely-sensed sea surface temperature distribution and chlorophyll concentration. The model allows the spatiotemporal mapping of combined anomaly in below average temperature values and above average chlorophyll levels. This mapping/modeling effort provides important information on surface water processes that are the main factors for water mixing in the euphotic zone. In the Eastern Mediterranean, such spatial relations follow the general pattern of summer surface temperature stratification versus the relative uniformity of surface waters during winter.

Marine productivity hotspots, resulting from water mixing in the euphotic zone, create favorable living, feeding and reproductive habitat conditions for many pelagic species. In Eastern Mediterranean, such regions are highly related to fish aggregation dynamics. The combined mapping of marine productivity hotspots and seasonal catch of sardine, anchovy and pelagic squids reveals areas that may be characterized either as known overexploited fishing grounds (candidate MPAs) or as new alternative unexploited fishing activity areas.

Finally, the modeling and monitoring of marine productivity hotspots may be an important spatial measure for the proper stewardship of marine fisheries resources. Techniques developed in this work for the Eastern Mediterranean are applicable to any marine region and other fisheries around the world. Productivity hotspot maps could facilitate the fisheries management process under an ecosystem perspective either as a tool for the identification of alternative fishing grounds or as basic information for the design of effective marine protected areas.

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