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Decadal trends in 50-year biogeochemical model simulations of the North Aegean Sea

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1. Introduction and objectives:

The main objectives of this study are to run and examine 50 years (from 1960 to 2009) physical- biogeochemical simulations of the North Aegean Sea (which represents a subsample of the full model domain of Mediterranean Sea) in order to detect the past variability and decadal changes in the surface fields.

The Aegean Sea presents great challenges to modelling studies since it has complex bottom topography with many islands, islets and straits that can make difficult the selection of the optimal horizontal model resolution in balance with the available computational resources. The North Aegean Sea is directly influenced by the outflow of the Black Sea water masses, through the Dardanelles Strait. This Black Sea contribution to the North Aegean basin is cold, brackish, and rather rich in biomass and nutrients. We examine the decadal trend and variations at surface of the physical variables of the North Aegean Sea, as well as the bloom/no bloom occurrences. Furthermore we apply novel statistical methods to distinguish between linear trends and breakpoints (change points) in the time series. The identification of concurrent breakpoints in many different variables will provide supporting evidence for the detection of potential regime shifts. We select 3 sub-domains of the North Aegean Sea (Figure 1) which have very distinct dynamics from each other. The first is the area of main impact of the Dardanelles discharge where waters originally from the Black Sea enter the Aegean Sea. The second area is a riverine discharge area in the west Aegean (Greek) coast (River Strymonas). The third sub-domain is located offshore in the south in an area with neither rivers nor Dardanelles-discharge direct and immediate interaction.

This study is organized as follows: section 2 describes the methodology and datasets examined, section 3 presents the results and discussion, and the summary and conclusions are given in section 4.

2. Methodology and data:

The ocean circulation model used in this study is the 3-D General Estuarine Transport model (GETM hereinafter). For a detailed description of the GETM equations, see Burchard et al. (2002) and Stips et al. (2004). We use the model GETM coupled operatively with the medium-complexity biogeochemical model described in Fasham et al. (1990).

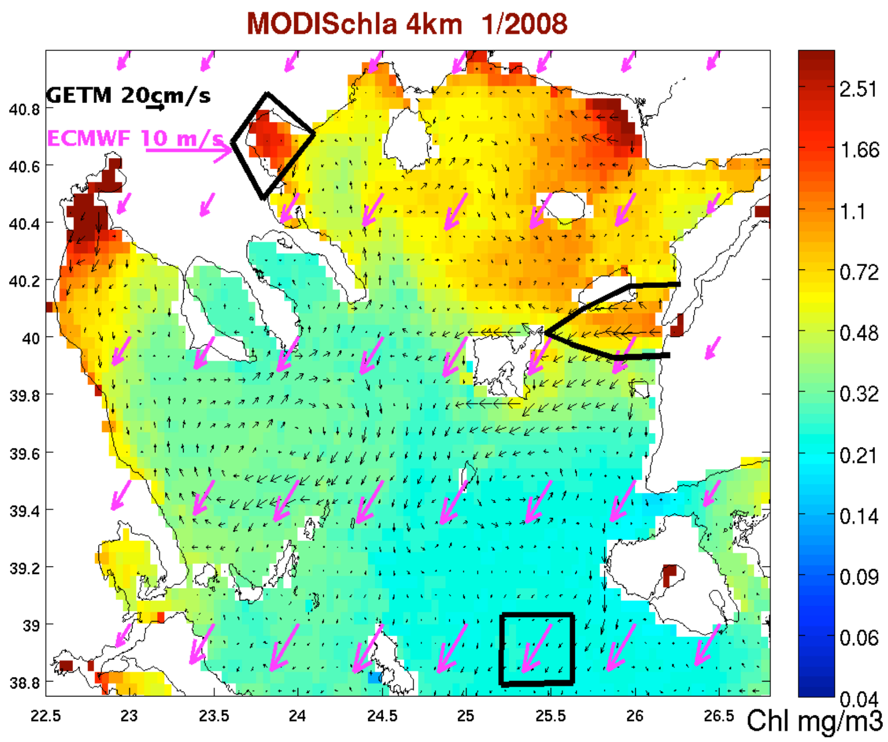

Figure 1: The black boxes are the three sub-domains in the North Aegean Sea: the area of main impact of Dardanelles discharge (east box), a riverine discharge area in the west Aegean coast (River Strymonas), and the south basin area. The image corresponds to phytoplankton pigments (mg/m3) from MODIS at 4 km resolution for 1/2008. The pink arrows are the concurrent ECMWF winds. The black arrows are the GETM surface currents for 1/2008.

The geographical domain for the model runs includes the entire Mediterranean Sea, but we specifically examine here the results for the North Aegean Sea. The horizontal resolution used for the coupled runs is 5’x5’ and the domain includes 25 vertical layers, within a multiannual time window starting in January 1961 to December 2009. The influence of the Dardanelles flow at the surface layer is simulated with a climatological monthly discharge. The current configuration includes 38 rivers discharging along the Mediterranean coasts.

The coupled physical-biogeochemical model is forced at surface with the atmospheric data from the European Center for Medium-Range Weather Forecast (ECMWF hereinafter) every 6-hours, which is the time frequency offered by the ECMWF datasets. The years from 1960 to 1990 are forced with the ERA40 reanalysis data, whereas from 1990 onwards the interim reanalysis data are used. The original data resulting from the spectral grid representation of the atmospheric model are spatially interpolated on a 0.5x0.5 degree grid. ETOPO1 Earth topography on a 1-minute resolution is used to build the bathymetric grid of the model domain. No tidal forcing is included in the model runs presented here.

We use the biogeochemical model developed by Fasham et al. (1990) [Fasham90 hereinafter] coupled to the GETM model. The Fasham90 model constitutes a compromise between the biologists wish for sufficiently complex ecosystem model structure and the modelers need to keep the model as simple as possible (Burchard et al., 2006). For this reason it has been used and validated widely within the oceanographic community. It uses nitrogen as ‘currency’ according to the evidence that in most cases nitrogen is the limiting macronutrient (Fasham et al., 1990). The structure of the model Fasham90 includes the following components: phytoplankton, zooplankton, bacteria, detritus, nitrate, ammonium, and dissolved organic nitrogen. Homogeneous initial conditions are prescribed for the ecosystem. The state variables are represented by their ensemble averaged concentrations, no matter if they are dissolved chemicals (e.g. nitrates) or particles (e.g. zooplankton cells). A two-way coupling between water column physics and biogeochemistry is applied. The dependence of the biogeochemistry on the physics is established via vertical mixing, temperature, and salinity dependence of process rates, light availability, among other mechanisms (Burchard et al., 2006). The feedback from the biogeochemistry to the water column physics is mainly due to modified turbidity changing the light absorption in the water. We examine the phytoplankton distributions and compare them with available satellite ocean-color observations.

The coupled model is also forced with riverine nitrate discharge. The values from 1960 to 2000 are provided by the project SESAME Deliverable 4.3.2. From 2001 to 2009, the nitrate values are reconstructed here using satellite chlorophyll (CHLA hereinafter) observations from OCTS, SEAWIFS and MODIS.

The idea for using statistical methods for estimating breakpoints in time series regression models was given by Bai, (1994) and was extended later to multiple breaks by Bai and Perron, (1998 and 2003). Basically we have to do a test that will assess deviations from the classical linear regression model. As a first guess it is reasonable to assume that a time series has b breakpoints, where the coefficients shift from one stable regression relationship to another one. Consequently there must exist b+1 segments with constant regression coefficients. These optimal segments have then to be found by a dynamic programming approach, minimizing the residual sum of squares for certain observation intervals. The F statistics can be used to estimate the optimal number of breakpoints and it is possible to construct confidence intervals. Principally it is possible to separately test for a change in the mean and for a change in the trend. How to apply this procedure together with some instructive examples is given in Zeileis et al., (2003). Zeileis et al., 2003 also provided the implementation in the statistical software R package *strucchange*. The R statistical software and the mentioned package can be freely downloaded from the Comprehensive R Archive Network (CRAN, http://cran.r-project.org/). For the statistical investigation we use anomalies from the 1960-1990 mean value (base line), a procedure that is normally applied in climate research.

3. Results and Discussion:

3.1 Reconstruction of nitrate values from 2001 to 2009:

We reconstruct the NO3 values with the help of the concurrent satellite CHLA at the mouth of the rivers. As seen in Figure 2 up-left plot, when plotted multi-annually, the monthly values of SESAME NO3 and satellite CHLA from 1997 to 2000 vary in such a way that years with high NO3 values correspond to high values of satellite CHLA. If examined monthly as in Figure-2 bottom-left plot, we can also see that the SESAME NO3 climatological monthly values and the concurrent satellite CHLA at the river mouths progress throughout the year quite in correlation, but with lag of approximately 1-2 months. Our approach benefits from these results and assumes that the SESAME NO3 values are approximately in linear correlation with satellite CHLA values in annual terms. The results for the reconstructed annual NO3 values are in Figure 2 bottom-right plot. This approximation tries to capture as much as possible the environmental inter-annual trends from both satellite CHLA and SESAME NO3 to reconstruct the monthly NO3 values from 2001 to 2009 (in Figure 2 up-left plot) to be used to force the coupled model.

3.2 Monthly results:

We first compare the sea surface temperatures (SST hereinafter) for the three sub-basins in the North Aegean Sea (Figure 1) with the concurrent monthly values of both satellite-derived and ECMWF SSTs from 1982 (first year available for the NASA Pathfinder SST database) to 2009. For all the comparisons performed (Figure 3) the correlations between the GETM results and the other SST datasets are larger than 0.96.

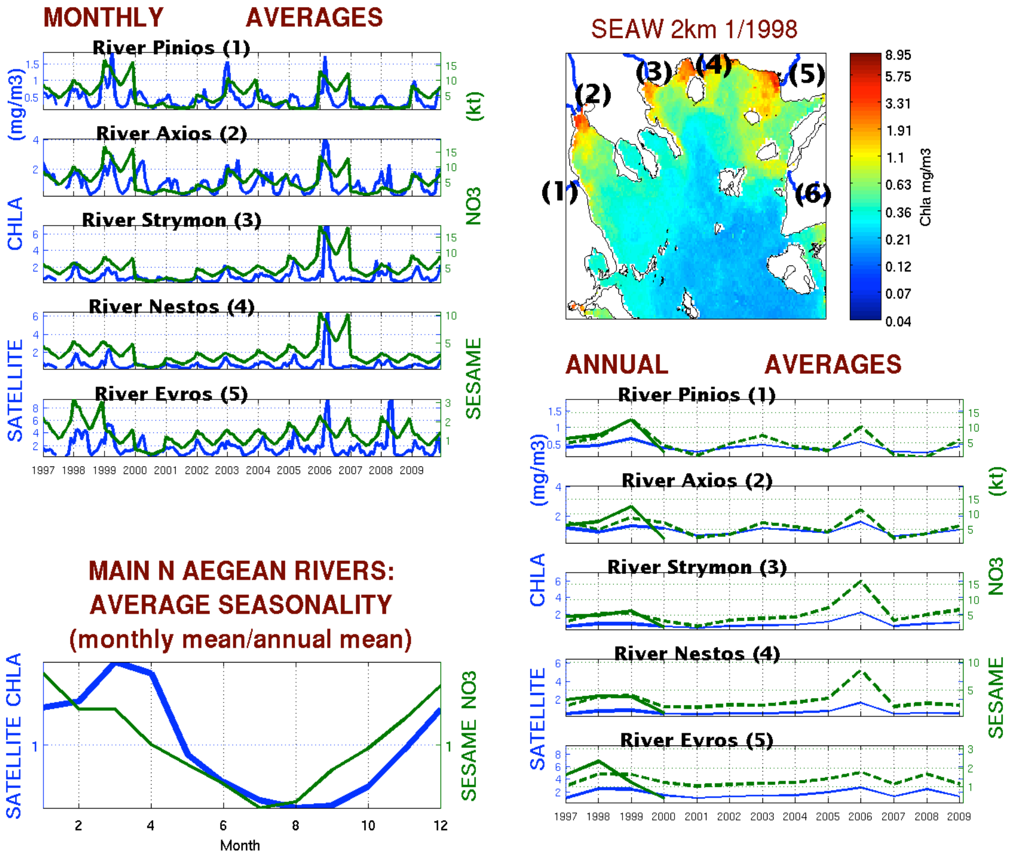

Figure 2: Bottom-left plot: NO3 river seasonality by SESAME deliverable is the green line, plotted with the corresponding satellite CHLA average seasonality in blue for the river mouths. Bottom-right plot: For each river, the solid lines indicate the satellite CHLA (blue) and SESAME NO3 (green) annual averages. The green dashed lines are the prediction for the annual NO3 based on satellite CHLA. Up-left plot: monthly averages of Satellite CHLA in blue (including OCTS values available in 1997 and SEAWIFS) in each river mouth, corresponding to the up-right basin map. The solid green lines are the monthly SESAME NO3 values (provided in SESAME until year 2000) and reconstructed here from 2001 to 2009.

The black arrows in Figure 1 are a sample of the monthly surface currents computed by GETM. In the vicinity of the Dardanelles Strait, the GETM currents at surface simulate the progression of the Black Sea water (BSW hereinafter) inflow within the North Aegean Sea. Multi-annually, the computed surface currents agree well with the direction seasonality reported in Zervakis and Georgopoulos (2002). In winter the BSW surface layer, after exiting the Dardanelles, follows a north-western path through the strait between the islands of Imbros and Limnos and can form an anticyclonic structure in the North Aegean Sea (Figure 1). In contrast, the BSW surface inflow follows in summer a south-western route to reach the western coast of the Aegean and move cyclonically towards the south. This south-west shift in summer has been attributed mostly to the forcing by the northerly Etesian winds that apply in late summer on the BSW jet (Zervakis and Georgopoulos, 2002). The seasonality of the winds for the third sub-domain in the south is very similar to that in Dardanelles.

The Black Sea is the major, but not the only source of nutrient-rich waters for the North Aegean Sea. Several rivers along the Greek and Turkish coasts also contribute. The second sub-domain corresponds to the mouth of Strymonas river (Figure 2). In contrast with Dardanelles and the south area, the west river area has lower surface currents and much weaker wind fields throughout the year, as seen in Figure 4.

For the Dardanelles and the Strymonas river areas, we find a general good agreement of model results with satellite-derived CHLA observations in bloom timing and inter-annual variation, but the bloom maximum values are underestimated in the model (Figure 4). Throughout the years, the main bloom is in early-spring with sometimes a secondary bloom in winter. Normally bloom corresponds to a period of low north-south winds (Figure 5). There is no general concurrency of bloom timing to neither riverine nor Dardanelles discharge-time, as indicated with vertical pink dashed lines in Figure 4 or 5.

There is also no simple correlation of the bloom timing with the sea surface (SST hereinafter) anomaly variation. Whereas the bloom-timing is maintained inter-annually, the SST anomaly shows a trend in the 2000s: colder winter-seasons and warmer summer-seasons meaning a stronger pronunciation of the seasonality (also found later when discussing the 5 and 10-years trends).

For the south area, we find stronger north-south winds and much lower CHLA than in the other two sub-domains (Figure 5). The model tends to overestimate the spring bloom values in this area. As seen in Figure 5, the years 2008 and 2009 present a peculiar repeated concurrency between SST anomalies and north-south winds: strong southward winds correspond quasi-linearly to cold SST anomalies (perhaps due to upwelling), and northward winds to warmer SST anomalies.

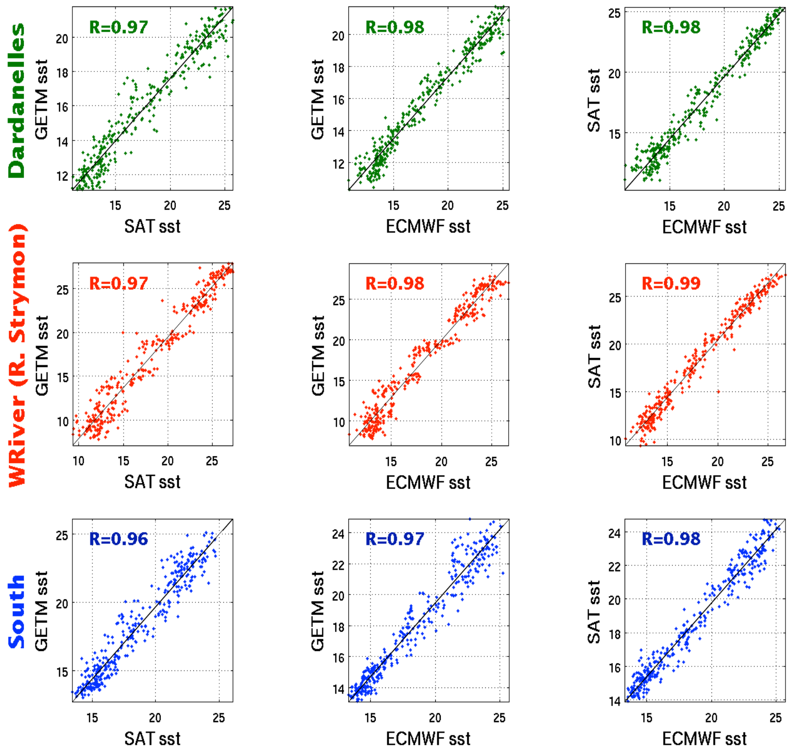

Figure 3: Comparison of sea surface temperatures from GETM, satellite-derived and ECMWF for the three sub-basins in the North Aegean Sea from 1982 to 2009.

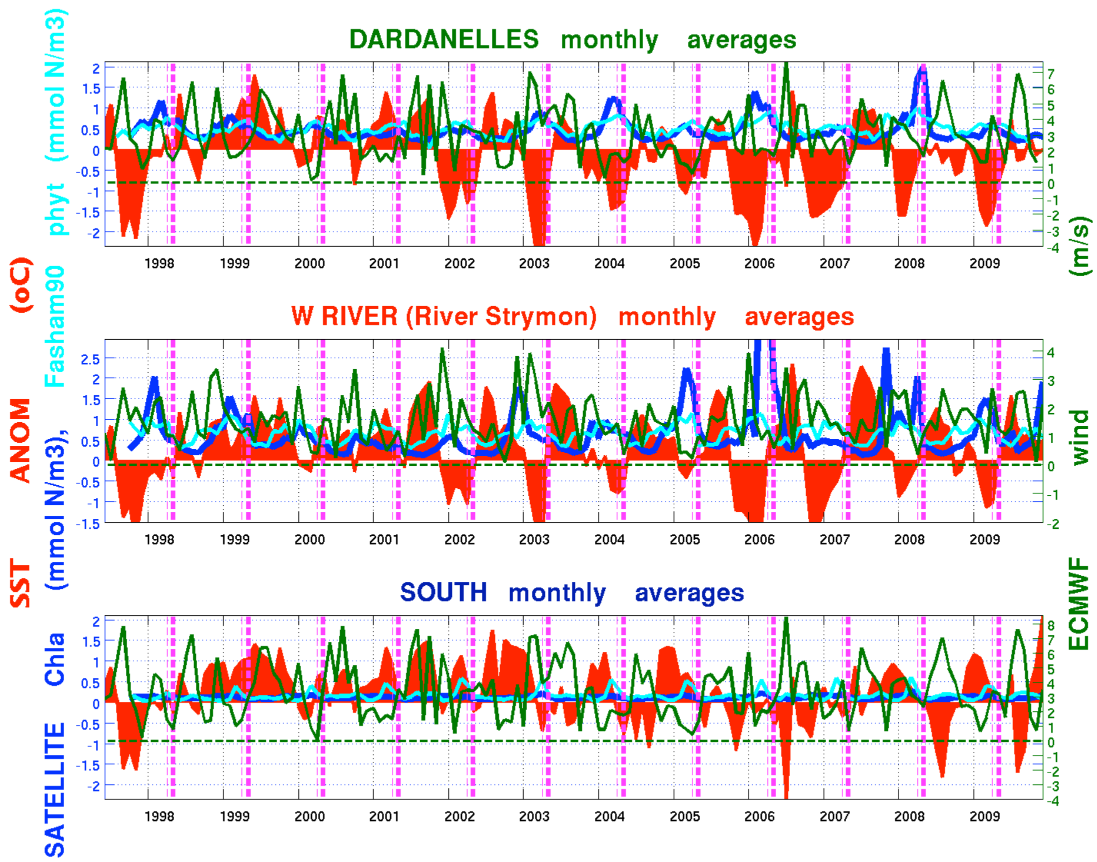

Figure 4: Multi-annual monthly values from October 1997 to December 2009 of: sea surface temperature anomaly in red [degC], satellite pigments [mmol N/m3] in dark blue, results of Fasham90 phytoplankton concentration [mmol N/m3] in light blue, wind [m/s] in green. The dashed pink lines indicate the month of maximum discharge for Dardanelles (thick line) and rivers (slim line).

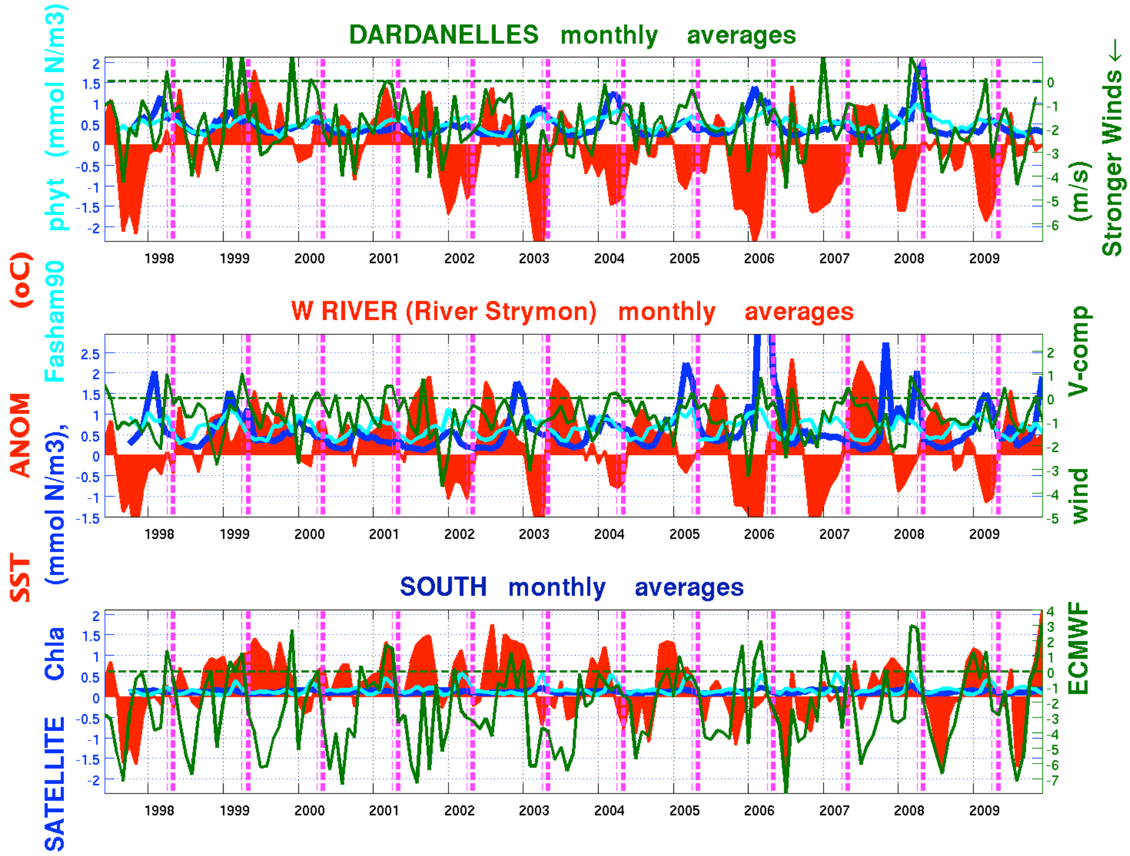

Figure 5: Same as in Figure 4 but the green line corresponds to the north-south component of the wind. Unlike the rest of the variables, larger (or stronger) southward wind values are more negative and correspond to the lower end of the plots.

3.3 Five-year and decadal results:

When the monthly results are averaged in 5-year (Figure 6) and 10-year climatologies (Figure 7), the phytoplankton model results show general good-agreement with satellite-derived CHLA observations in bloom timing and inter-annual variation. However, bloom peaks are underestimated in the Strymonas area, and overestimated in the south area.

From the 60s, the pattern of main blooms in early-spring and winter is kept, normally coinciding with low southward winds (Figures 6 and 7). No simple correlation can be seen between bloom timing and SST anomaly pattern.

Regarding the inter-annual variation of the north-south wind, Figures 6 and 7 show a trend to stronger southward-winds that initiates in the 1990s.

For the 3 areas, the SST anomalies can be grouped in four generic trends:

- From 1960 to 1969: especially warmer winters and a bit colder summers.
- From 1970 to 1989: colder trend throughout the seasons.
- From1990 to 1999: warmer throughout the seasons.
- From 2000 to 2009: tendency towards extremes with colder winters and warmer summers.

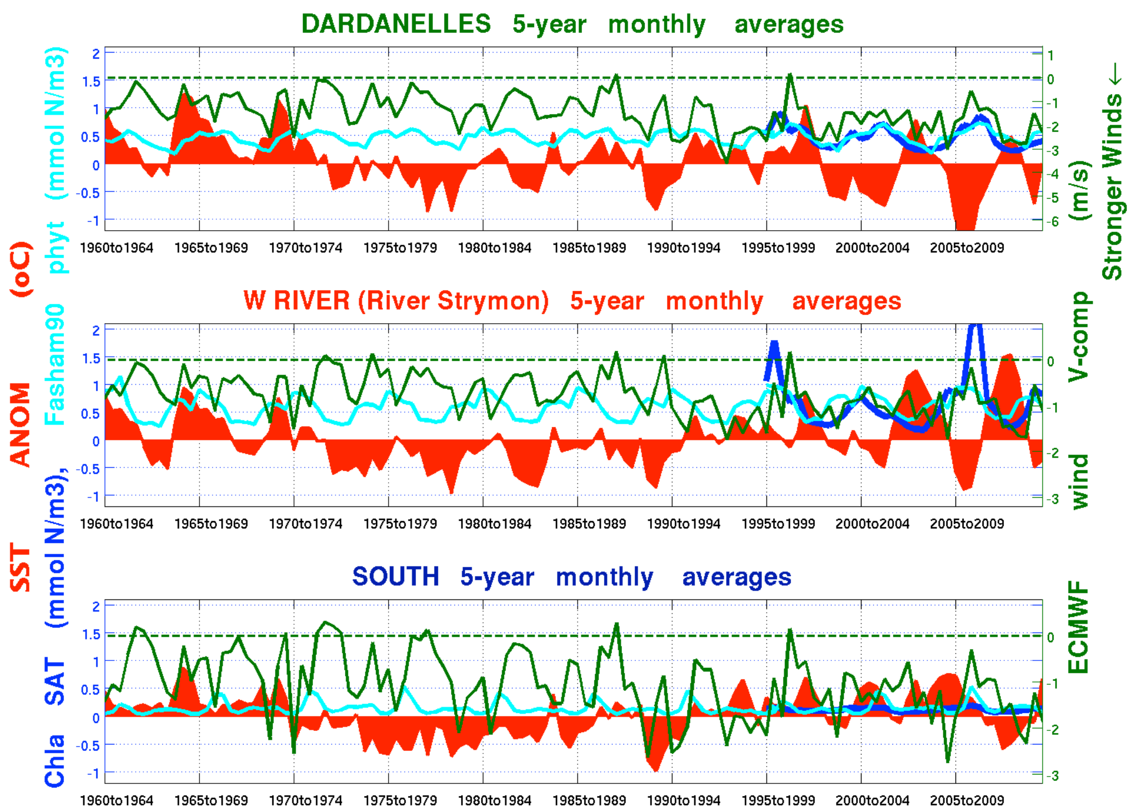

Figure 6: Same variables and areas as in Figure 5 but averaged in 5-year climatologies.

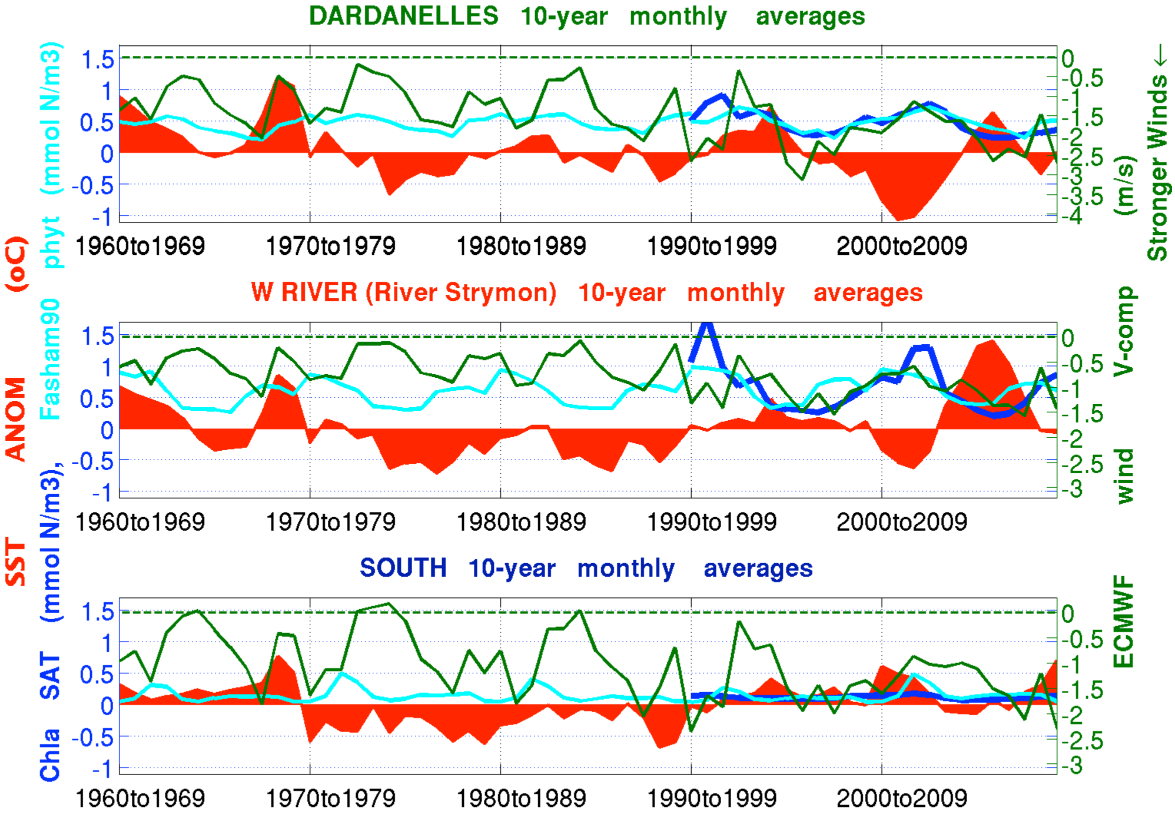

Figure 7: Same as in 6, but averaged in 10-years climatologies.

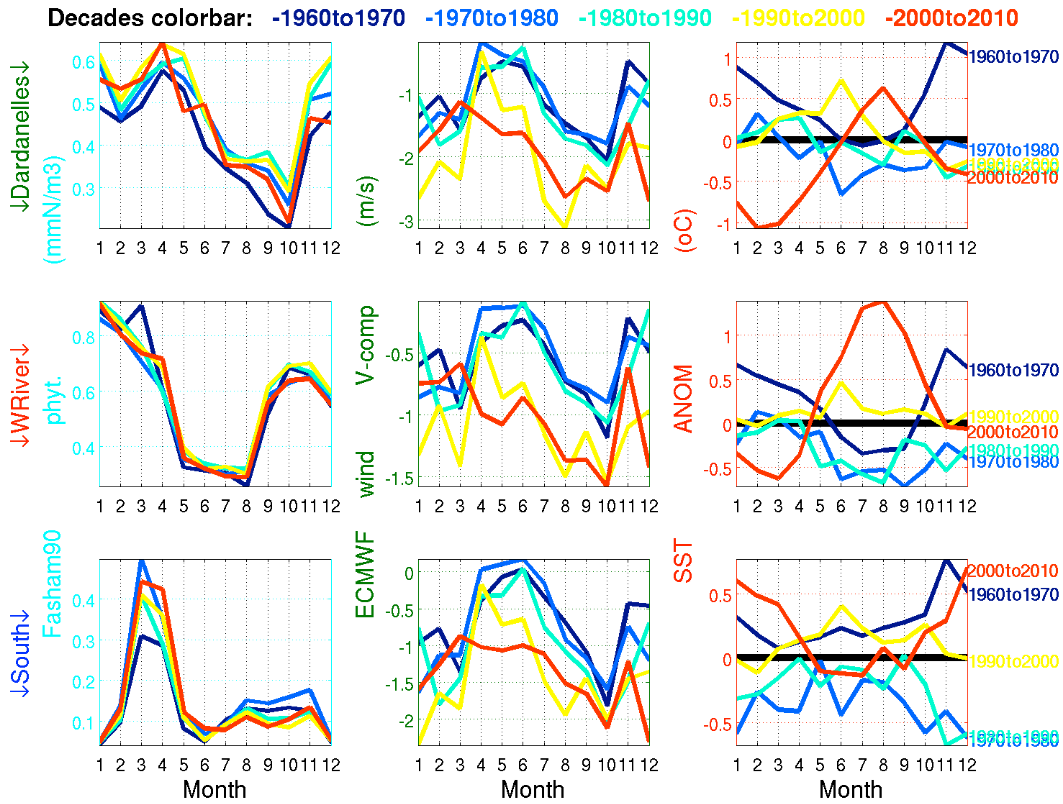

Figure 8: Decadal trends for Fasham90 phytoplankton concentration results (left column of plots), ECMWF north-south wind (central column), and SST anomalies (right column) for the three sub-domains in the North Aegean Sea. Each decade has its own color as indicated by the decadal colorbar.

3.4 Detection of breakpoints

The foundation for estimating breakpoints in time series was given by Bai, 1994 and was later on implemented in the statistical software R package *strucchange*. The R statistical software and the package can be freely downloaded from the Comprehensive R Archive Network (CRAN, http://cran.r-project.org/) was used for the present analysis. In Figure 9 artificial data with 2 distinct different regimes (step function) are shown, together with the breakpoint identified by the software and the corresponding confidence 5% interval. Nevertheless it is also possible to calculate the linear trend which is statistically significant at the 5% level. The same is valid for data with a linear trend, in this case the software finds significant breakpoints in the mean. It is therefore necessary to remove the significant trend before estimating breakpoints in the mean of a time series. This example clarifies therefore the inherent risk of applying statistical tools to data of unknown dynamics. It should be clear that the statistics cannot be used to determine the dynamics of a physical or a geophysical system but can be only used to confirm the physical reasoning. Therefore we must also consider the question if the ecosystem and the climate of the Aegean Sea are behaving linear (slow changes, smooth transitions) or non-linear (abrupt changes, breakpoints, regime shifts).

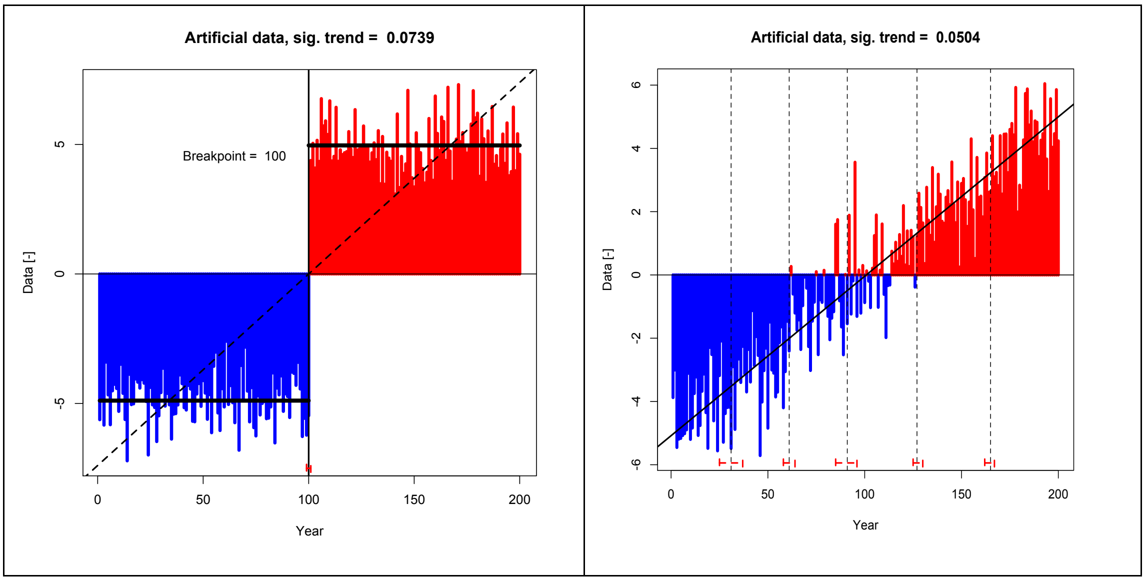

Figure 9: Examples for breakpoint detection (mean) using artificially generated data with noise. Left graph significant trend and breakpoint identified in step function. Right plot: the same for linear function.

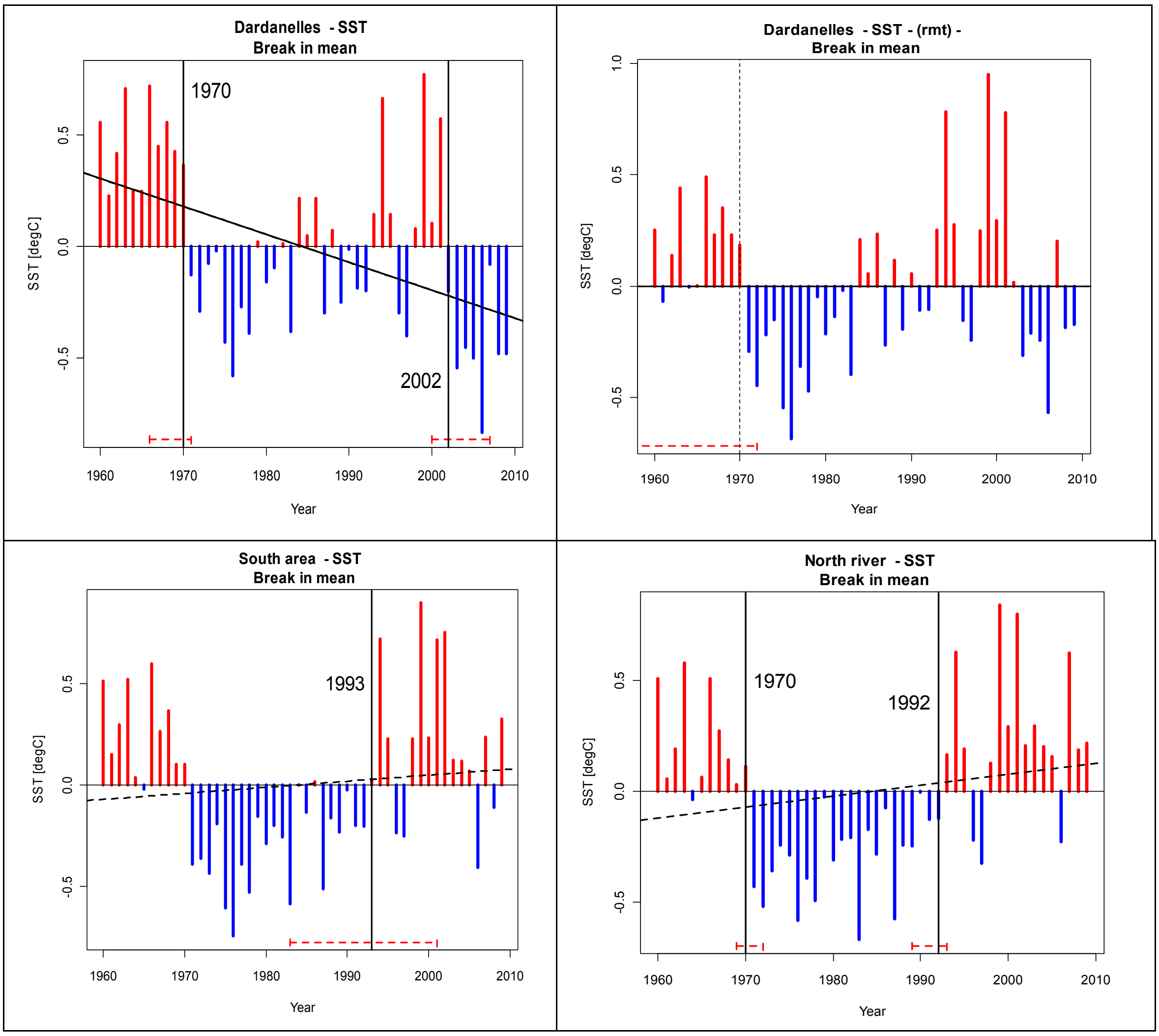

Figure 10: Identified SST breakpoints and trends in the three investigated areas. The upper two figures from the Dardanelles outflow area show the disappearance of seemingly significant breakpoints, when removing the linear trend from the data.

The results for the test on breakpoints in the SST data (50 year annual mean values) together with the calculated linear trends are shown in Fig. 10. In the Dardanelles outflow region we find a significant decreasing temperature trend. If we test for abrupt changes in the data mean we find two clear and significant breakpoints in 1970 and 2002 at Dardanelles. But these two breakpoints might have been caused by the increasing SST trend, because if we remove the linear trend, both breakpoints disappear. The South area and the North river area do not have a significant trend in SST. The south area has two significant breakpoints at 1970 and 1992 respectively.

As in section 3.3 we are looking specifically at the time series of the south component of the wind speed (Figure 11), as this component has a dominant influence on the dynamics in the Aegean Sea. In the Dardanelles area there the wind speed is significant increasing during the last 50 years. Similar to the SST results the seemingly significant breakpoint in 1988 at the Dardanelles area will disappear when removing the linear trend. Both South area and North river do not have a significant linear trend nor any significant breakpoint in the wind speed.

Next we are investigating breakpoints in the phytoplankton variable of the used ecosystem model which corresponds to the satellite derived CHLA contents. Results are shown in Figure 12. A significant increasing linear trend is found in Dardanelles and North river region but not in the open southern waters. Again, when removing the significant trend no breakpoints can be detected in the data. Nevertheless it is obvious that in all the 3 regions the absolute phytoplankton biomass is much higher in the decade from 2000 to 2009 compared to decade 1960-1969. There is no significant linear trend and no significant breakpoint at the South region.

Finally we are looking at bottom density, air temperature and wind speed in the region North of the island Crete, a very important dynamic region. The bottom density shows an increasing trend during this time, but there are no significant breakpoints in the data mean values in all these variables.

In summary the thorough statistical investigation specifically regarding change points in the 50 year time series did not reveal a clear regime shift in the Aegean Sea during this period. This finding stays in stark contrast to results published by Raitsos et al. (2010), who claim to have found breakpoints about 1998 in both regional and Northern hemisphere temperature (NHT) and related that to the appearance of alien species in the Aegean Sea. In our opinion, their regime shift detection method is not based on any rigorous statistical testing, but on the application of an adjusted colour scale. Testing the same NHT data with the here described methods does not result in any significant breakpoints at that time.

Similarly the trend investigations do not result in convincing clear trends, on the contrary SST does even show a cooling tendency in the selected areas.

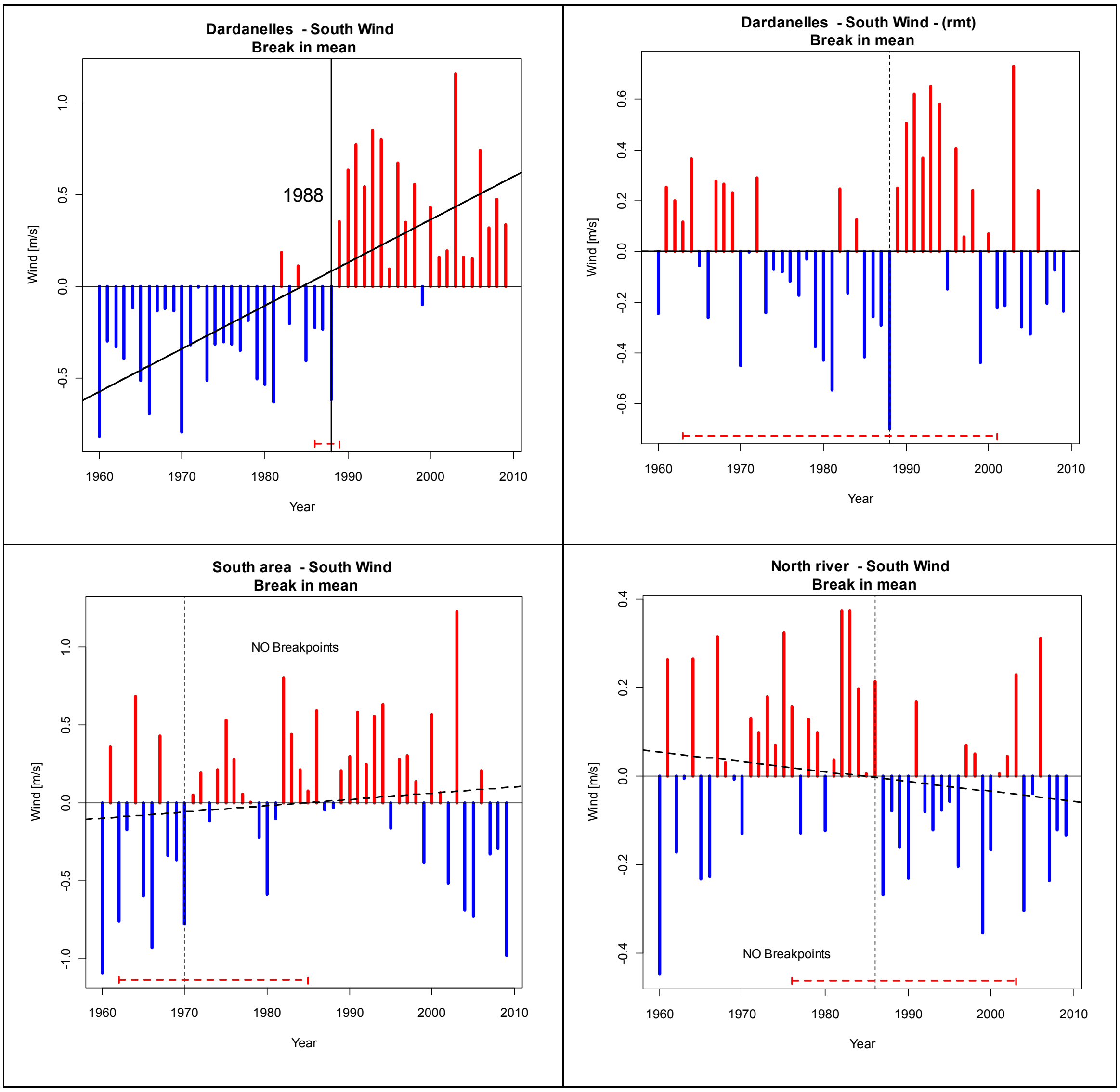

Figure 11: Breakpoints in the south component of the wind speed for the three investigated regions. The upper two figures from the Dardanelles outflow area show the disappearance of seemingly significant breakpoints, when removing the linear trend from the data.

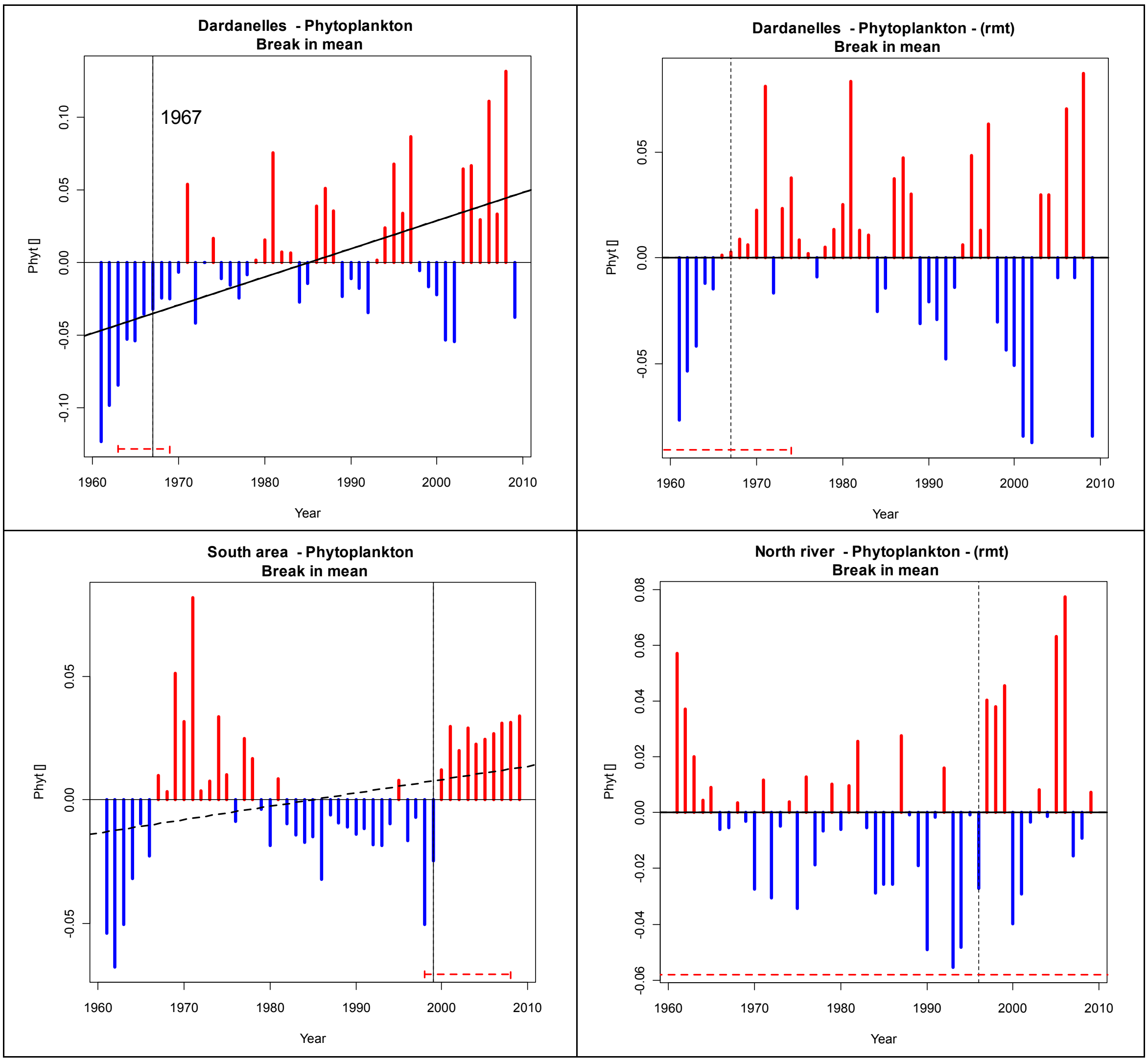

Figure 12: Breakpoints in the phytoplankton variable of the ecosystem model (corresponding to CHLA concentration) for the three investigated areas. The upper two figures from the Dardanelles outflow area show the disappearance of seemingly significant breakpoints, when removing the linear trend from the data.

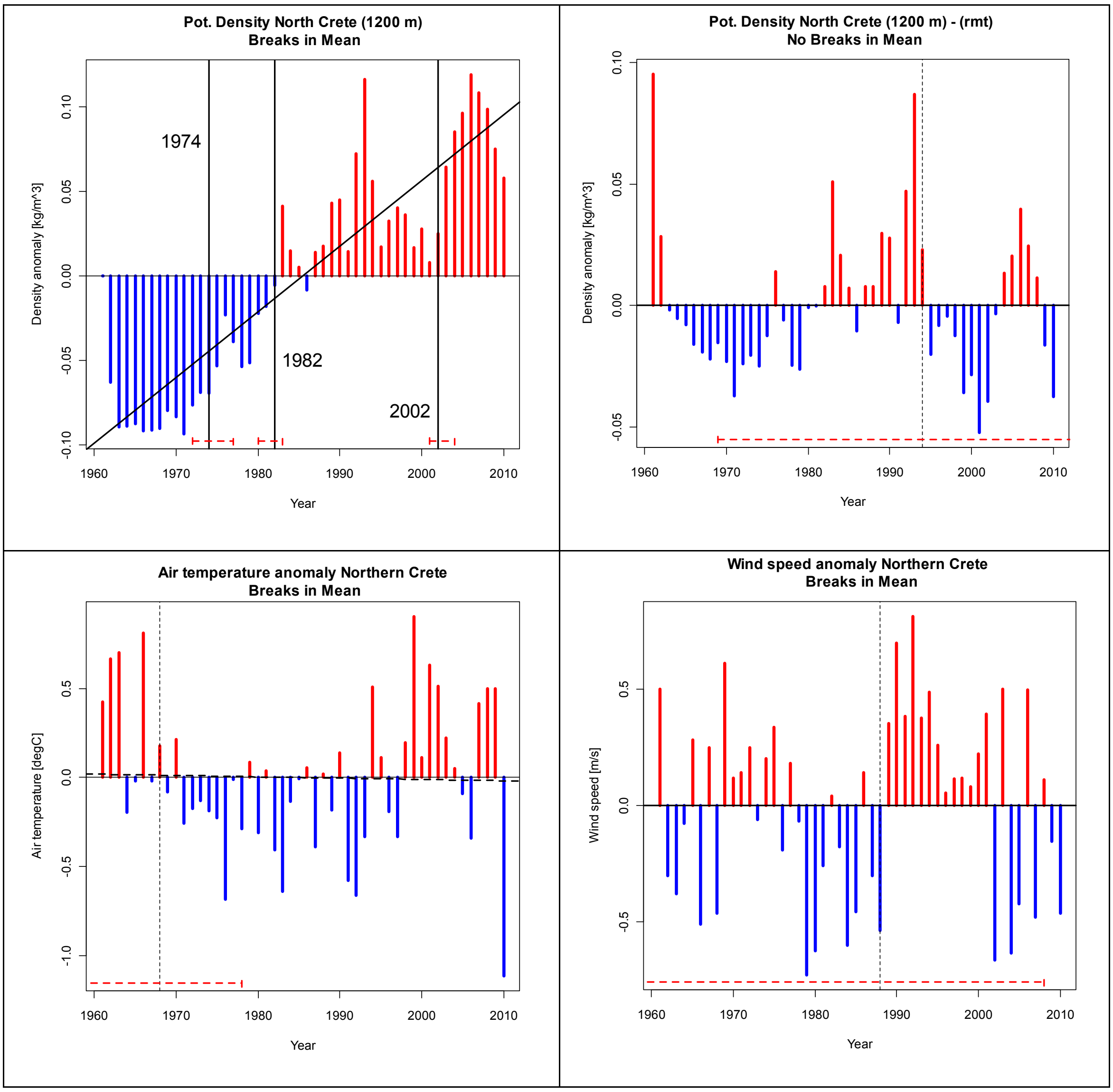

Figure 13: Breakpoints in bottom potential density, air temperature and wind speed of the ecosystem model for the region north of Crete. The upper two figures show the disappearance of seemingly significant breakpoints, when removing the linear trend from the data.

4. Summary and conclusions:

The GETM surface currents describe well the known seasonal variation in direction of the Dardanelles discharge, and general surface circulation in North Aegean Sea. The SSTs agree well with satellite-derived and ECMWF SST datasets, with correlations larger than 0.96.

We have reconstructed the values of riverine NO3 from 2001 to 2009 using satellite CHLA and SESAME NO3 values. Our approach tries to capture if possible the environmental inter-annual trends from both satellite CHLA and SESAME NO3 datasets.

We find general good agreement of model results with satellite-derived CHLA observations in bloom timing and seasonality, but bloom peak values are not reached in the Dardanelles and Strymonas River areas. From the 60s, the pattern of blooms in early-spring and winter is kept, both normally associated with low north-south winds.

The decadal trends for the phytoplankton concentration, north-south winds and SST anomalies for the three areas in the North Aegean Sea (Figure 7 and Figure 8) are:

- Phytoplankton concentration: the seasonality of the bloom occurrences is kept monthly for the 50 years, with no significant variation. Only the individual bloom-peaks vary from one decade to others. The decadal mean of the first and the last decade are respectively the lowest and the highest value found and the difference is significant.

- North-south winds: from 1990, the southward winds tend to be stronger at least in the northern regions. In comparison, lower winds are present in the 70s and 80s.

- SST anomalies: during the 70s and 80s we have the coldest temperatures within our time-frame; the 90s are warmer in general. From 2000, we have colder winters and warmer summers, in contrast with the 60s with warmer SSTs in general.

With regard to the investigation of trends, breakpoints and regime shifts (which would be indicated by the appearance of concurrent breakpoints in many different physical or ecological variables) we must conclude that the trends in North Aegean Sea are not persistent. Only some variables have a significant trend in only some of the selected areas. The same is true for the few identified breakpoints. Care has to be taken to apply statistical methods in a correct manner, as removing the linear trend to avoid the false detection of breakpoints.

SST and air temperature are pointing to a breakpoint at about 1992/1993. Looking at the presented anomalies the most prominent features are the distinct character of the first (1960-1969) and last (2000-2009) decade, whereas the three middle decades have a variable character.

Without investigating more parameters it seems not to be possible to identify a clear regime shift in the Aegean Sea, at least not at the by Conversi et al. (2010), proposed date for a Mediterranean regime shift at the end of the 1980s. This must not be a contradiction, as nearly all the parameters considered in Conversi et al. (2010) are from the Western Mediterranean and Adriatic Sea and not from the Aegean Sea. Therefore it might be that the Aegean Sea has an own different dynamics than the whole Mediterranean Sea. We did not find the speculated regime shift in SST at about 1998 of Raitsos et al. (2010), when applying our statistical testing methods and it could likely be an artefact of their used colour mapping.

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Abstract

This study examines 50 years (from 1960 to 2009) of physical- biogeochemical simulations of the North Aegean Sea in order to detect the past variability and decadal changes in the surface fields. We examine the decadal trend and variations at surface of the physical variables of the North Aegean Sea, as well as the bloom/no bloom occurrences. Furthermore we apply novel statistical methods to distinguish between linear trends and breakpoints (change points) in the time series. The identification of concurrent breakpoints in many different variables will provide supporting evidence for the detection of potential regime shifts. We select 3 sub-domains of the North Aegean Sea that have very distinct dynamics from each other. The first is the area of main impact of the Dardanelles discharge where waters originally from the Black Sea enter the Aegean Sea. The second area is a riverine discharge area in the west Aegean (Greek) coast (River Strymonas). The third sub-domain is located offshore in the south in an area with neither rivers nor Dardanelles-discharge direct and immediate interaction. The decadal mean of the simulated chlorophyll of the first and the last decade are respectively the lowest and the highest value found and the difference is significant.

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