Winter atmospheric circulation signature for the timing of the spring bloom of diatoms in the North Sea

Gerrit Lohmann[1] and Karen H. Wiltshire[2]

1: Alfred Wegener Institute for Polar and Marine Research
Bussestrasse 24
D 27570 Bremerhaven
Germany
Telephone: +49 (0)471 4831-1758 /1760
Fax: +49 (0)471 4831-1797
Email : Gerrit.Lohmann@awi.de

2: Biologische Anstalt Helgoland
Alfred Wegener Institute for Polar and Marine Research
Postfach 180
D 27483 Helgoland
Germany

Corresponding author: karen.wiltshire@awi.de

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Abstract

Analysing long-term diatom data from the German Bight and observational climate data for the period 1962-2005, we find a close connection of the inter-annual variation of the timing of the spring bloom with the boreal winter atmospheric circulation. We examine the fact that high diatom counts of the spring bloom tend to occur later when the atmospheric circulation is characterized by winter blocking over Scandinavia. The associated pattern in the sea level pressure shows a pressure dipole with two centres located over the Azores and Norway, and is tilted compared to the North Atlantic Oscillation. The bloom is earlier when the cyclonic circulation over Scandinavia allows an increased inflow of Atlantic water into the North Sea which is associated with clearer, more marine water, and warmer conditions. The bloom is later when a more continental atmospheric flow from the east is detected. We find that the mean diatom bloom can be predicted from the sea level pressure one to three months in advance. Using historical pressure data, we derive a proxy for the timing of the spring bloom over the last centuries, showing an increased number of late (proxy-)blooms during the 18^{th} century when the climate was considerably colder than today. We argue that these variations are important for the interpretation of inter-annual to centennial variations in the biological processes, as well as past and future effects on the primary production and food webs.

Introduction

Climate influences a variety of ecological processes (Stenseth et al., 2002). These effects operate through local parameters such as temperature, wind, rain, and ocean currents, as well as interactions among these. In the temperate zone, local variations are often coupled over large geographic areas through teleconnections (Wallace and Gutzler, 1981; Hoskins and Karoly, 1981; Liu and Alexander, 2007). These teleconnections are linked to transient behaviour of atmospheric planetary-scale waves and internal modes of climate system variability (e.g. El Niño-Southern Oscillation, North Atlantic Oscillation, Pacific Decadal Oscillation, Atlantic multidecadal oscillation). Such modes may also produce significant changes in regional climate, and certain regimes may be favoured, or amplified by external forcing.

It is therefore logical to analyse long-term ecological time series in the context of such teleconnection patterns. In a previous paper (Ionita et al., 2008), we investigated the teleconnections of salinity at Helgoland Roads station (54.12°N, 7.9ºE, Germany) for the period 1962-2000. We found that the main driver of salinity anomalies is the river discharge anomalies from the previous month. These discharge anomalies are strongly related with precipitation anomalies from the Elbe catchment which are accompanied by a wavetrain atmospheric circulation pattern that connects the tropical Atlantic Ocean and northern part of Europe. Such teleconnection patterns can be described as an atmospheric bridge (Liu and Alexander, 2007) and are also related to weather-type connections like blocking in the North Atlantic realm (Shabbar et al., 2001; Luo and Wan, 2005; Barriopedro et al., 2006; Ionita et al., 2008; Rimbu and Lohmann, 2010, 2011).

Here, we explore and describe the nature and drivers of environmental and biotic evolution, using phytoplankton data from the same location. The data set is one of the longest aquatic data sets in history, the Helgoland Roads time series (Wiltshire and Manley 2004, Wiltshire et al. 2008, 2010). Specifically, the time evolution of the blooming of diatoms and its relation with the atmospheric circulation are considered by using field correlation maps which is often also used for interpreting dynamical links to large-scale climate circulation (e.g., Rimbu et al., 2001; Lohmann et al., 2004). The link of the large-scale variability patterns with long-term environmental data goes beyond the standard time series analysis. We will show that high diatom counts in the spring bloom tend to occur later when the atmospheric circulation is characterized by a winter blocking over Scandinavia.

Methods

The biological long-term time series of Helgoland Roads has been continuously recorded by the Biological Station Helgoland (BAH) since 1962 on every working day. It consists of measurements of temperature, Secchi-depth, salinity, inorganic nutrient concentrations and data on phytoplankton, micro-organisms and zooplankton (Franke et al., 2004, Wiltshire et al 2010). The quality of the time series has been reviewed extensively (Wiltshire and Dürselen 2004, Raabe and Wiltshire, 2008).

Wiltshire and Manley (2004) combined the temperature and phytoplankton data from one of the longest aquatic data sets in history, the Helgoland Roads (North Sea, 54°11.3' N, 7°54.0' E) time series, to document the effects of climate change on the base of marine food webs. Diatoms in marine environments typically exhibit a "bloom and bust" lifestyle. When conditions in the mixed water column (nutrients and light) are favourable (*e.g.* at the start of spring) their competitive edge allows them to quickly dominate phytoplankton communities ("bloom"). It has been conclusively shown that the mean diatom day (MDD) is the most useful parameter characterizing the timing of the spring bloom at Helgoland Roads, and not, for example the day of maximum diatom abundance (see Wiltshire and Manley, 2004, Wiltshire et al., 2008). The MDD is defined as:

$$MDD = \frac{\sum f_i d_i}{\sum f_i}$$

where f_i is the diatom count on day d_i for the period January-March, and the sum is over the available samples. Fig. 1 shows the time series for the period 1962-2005.

For our statistical analysis we use several instrumental data sets. Gridded data sets are available for the last 100 to 150 years, by sophisticated interpolation of station data (e.g. Trenberth and Paolino, 1980) or data assimilation schemes (e.g. Compo et al., 2010). Monthly sea level pressure (SLP) from the Northern Hemisphere is taken from Trenberth and Paolino

(1980), ERA40 (Uppala et al., 2005), the 20^{th} century reanalysis data (Compo et al. 2010), and the ADVICE project. The Trenberth and Paolino data set is on a 5-degree latitude/longitude grid, begins in 1899 and covers the Northern Hemisphere from 15°N to the North Pole. The dataset continues to be updated regularly as new data become available. ERA40 and the 20th century reanalysis is used on a 2.0 degree latitude x 2.0 degree longitude grid. The ADVICE pressure data set (station data and gridded) is described in Jones et al. (1999) and covers the 1780-1995 period. Monthly grid-point pressure data are reconstructed from station records of pressure for Europe since 1780 and has a horizontal resolution of 2°. The region encompasses 35°–70^{o}N to 30^{o}W–40^{o}E. The reconstructions are based on a regression relating surface pressure patterns to those of the station pressure data.

We use several long-term temperature data sets COADS (Woodruff et al., 2005), CRU (Jones et al., 1999), 20^{th} century reanalysis data (Compo et al., 2010), and a long-term reconstruction of Luterbacher et al. (2004) and analyse the relation with MDD for the region of the North Sea. COADS has a horizontal resolution of 2° and covers the time period 1800-2007, CRU 0.5° and 1850-2011, 20^{th} century reanalysis data 2°, and the Luterbacher et al. data set 2°. From COADS and the 20^{th} century reanalysis data, we select additional variables (wind, cloud cover) which are possibly related to changes in productivity. We correlate the fields for the Northern Hemisphere with MDD on a monthly basis. We apply a standard t-test for the significance.

For several applications it is useful to calculate climate indices. These indices are derived from mean values over a specified area where the original data have been interpolated on a 1° latitude x 1° longitude grid. For all correlation analyses, the data are detrended.

Additionally to the monthly means, daily data are used for diatoms and Secchi (Wiltshire and Manley, 2004, Wiltshire et al., 2008), as well as SLP from ERA40 (Uppala et al., 2005). Secchi is a measure of the clarity of water, especially seawater. Secchi depth is measured using a circular plate, known as a Secchi disk, which is lowered into the water until it is no longer visible. High Secchi depths indicate clear water; whereas low Secchi depths indicate cloudy or turbid water. At Helgoland Roads the first “spring bloom” occurs in January–February (days 20–50), and towards the end of March (days 70–90) the late, second spring bloom starts. Thus, the optimal time frame for analysing the spring bloom timing is in the first quarter (first 90 days of the year).

Results

From the correlation of the climatic fields with the MDD we obtained the highest correlation for January sea level pressure (Trenberth and Paolino, 1980). Figure 2 shows the correlation map together with the principal wind directions. The bloom is earlier in those years when the atmospheric circulation allows an increased inflow from the Atlantic (black arrow), and later in the case of a more continental influence with a high pressure over Norway (grey arrow). Due to large-scale teleconnections in the atmosphere, the MDD-sea level pressure relation is opposite over the Azores and east of Florida (Fig. 2).

In order to get an idea about the meteorological situation we select the years 1974 and 1996 as examples for an early and late MDD. Fig. 3 shows the atmospheric SLP and wind for these particular Januaries: In 1974, we see a pronounced low pressure centre south of Iceland and a high pressure over the subtropical North Atlantic area and Eastern Europe. In contrast to 1996, a pronounced high pressure over Scandinavia/Russia and a low pressure south of Iceland is detected. The atmospheric circulation shows more a wave-like structure with a pronounced blocking and easterly winds over the German bight.

Fig. 4a shows the MDD and atmospheric circulation indices as a proxy for the MDD. This proxy-MDD index is calculated from the mean SLP difference between a northern (0-20°E; 60-70°N) and a southern (20-0°W; 30-40°N) region for January. The SLP data were taken from Trenberth and Paolino (1980) for the period 1962-2005 and Jones et al. (1999) for the period 1962-1995. Correlation of MDD with our SLP index derived form Trenberth and Paolino (1980) is r=0.7 explaining 50% of the variance (r^2).

It is furthermore interesting to calculate the long-term evolution of the atmospheric circulation index based on the long-term SLP data from Jones et al. (1999) covering the last centuries (Fig. 4b). A histogram of this SLP time series shows high values of about 90 days for the cold century (1780-1888) related to some years prior to 1850 (Fig. 5). That means that the mean climate conditions seem to affect the blooming though more blocked situations (grey arrow in Fig. 2).

We furthermore find a consistent pattern with surface temperature (Fig. 6): the January temperature is lower prior to later MDD. The pattern shows a coherent cooling in Denmark and parts of northern Germany. For the other months we find no significant correlation with local and remote temperatures in the North Atlantic realm, even when considering leads and lags (not shown). We note that the January surface temperature can explain less than 25% of the variance whereas the SLP index explains about 50% of the variance. We detect a positive temperature relation over northern Africa and eastern Canada which stems from the SLP teleconnection pattern (Fig. 2). We find that the link between MDD and climate (SLP and surface temperature) is generally very similar when applying different climate data sets mentioned in the methods section, emphasizing the robustness of the results.

In order to get a synoptic view (related to weather), we display the number of diatoms, Secchi depth, and SLP for the two years: 1974 (as an example for early MDD) and 1996 (as an example for late MDD). Fig. 7a shows the numbers of diatoms in these particular years for the first three months of the years. The numbers of diatoms increase in 1996 in the second half of March, whereas the numbers of diatoms is general high in the first 73 days in 1974. In order to make the link with the daily atmospheric circulation, we calculate the SLP over Norway (0-20°E; 60-70°N) from ERA40 (Uppala et al., 2005). In the second half of January 1996, a pronounced high-pressure centre lasts about two weeks (Fig. 7b). The index is above the 83% percentile considering the ERA40 period into account. For 1974, low pressure is detected in January and February (red line in panel b). Similar situations are seen for high and low index years in the MDD (not shown). Furthermore, the secchi depth is displayed (Fig. 7c). Fig. 7c shows generally low values in Secchi for 1974 in the first two months of this year, whereas high values in 1996.

Discussion and Conclusions

We combine phytoplankton data from Helgoland Roads (North Sea) with instrumental and historical climate data to evaluate the climate effects on biology. Due to the pivotal position of phytoplankton at the base of the marine foodweb it is logical that changes in the timing of phytoplankton blooms will inevitably affect the performance of other members of both the pelagic and benthic food webs (e.g.: Townsend et al. 1994, Smetacek 1999, Edwards and Richardson 2004, Wiltshire et al. 2010). The motivation for considering an integral measure of the mean diatom day (MDD) was the idea that the timing of seasonal diatom blooms will shift with the average environmental conditions occurring earlier in the year (Bleckner et al. 2007, Weyhenmeyer 2001, Wiltshire and Manley, 2004, Wiltshire et al 2008).

Here, we show that timing of the spring bloom of diatoms is related to the boreal winter large-scale atmospheric circulation characterized by a pressure dipole between Scandinavia and west of the Iberian peninsula. From our analysis we detect that the MDD of the spring bloom is delayed when the North Sea is under the influence of more continental climate and less zonal flow associated with a high-pressure centre over Norway (Fig. 2). From our pattern analysis, one can infer directions for the mechanism of interannual variations in MDD. We find that the MDD of the spring bloom was shifted to lower values (earlier in the year) when the atmospheric circulation was characterized by a pronounced low pressure over Norway. A pronounced high pressure on the other hand leads to a delay of the spring bloom. Along with such atmospheric circulation, the temperatures in Denmark (and to a weaker degree on Helgoland) are lowered. The MDD pattern (Fig. 2) is different from the response of the local SST to the atmospheric circulation which instead would have showed an NAO pattern with a zonal wind structure (Hurrel and von Loon, 1997). These differences in atmospheric circulation indicate that temperature is not the sole driving mechanism (also found via a correlation analysis with local temperature which is higher over land than over sea, Fig. 5).

Indeed, it may also be assumed that the onset of primary production is less dependent on temperature than on light (Eilertsen et al. 1995; Eilertsen and Wyatt 2000; Sommer et al.

1986). Consequently a rise/lowering in temperature should not directly affect the beginning of the seasonal production. In reality the development of a bloom depends on the interplay of multiple factors, like light and nutrient availability as well as grazing pressure and species assemblages of both the grazing as well as the grazed communities (Irigoien et al. 2005). In well-mixed coastal waters such at Helgoland Roads with a maximum depth of 10m, stratification, however, rarely plays a role. The amount of incident light, can be the limiting factor in the early winter months at Helgoland Roads.

Here, we have not analysed the trend in MDD which is much smaller than the interannual variations. Hydrographic analyses by Stockmann et al. (2009) showed that current directions changed in the late 1970ties in the German Bight with the input of water from the northwest (open North Sea) at Helgoland Roads having increased substantially over the last 40 years in winter. An increase in salinity and light penetration depths was also found (Wiltshire et al 2008, Raabe and Wiltshire 2008) also indicating that Helgoland Roads is less influenced by coastal waters in the meantime in winter. This would mean that the phytoplankton has better growing conditions in winter and the spring bloom should start to come earlier. Also as a logical next step, we will evaluate the pattern of climate changes in the Northern Hemisphere, as e.g. in the seventies of the last century (Dima and Lohmann, 2007) and associated changes in blocking activity (Häkkinen et al., 2011), to discover biological responses to these changes.

The atmospheric circulation could have been related to winter trigger mechanisms, such as mixing, which are required for ending dormancy (Itakura et al., 1997; Lewis et al., 1999). Secchi transparency indicate that low transparency (as in the year 1974) is not linked to lower values for MDD. For years with an early MDD, it is conceivable that the atmospheric circulation affect local quantities through an increased inflow of Atlantic water into the North Sea due to measured increased winds from the northwest, associated to more marine water and warmer conditions, favouring earlier blooming.

Our finding that the timing of the spring bloom is related to atmospheric forcing is also consistent with model studies showing that interannual variability has local effects on the primary production due to changes in light conditions, wind mixing, and the long-range transport of nutrients (Skogen and Moll, 2000). In their model, the interannual variability of the mean North Sea primary production due to the wind forcing is 15 to 25%, whereas the total effects of the river were estimated to be less than 10% of the total production. We argue that the atmospheric circulation is important for the interpretation of inter-annual to centennial variations in the biological processes as well as for high-resolution proxy data from this area (Hebbeln et al., 2003). In a further study, we will evaluate the occurrence of different algal species related to early and late spring blooms.

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Fig. 1: Time series of the mean diatom day (MDD) characterizing the timing of the spring bloom (Wiltshire and Manley, 2004). Day 30 corresponds to the end of January, day 90 to the end of March, respectively.

Fig. 2: Correlation map of the MDD with January SLP using the data set of Trenberth and Paolino (1980). Coloured regions are significant on a 95% confidence level. The arrows indicate the wind direction. The bloom is earlier in those years when the atmospheric circulation allows an increased inflow from the Atlantic (black arrow), and later in the case of a more continental influence (grey arrow).

Fig. 3: Atmospheric circulation for the years a**)** 1974 (low value in MDD) and b) 1996 (high value in MDD). Units are hPa and m/s, respectively. The contours of the SLP fields are approximately the surface wind directions. On the Northern Hemisphere, the circulation is clockwise for positive SLP, and anti-clockwise for negative SLP anomalies.

Fig. 4: The MDD (red dashed curve) and atmospheric circulation indices as a proxy for the MDD. These indices were calculated from the difference between a northern (0-20°E; 60-70°N) and a southern (20-0°W; 30-40°N) SLP in January. The data were taken from a) Trenberth and Paolino (1980) (green), and b) Jones et al. (1999) (blue).

Fig. 5: Histogram of the time series in Fig. 3b for the periods 1780-1888 (mean: 61.5 days) and 1889-1995 (mean: 58 days). Notice the high values of about 90 days for the cold century related to some years prior to 1850 (cf. Fig. 3b).

Fig. 6: Correlation map of the MDD with January surface temperature using the data set of Compo et al. (2010). Coloured regions are significant on a 95% confidence level.

Fig. 7: Synoptic view of a) number of diatoms, b) Secchi depth, and c) SLP index for 1974 (low value in MDD) and 1996 (high value in MDD). We show the first three months of the years. Day 1 corresponds with January 1. The daily SLP is calculated over Norway (0-20°E; 60-70°N) using ERA40 (Uppala et al., 2005). In c), the 17, 50, and 83% percentiles are displayed considering the ERA40 period into account.

Figures Lohmann & Wiltshire 2012:

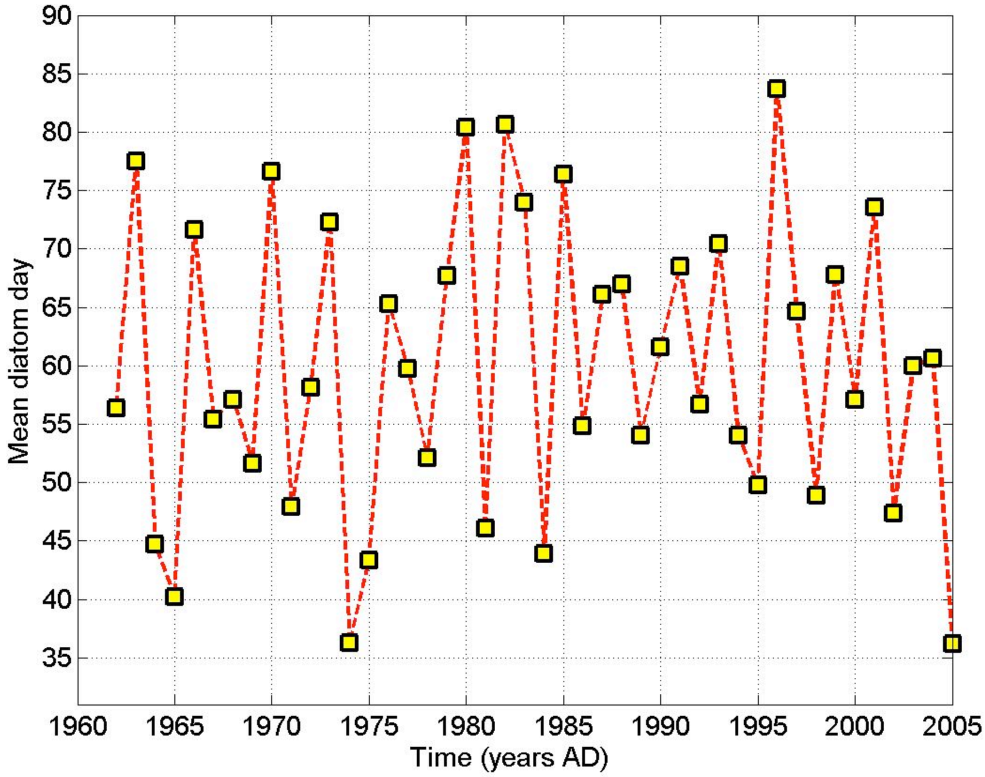
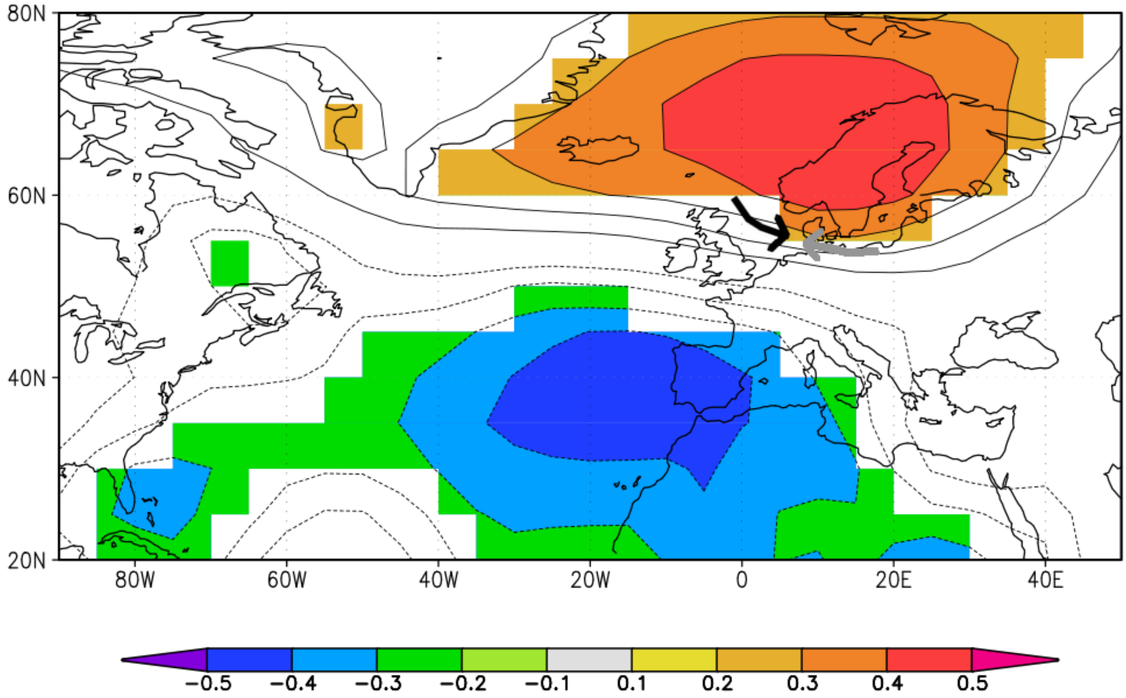


FIG 1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0.5

FIG2

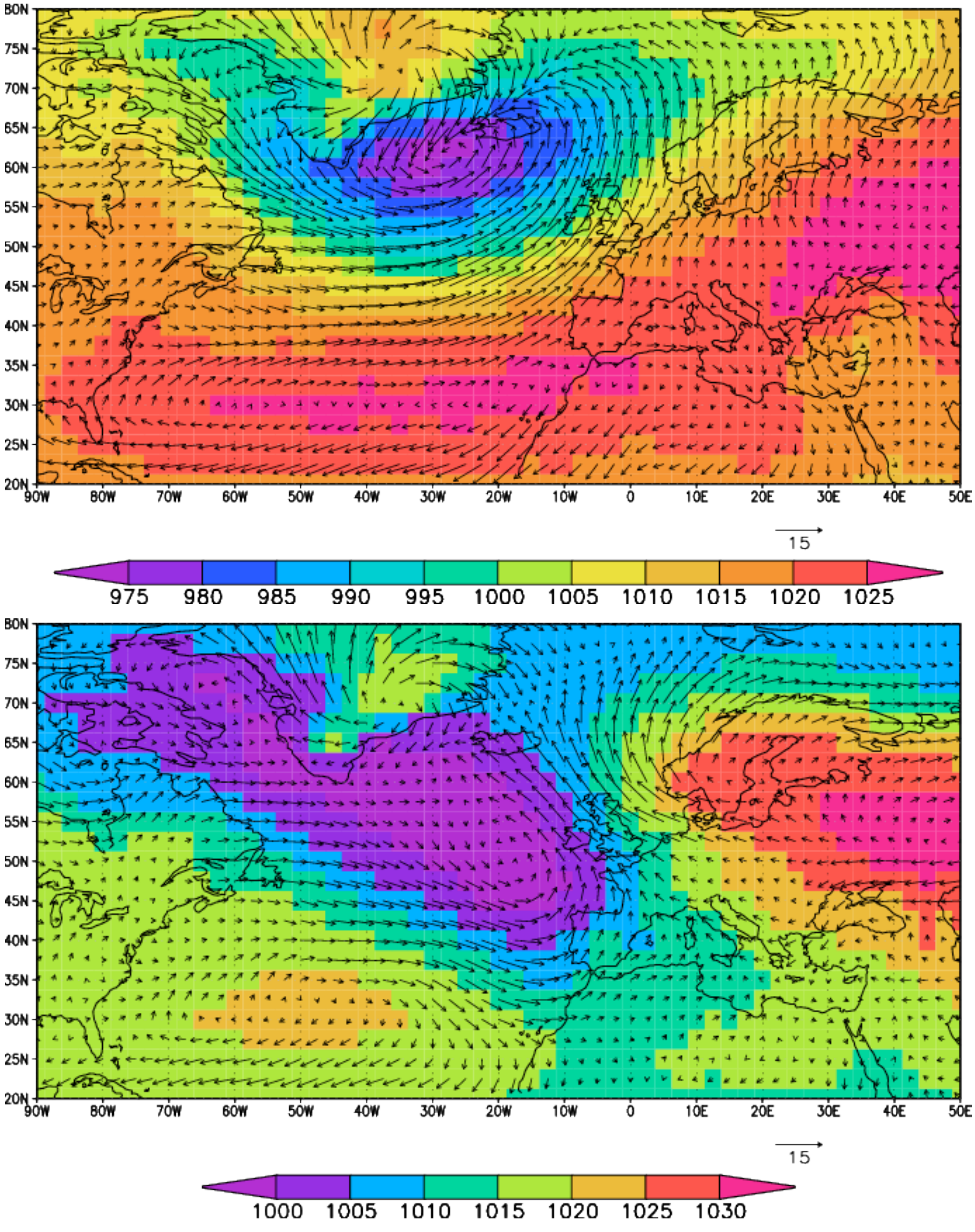
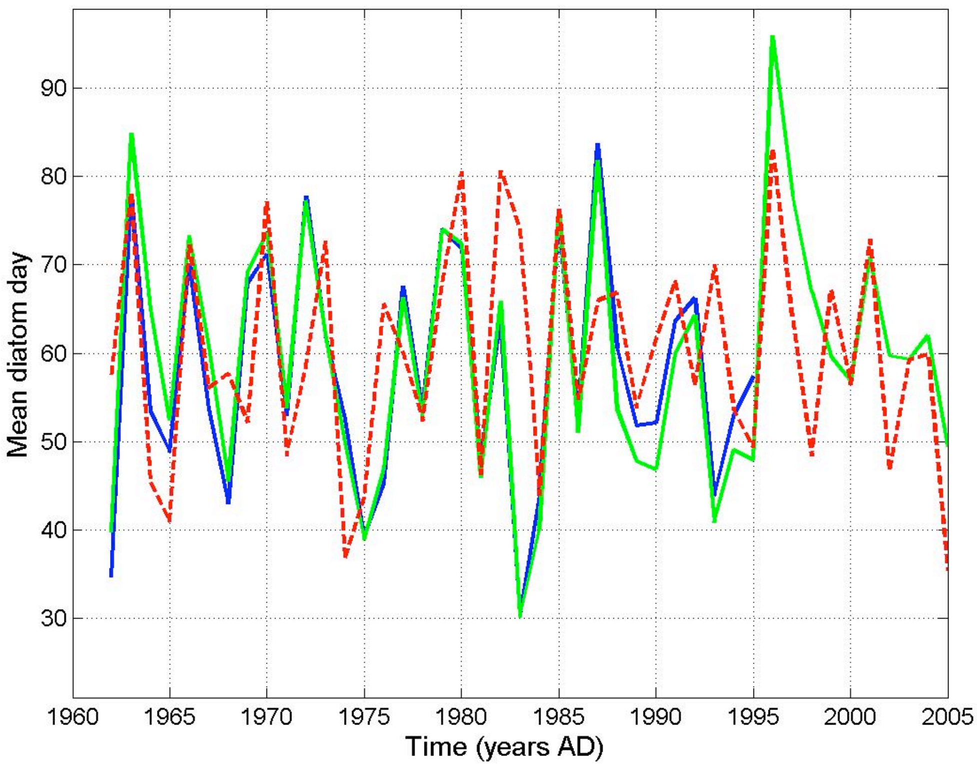

80N
75N
70N
65N
60N
55N
50N
45N
40N
35N
30N
25N
20N
90W 80W 70W 60W 50W 40W 30W 20W 10W 0 10E 20E 30E 40E 50E
15
975 980 985 990 995 1000 1005 1010 1015 1020 1025
15
1000 1005 1010 1015 1020 1025 1030

Fig. 3


Mean diatom day
90
80
70
60
50
40
30
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
Time (years AD)

476 FIG4a

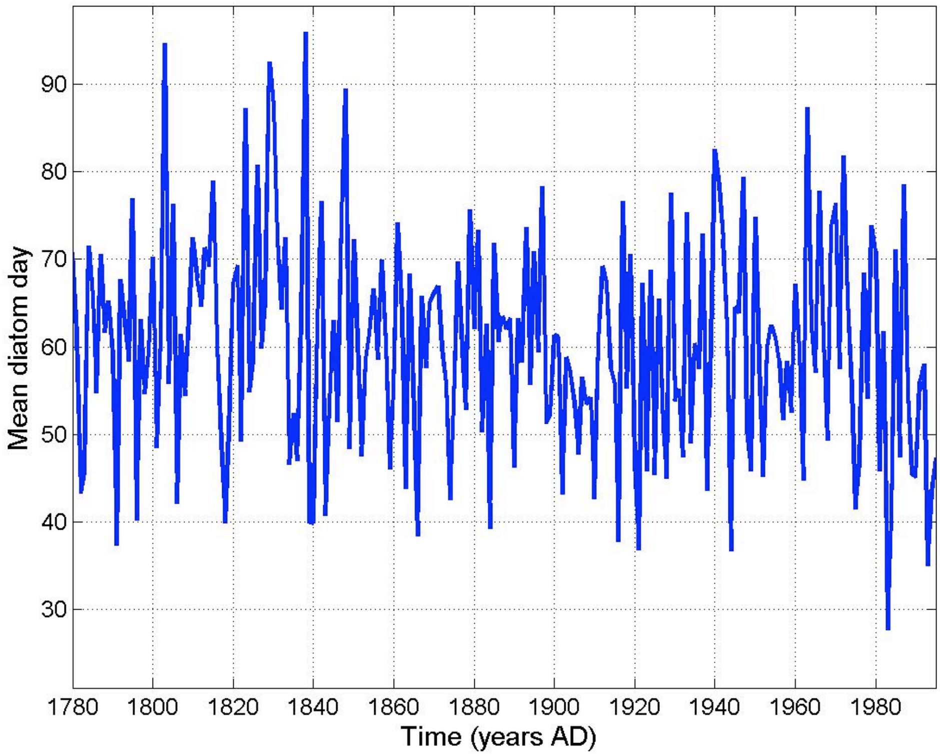

Mean diatom day
Time (years AD)
90
80
70
60
50
40
30
1780
1800
1820
1840
1860
1880
1900
1920
1940
1960
1980

FIG 4b

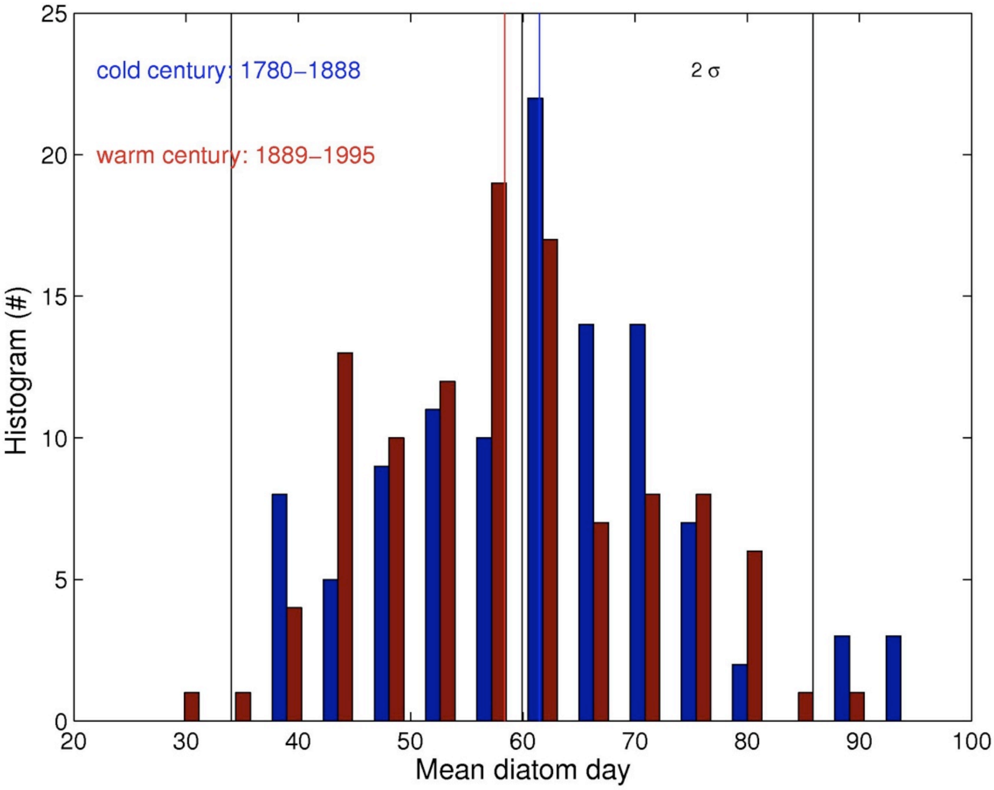

cold century: 1780−1888
warm century: 1889−1995
2 σ
Histogram (#)
Mean diatom day
0
5
10
15
20
25
20
30
40
50
60
70
80
90
100

FIG 5

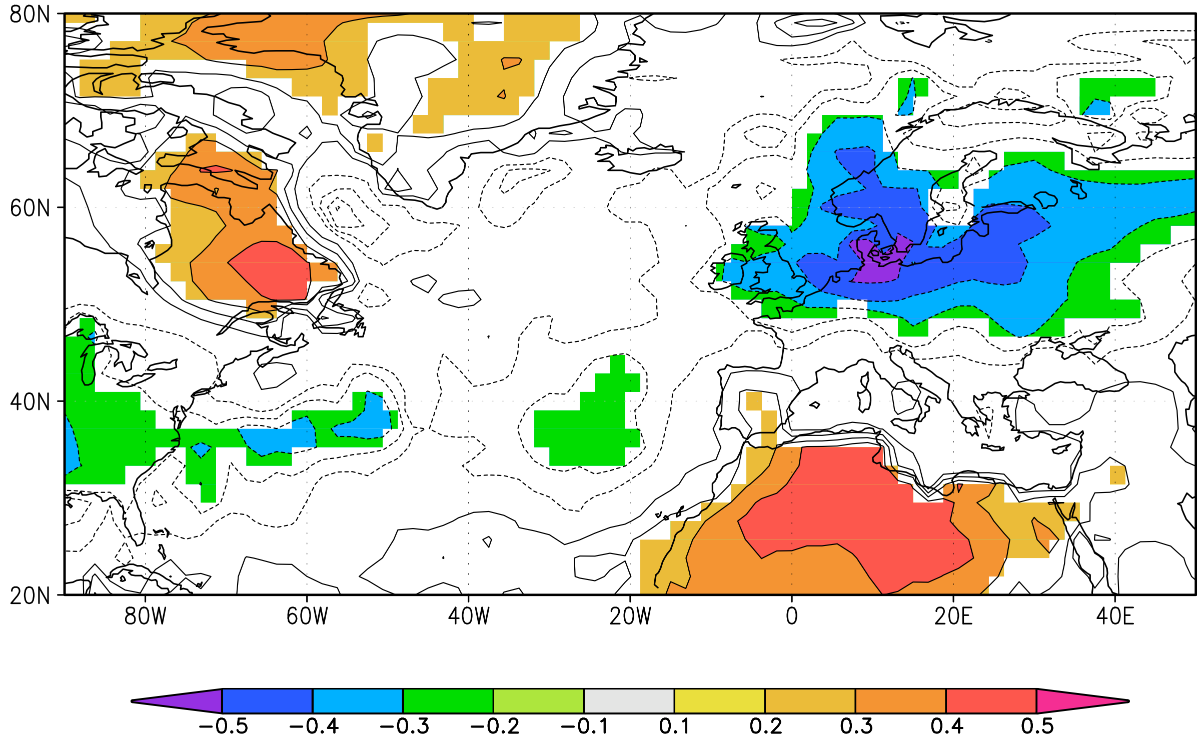

80N
60N
40N
20N
80W
60W
40W
20W
0
20E
40E
−0.5
−0.4
−0.3
−0.2
−0.1
0.1
0.2
0.3
0.4
0.5

Fig. 6

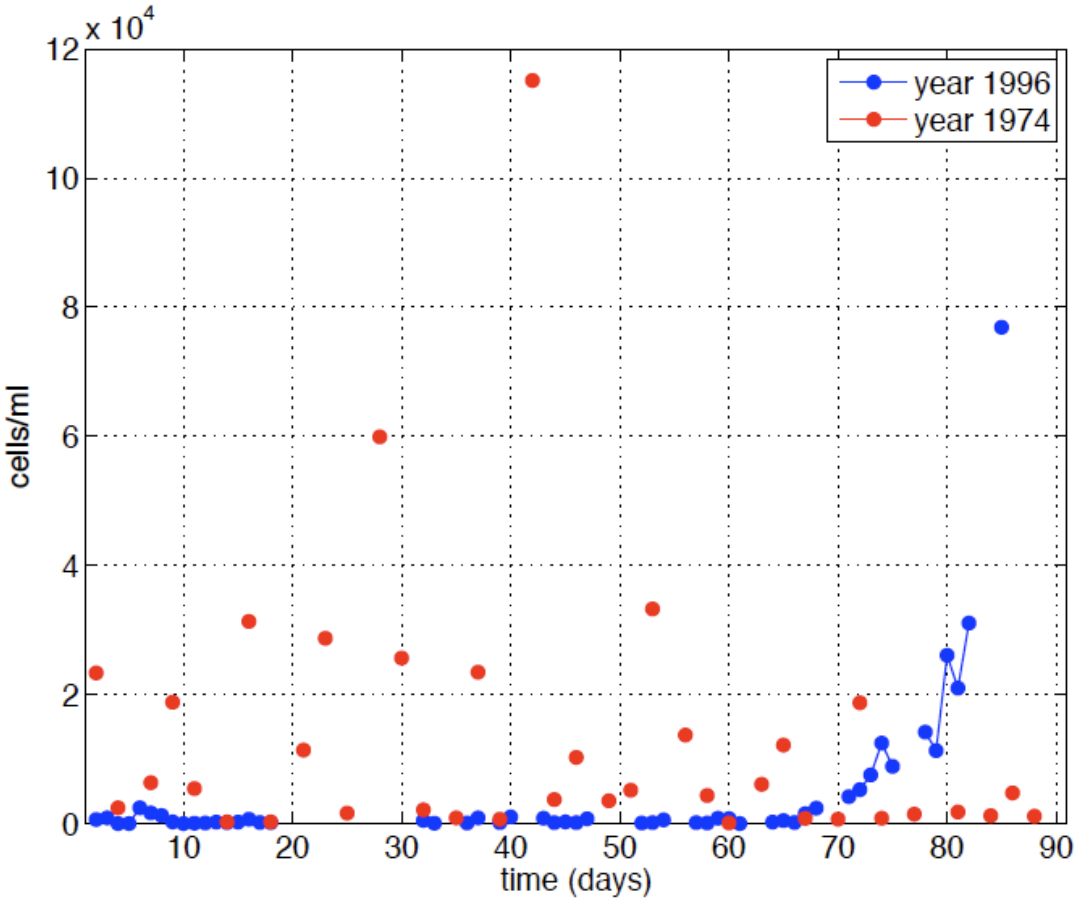

x 10^4
12
10
8
6
4
2
0
cells/ml
10
20
30
40
50
60
70
80
90
time (days)
year 1996
year 1974

Fig. 7a

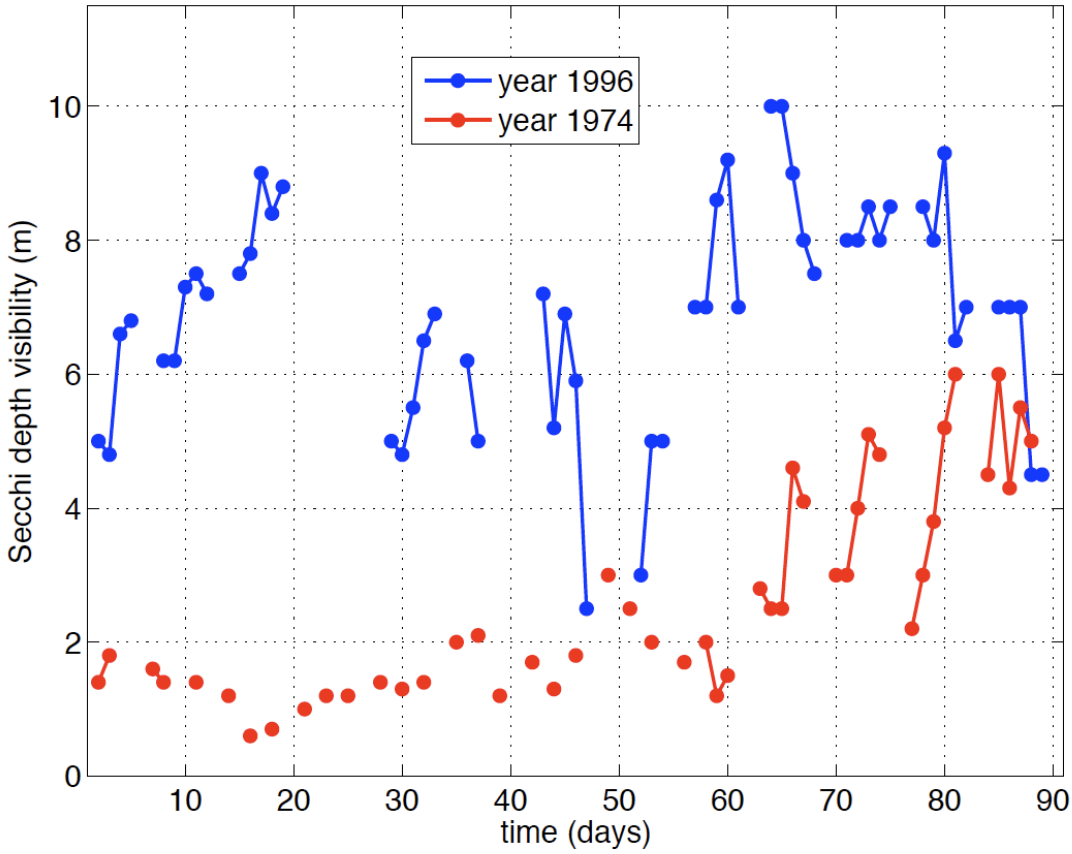
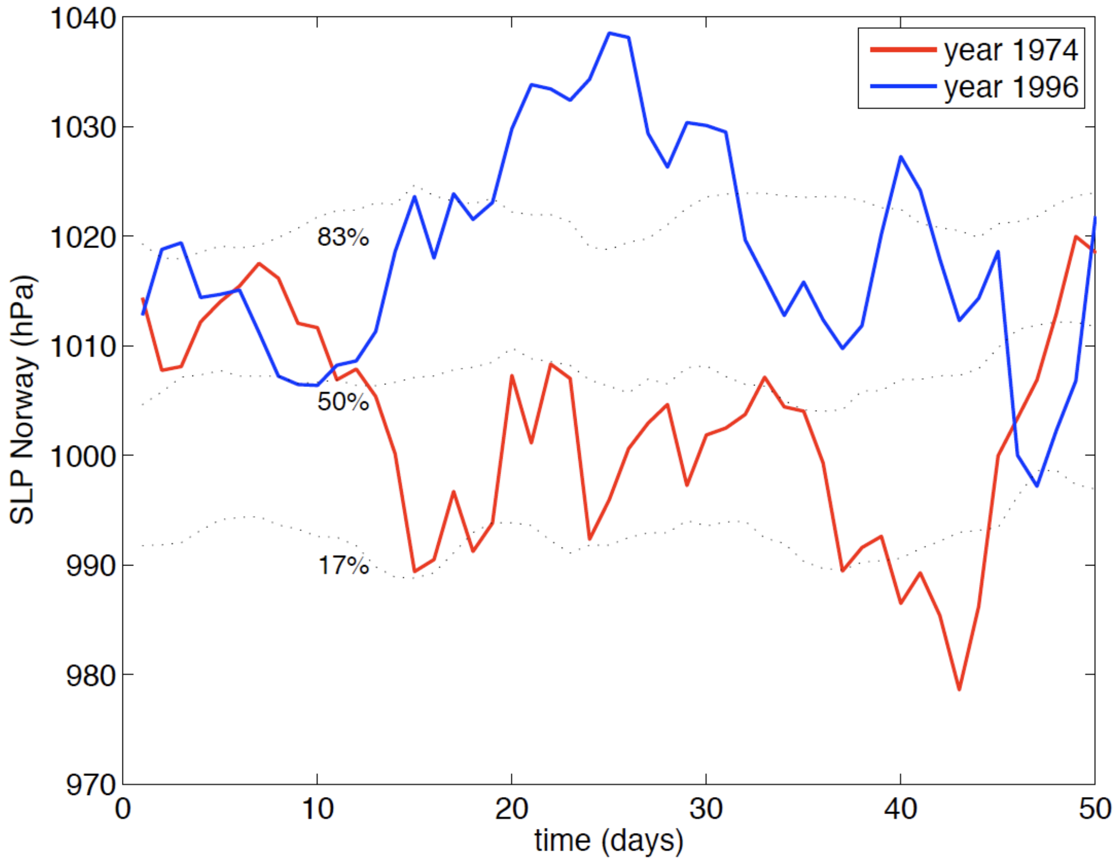

year 1996
year 1974
Secchi depth visibility (m)
time (days)
0
2
4
6
8
10
10 20 30 40 50 60 70 80 90

Fig. 7b

Fig. 7c



year 1974
year 1996
83%
50%
17%
SLP Norway (hPa)
time (days)
1040
1030
1020
1010
1000
990
980
970
0
10
20
30
40
50