Principal Oscillation Pattern Analysis of Sea Surface Temperature Data

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Abstract

Global sea surface temperature (SST) fields can be derived from measurements made by the Along Track Scanning Radiometer (ATSR) on board of the ERS-1 satellite. A time series of such SST fields of the North Atlantic ocean for the period from January 1992 to July 1995 is investigated using the method of empirical orthogonal functions (EOFs) and principal oscillation patterns (POPs). The POPs show the strong annual and semi-annual cycle as well as mesoscale and small scale oscillation patterns. These principal oscillation patterns of the SST are compared with principal oscillation patterns derived from zonal and meridional wind speeds. In addition, POPs from sea surface height patterns derived from measurements performed by the altimeter on board of the TOPEX/POSEIDON satellite are used for comparison.

Keywords: sea surface temperature, POP-analysis, sea surface height

Introduction

In this paper we investigate the circulation pattern of the North Atlantic ocean region (20° N - 65° N, 80° W to 0°) as represented in the sea surface temperature (SST). The SST measurements have been performed by the Along Track Scanning Radiometer (ATSR) on board of the ERS-1 satellite during the time period from 01/92 to 07/95. The ATSR is a four channel, dual view, self calibrating infrared radiometer which is capable of measuring the SST with an accuracy of about 0.5 K in conditions of 80% cloud cover and a spatial resolution of 50 km (ESA, 1993). Using the statistical methods of empirical orthogonal functions (EOFs) and principal oscillation pattern (POP) analysis (Hasselmann, 1988, Gallagher et al., 1991) we extract dominant temporal and spatial scales of the North Atlantic area. A similar analysis for the region of the tropical Pacific ocean can be found in Pauluhn and Burkert, 1996 . The oscillation periods found by this methods are compared to time scales calculated by conventional spectral analysis. A global comparison of ATSR measured SST fields and sea surface height (SSH) fields measured by the altimeters of the French-U.S. TOPEX/POSEIDON satellite has been performed by Knudsen et al. (1996). The current system of the North Atlantic plays an important role in the global oceanic circulation and the North Atlantic mesoscale variability has been widely investigated. Le Traon et al. (1990) and Le Traon (1991) used altimetric SSH fields to calculate wavenumber spectra and autocorrelation functions and found a decrease of eddy scales from west to east and from south to north. The subpolar gyre system has thoroughly been described by Heywood et al. (1994), and White and Heywood (1995) who used satellite altimeter data to show the relationship between eddy kinetic energy and instabilities of the mean currents and the wind stress, respectively.

The paper is organized as follows. After a description of the data and the analysis method, the POP results for the time series of the SST fields are presented and compared to the corresponding patterns of the wind fields. For selected areas (chosen according to the pattern structure) spatial averages have been calculated and the resulting time series have been spectral analyzed. The resulting oscillation periods are compared with the dominant modes found in the statistical description. Additionally, some POP results of sea surface height (SSH) fields as measured by the altimeters of the TOPEX/POSEIDON satellite are given. As the time period of the data take of the TOPEX/POSEIDON SSH time series (10/92 to 04/96) is not the same as that of the ATSR SST time series(01/92 to 07/95), these results can only very roughly be compared assuming there are modes which can be said to be stationary for that period.

Description of the Data

ATSR sea surface temperature data

The ATSR SST data are provided on CD-ROM by the Rutherford Appleton Laboratory as 5d averages on a 0.5° x 0.5° grid. As the data coverage is too low for the 5d period, the SST measurements have been averaged onto an 2° x 1° grid with a temporal sampling of 20d. The investigated time period starts 01/92 and ends 07/95. For the following analyses the mean value, a linear trend and a sine curve representing the annual cycle, have been removed. The calculations have been performed on this time series of SST anomalies.

ECMWF wind data

The wind speed time series is derived from the twice-daily 1000mb wind field analyses for the months 01/92-07/95 provided by the European Centre for Medium-Range Weather Forecast (ECMWF), Reading, UK. These data have been averaged onto a grid of 2° x 2° but the influence of this different gridding on the POP analysis can be neglected. Again we used 20d averages and removed the mean, a linear trend and the annual cycle.

TOPEX/POSEIDON sea surface height data

The TOPEX/POSEIDON SSH data are taken from the 10d cycles available on the Geophysical Data Records (AVISO, 1996) . The time period for the SSH measurements extends from 10/92 to 04/96 as TOPEX/POSEIDON data are available only since 10/92. Although there is an overlap of the time intervals of more than 33 months this is quite different from both the above described data sets and the principal oscillation patterns of the time series cannot be compared strictly. The SSH values were corrected for instrumental and geophysical effects as described in (AVISO, 1996) and the correction for the TOPEX altimeter oscillator drift algorithm has been applied (Hancock and Hayne, 1996). Like before, the data were interpolated onto a 2° x 1° grid and 20d averages were formed. To eliminate the aliasing of the M2 tide (Stammer and Wunsch, 1994) , a low pass Hanning filter was applied removing time scales less than 2 months. Also in the altimetric data time series we removed the mean, a linear trend and the annual cycle.

The investigated regions NA I and NA II:

For the POP calculations the area of the North Atlantic has been divided into two parts, a northern region NA I (40° N - 65° N, 60° W to 0°), and a southern region NA II (20° N - 45° N, 80° W to 10°W). Figure 1 shows also the bottom topography and the regions selected for spatial averaging. For the northern part NA I three regions, for the southern part NA II, six regions have been selected.

Areas of the Region NA I:

1: 40° N - 55° N, 54° W to 42°W (Grand Banks of Newfoundland)
2: 40° N - 55° N, 40° W to 20°W (centre of the northern part, Mid-Atlantic Ridge)
3: 55° N - 65° N, 30° W to 0° (north east part)

Areas of the Region NA II:

1: 40° N - 45° N, 72° W to 40°W (south of Newfoundland)
2: 26° N - 40° N, 78° W to 66°W (North American Basin, Hatteras Abyssal Plain)
3: 28° N - 40° N, 54° W to 46°W (central part, west of Mid-Atlantic Ridge)
4: 28° N - 40° N, 42° W to 28°W (central part, Mid-Atlantic Ridge)
5: 28° N - 40° N, 28° W to 22°W (central part, east of Mid-Atlantic Ridge)
6: 20° N - 27° N, 30° W to 10°W (south east part, south of Canary Basin)

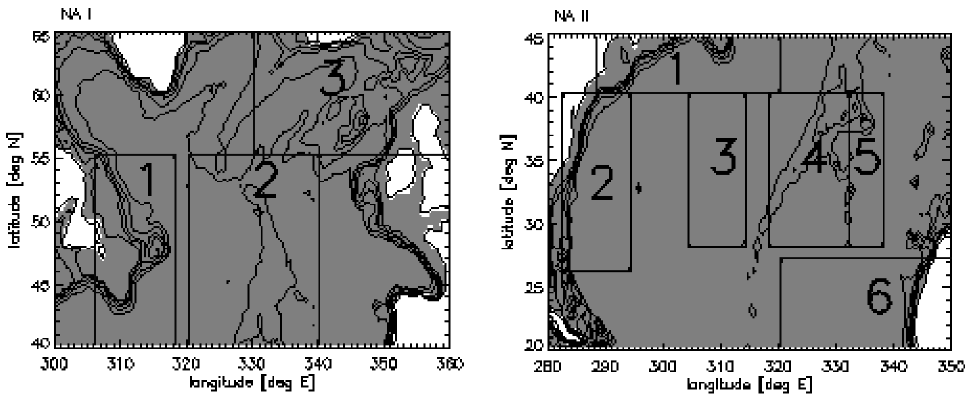

Figure 1: The areas NA I and NA II and the bottom topography. The regions selected for the spatial averaging and the spectral analysis are also shown.

The annual seasonal cycles of the different areas are shown in figure 2. As expected, there are significant latitude dependent differences in amplitude and mean values.

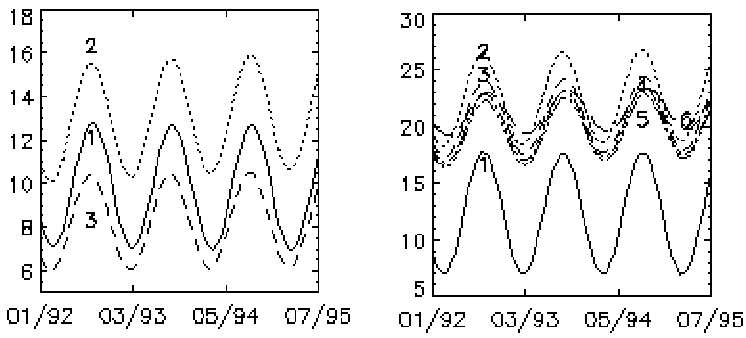

Figure 2: The annual signal od the SST in the areas 1-3 of the northern part (NA I) and in the areas 1-6 of the southern part (NA II).

EOF and POP analysis

As a means of decomposition of the SSH anomaly fields into a few dominant interaction patterns with different time scales the method of empirical orthogonal functions (EOFs) and principal oscillation patterns (POPs) (Hasselmann, 1988, Gallagher et al., 1991, von Storch and Navarra, 1995) has been used.

The EOF and POP analyses are a statistical approach to estimate the normal modes of a system with many degrees of freedom and complex and possibly unknown dynamics. The EOFs are calculated as the eigenvectors of the covariance matrix of the stochastic field. An EOF describes a certain spatial structure of the physical field and the corresponding eigenvalue indicates how much of the total variance is explained by this EOF. The corresponding expansion coefficients in the time domain are called the principal components. The description is then restricted to the first EOFs and thus higher-frequent noisy components are eliminated. In a further simplification the time evolution of the system is modelled by a linear vector process. The corresponding (estimated) Greens function or system transfer matrix has in general real and complex eigenvalues and eigenvectors. These eigenvectors are called principal oscillation patterns (POPs). The principal components of the EOF analysis can be expressed in terms of these real and complex (time-independent) POPs and the corresponding real and complex (time-dependent) amplitudes (for an example see figure 11). The process is thus decomposed into several POP modes, each having a characteristic period and damping time. A complex POP pattern is a linear combination of two trigonometric sine or cosine functions with a phase shift of 90°, and real POPs describe damped patterns.

Nevertheless, it has to be taken into account that the EOF method is based on the assumption of stationarity of the process which is in general not fulfilled. Propagating features are not captured by these analysis methods which are strongly limited by the temporal and spatial boundary conditions. Besides, the POP model is a linear approximation of the process and consequently only extracts the linear oscillation modes of the system.

Results of the POP analysis

We found that it had been necessary to take 20 EOFs for the calculation of the POPs to retain more than 80% of the variability. In a first step the POP analysis has been performed without removing the annual cycle. It turned out that the seasonal signal was the dominant mode in all of the data sets and especially in the SST time series the seasonal signal was so strong that it accounted for nearly 70% of the variability.

NA I

Table 1 gives the dominant POP oscillation modes for the ATSR SST time series from 01/92 to 07/95 for the northern part of the investigated area NA I (40^{o} N - 65^{o} N, 60^{o} W to 0^{o}). Results of the POP calculation that either do not represent an oscillation (damped patterns) or that do not contribute significantly to the variability have been omitted.

SST:

POP No.	% Variance	Oscill. Period (months)	Damping Time (months)
3	2	4.4	0.8
4	3	3.2	2.1
6	23	6.4	5.0
7	5	5.7	1.3

Table 1: Dominant POP modes of the SST in the area NA I.

Table 2 gives the dominant POP oscillation modes for the time series of the zonal (U) and meridional (V) wind speeds from 01/92 to 07/95 for the northern part NA I.

zonal wind speed U:

POP No.	% Variance	Oscill. Period (months)	Damping Time (months)
1	10	7.0	1.2
2	1	2.7	1.7
3	8	3.9	0.9
4	together 40	7.7	0.9
5		5.7	0.9
6		9.8	0.7
7		3.8	0.6
11		3.3	0.3

meridional wind speed V:

POP No.	% Variance	Oscill. Period (months)	Damping Time (months)
1	29	7.9	1.3
2	3	4.1	1.1
4	together 34	6.8	1.1
6		11.1	1.0
3	together 6	2.8	0.9
7		5.2	0.8
10		3.4	0.6

Table 2: Dominant POP modes of the zonal wind speed (U) and the meridional wind speed (V) in the area NA I.

Table 3 gives the dominant POP oscillation modes for the time series of the sea surface height SSH from 10/92 to 04/96 for the northern part NA I.

SSH:

POP No.	% Variance	Oscill. Period (months)	Damping Time (months)
1	1	3.8	5.3
2	11	5.6	11.0
3	4	4.5	3.7
5	40	17.1	0.4
6	2	5.4	2.1
7	6	7.9	3.5
8	2.5	19.5	8.0

Table 3: Dominant POP modes of the SSH in the area NA I.

The modes 3 and 4 of the SST show small spatial scales in the western part of the region and correspond to mode 11 of the zonal wind field and to mode 10 of the meridional wind field. Mode number 3 (see also figure 3) consists of a north-south oscillation along the polar front. The polar front is also known as the subpolar or subarctic front and forms a meandering continuous band of strong horizontal temperature gradients from the Newfoundland Rise toward the Mid-Atlantic Ridge (Heywood et al., 1994). This front is also visible in mode number 3 of the SSH time series (figure 4). The area near the Newfoundland Rise and the Flemish Cap where the Labrador current entrains colder fresher water is dominated by strong eddy activity (see figure 5). In figure 5 also an east-west oscillation can be seen. Additionally there are hints to a bifurcation of the North Atlantic Current at 50° N, 30° W in the POP modes 4 and 5 of the SST time series. This bifurcation is also found in the 5th mode of the SSH time series (see figure 6). The bottom topography has been included in the figures to show the corrensponndence between topographic features and the observed patterns. The mode of 2.7 months oscillation period seems to be induced by the wind field. A strong pattern of the semi-annual cycle is found in the SST time series (mode number 6). The modes of the SSH show some larger time scales up to 20 months. In the figures the contour interval is 0.2 units, and dotted lines denote negative anomalies.

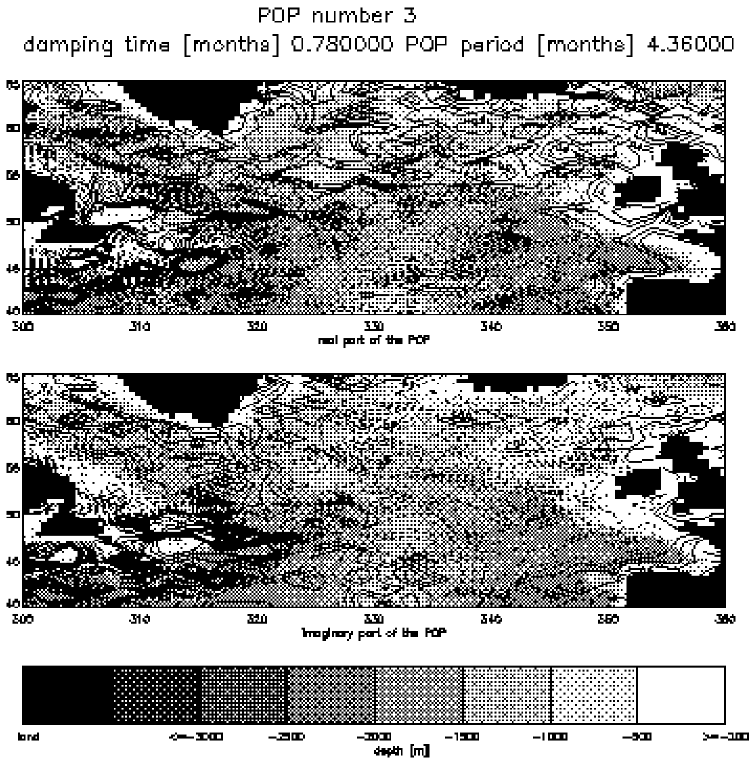

Figure 3: Real (upper panel) and imaginary part (lower panel) of the SST POP mode with oscillation period 4.4 months.

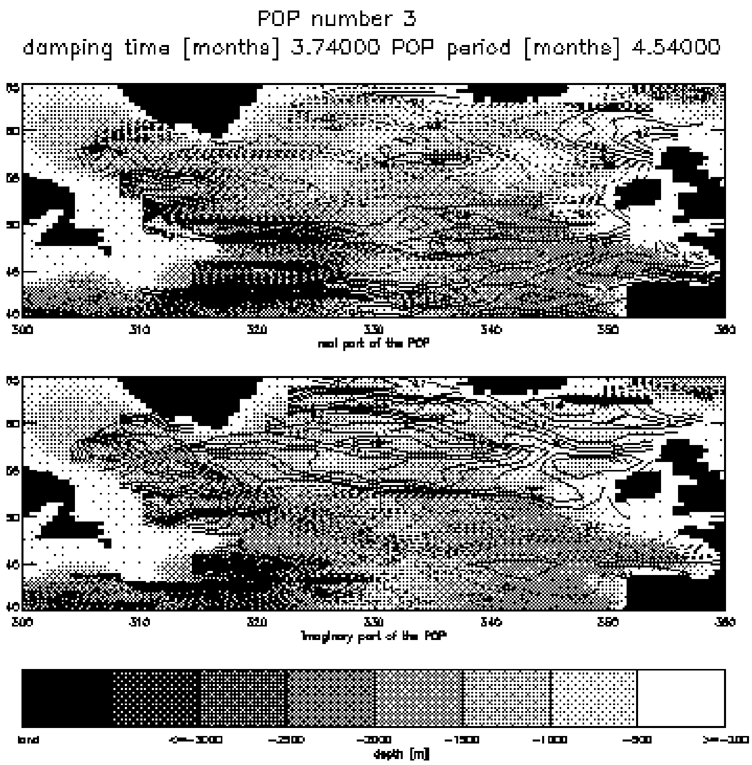

Figure 4: Real and imaginary part of the SSH POP mode with oscillation period 4.5 months.

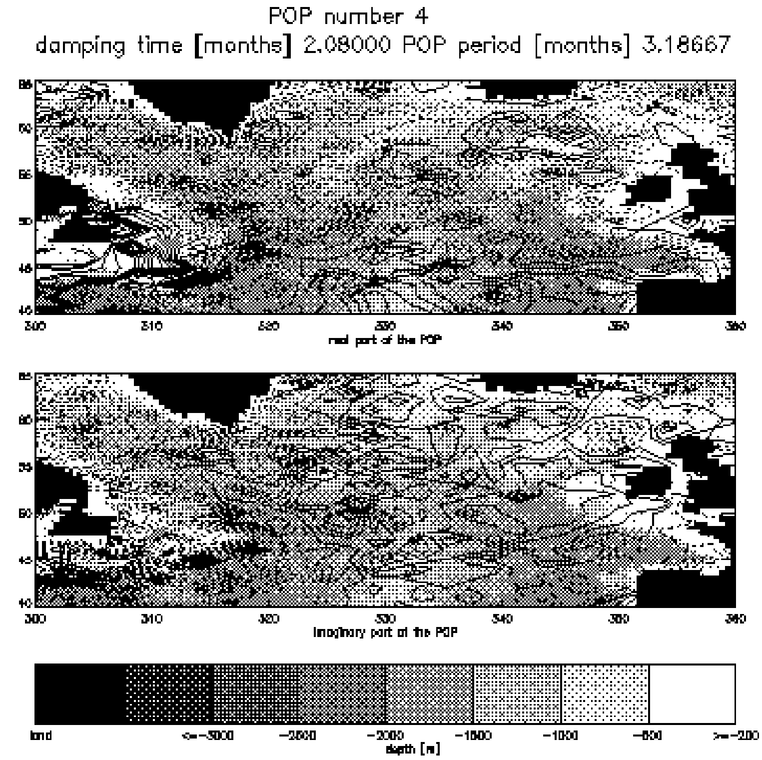

Figure 5: Real and imaginary part of the SST POP mode with oscillation period 3.2 months.

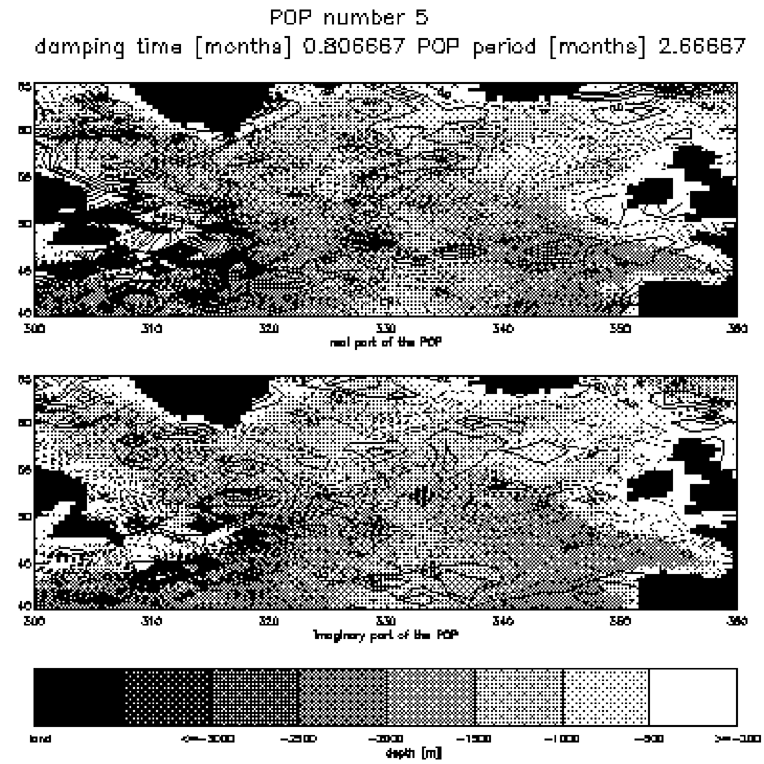

Figure 6: Real and imaginary part of the SST POP mode with oscillation period 2.7 months.

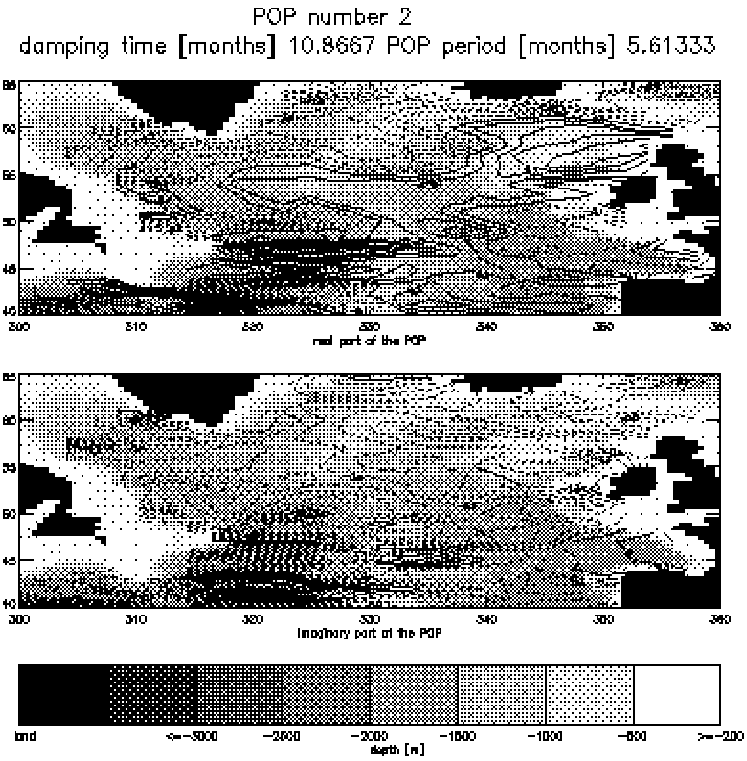

Figure 6: Real and imaginary part of the SSH POP mode with oscillation period 5.6 months.

NA II

Table 4 gives the dominant POP oscillation modes for the ATSR SST time series from 01/92 to 07/95 for the southern part of the investigated area NA I (20° N - 45° N, 80° W to 10° W).

SST:

POP No.	% Variance	Oscill. Period (months)	Damping Time (months)
1	2	22.6	0.5
2	7	2.9	1.2
4	15	6.0	5.2
5	8	5.3	2.0
6	4	6.4	1.7
7	1	5.8	0.6

Table 4: Dominant POP modes of the SST in the area NA II.

Table 5 gives the dominant POP oscillation modes for the time series of the zonal (U) and meridional (V) wind speeds from 01/92 to 07/95 for the southern part NA II.

zonal wind speed U:

POP No.	% Variance	Oscill. Period (months)	Damping Time (months)
1	7	8.2	1.2
2	3	2.7	1.7
3	1	4.5	0.9
4	together 5	3.2	0.9
5		5.4	1.0
6		2.8	0.7

meridional wind speed V:

POP No.	% Variance	Oscill. Period (months)	Damping Time (months)
1	12	5.5	1.4
3	together 4	4	1.1
6		23.8	0.6
4	together 6	9.4	0.9
5		6.3	0.9

11		3.3	0.6
7	70	3.0	0.8
9	together 7	4.0	0.8
10		2.8	0.8

Table 5: Dominant POP modes of the zonal wind speed (U) and the meridional wind speed (V) in the area NA II.

Table 6 gives the dominant POP oscillation modes for the time series of the sea surface height SSH from 10/92 to 04/96 for the northern part NA II.

SSH:

POP No.	% Variance	Oscill. Period (months)	Damping Time (months)
3	7	6.1	3.9
4	together 15	6.8	5.2
5		7.9	8.8
6	3.3	27.4	12.8
7	4.3	15	8.0
8	60	5.7	0.6

Table 6: Dominant POP modes of the SSH in the area NA II.

The SST oscillation patterns number 1 and 2 show small spatial scales around the Flemish Cap (eddy activity) and larger scales farther east. The bifurcation of the Gulf Stream at 40^o N, 45^o W (Heywood et al., 1994) is visible in mode number 1 which is shown in figure 7 where also the branching into the Azores current can be seen. This mode has an oscillation period of nearly two years. The branching and bifurcation of the Gulf Stream into the Azores current is also seen in POP mode number 5 figure 8 where strong eddy activity is found near that area. This mode has an oscillation period of 5.3 months. In the SSH time series the mode number 8 represents a similar mode with an oscillation period of 5.7 months showing strong eddy activity near the branching point of the Gulf Stream into the Azores current (see figure 9). Again some patterns (e.g. mode 2 of the SST) can be said to be wind driven. The 4th SST POP pattern is the strong semi-annual cycle. It is shown in figure 10. For this POP pattern we also show the corresponding time coefficients (principal components) for the real and imaginary parts of the POP pattern (figure 11). The time series of the coefficients of the real part is indicated by the solid line, the time series of the coefficients of the imaginary part is given by the broken line. The semi-annual cycle is also very pronounced in the SSH time series (see figure 12). It is found in the SSH mode number 3, where also the influence of topography on the SSH is clearly visible. The Mid-Atlantic Ridge acts as a borderline between smaller scales in the western part and larger spatial scales east of it. The zonal wind speed in the southern part NA II is strongly dominated by the annual seasonal cycle. After removal of the annual oscillation not much of the variability is retained.

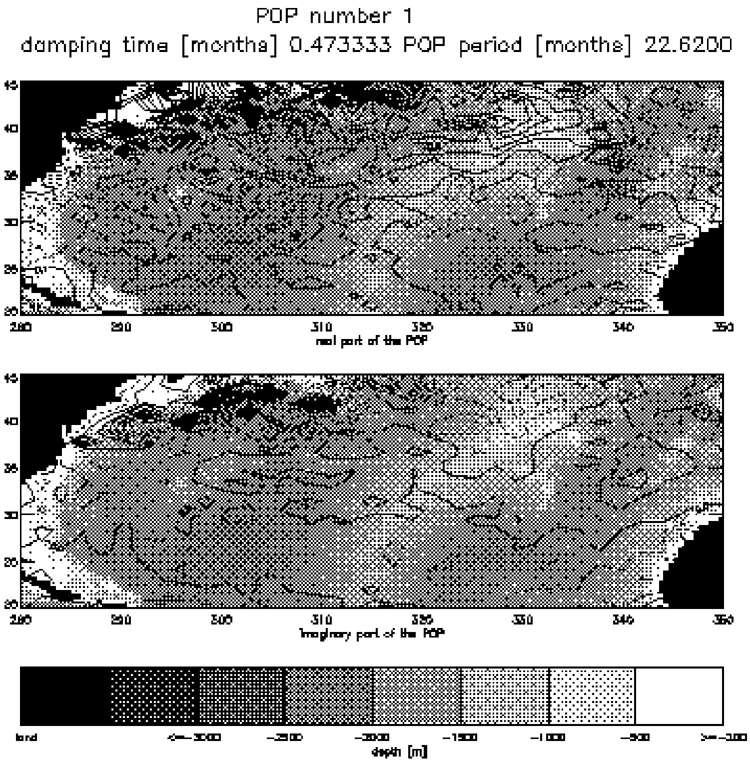

Figure 7: Real and imaginary part of the SST POP mode with oscillation period 22.6 months.

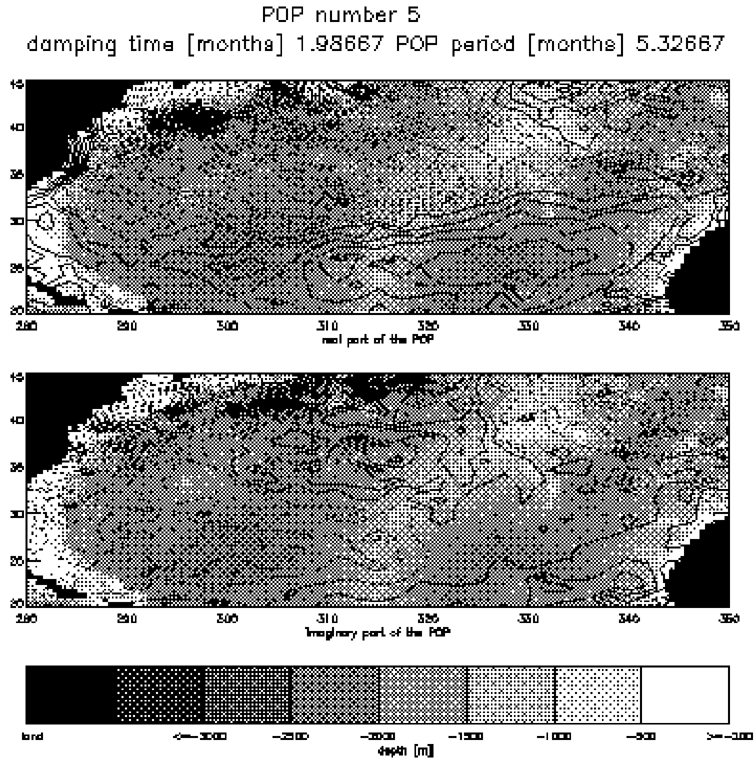

Figure 8: Real and imaginary part of the SST POP mode with oscillation period 5.3 months.

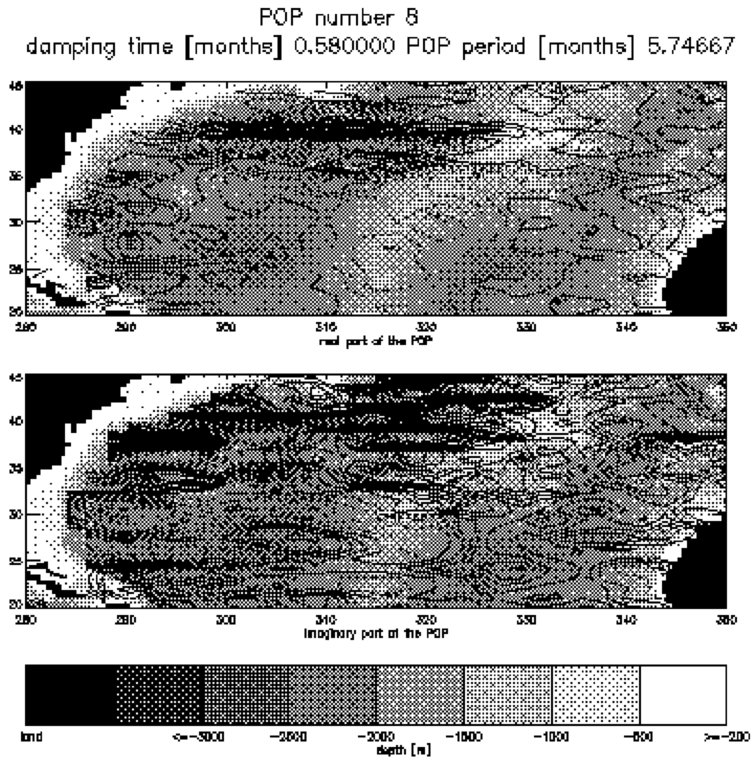

Figure 9: Real and imaginary part of the SSH POP mode with oscillation period 5.7 months.

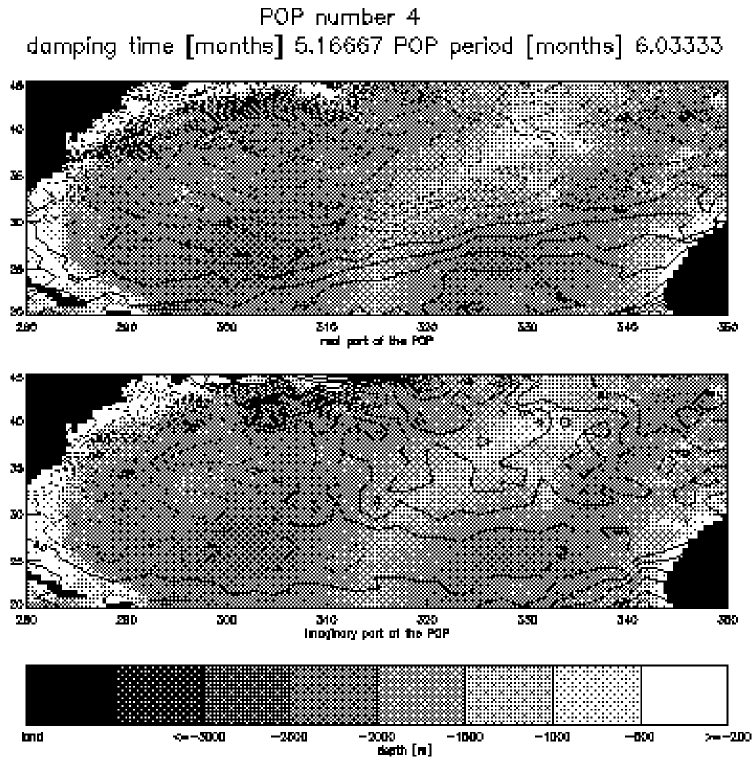

Figure 10: Real and imaginary part of the SST POP mode with oscillation period 6.4 months.

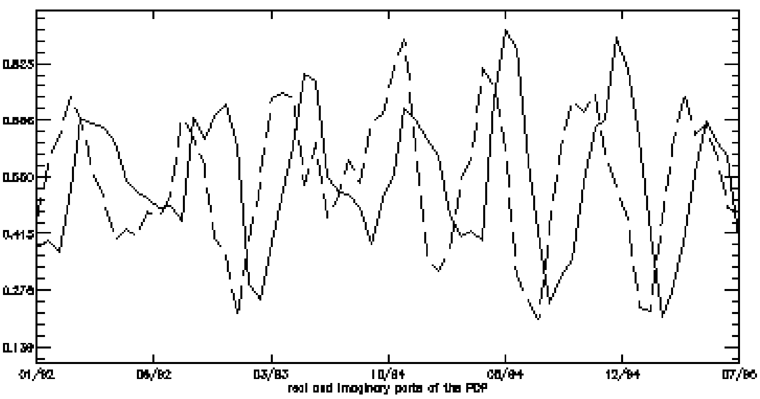

Figure 11: POP coefficients of the real part (solid line) and of the imaginary part (broken line) for the SST POP mode with oscillation period 6.4 months.

POP number 3
damping time [months] 3.92667 POP period [months] 6.12000

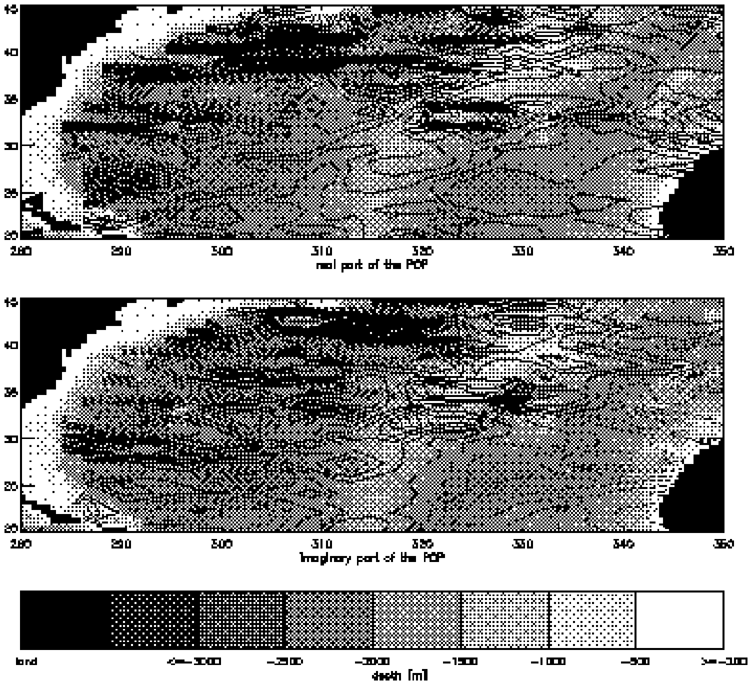

Figure 12: Real and imaginary part of the SSH POP mode with oscillation period 6.1 months.

Spectral Analysis

The Fourier spectral analysis yielded peaks in the spectra of the region NA I at the following periods (ordered decreasing in strength):

1: 5.3 months, 2.0 months, 10.6 months (weaker modes are found at periods of 1.5 months)
2: 14.2 months, 8.5 months, 21.3 months, and 4.3 and 3.9 months
3: 5.3 months, 6.1 months (weaker modes are found at periods of 3.0 months and 14.2 months)

The dominant periods in the spectrum of the region NA II are found at:

1: 5.3 months, 3.3 months, 10.6 months, 14.2 months (weaker modes are found at periods of 3.9, 2.8, and 2.2 months)
2: 5.3 months, 6.1 months (a weaker mode is found at a period of 4.7 months)
3: 21.3 months, 3.9 months, 14.2 months (weaker modes are found at periods of 10.7, 8.5, 6.1, 5.3, and 4.7 months)
4: 21.3 months, 3.9 months, 8.5 months (weaker mode are found at periods of 7.1 and 14.2 months)
5: 21.3 months (weaker mode are found at periods of 7.1 and 8.5 months)
6: 5.3 months, 21.3 months, 14.2 months, 8.5 months

The most interesting feature is the 5.3 months oscillation that is found in nearly all regions of the North Atlantic apart from the central region with the Mid-Atlantic Ridge. The predominant mode of this region is an oscillation with a period of 21.3 months. To farther investigate the connection with time scales found in the atmospheric circulation a spectral analysis of a monthly time series (1950-1996) of the North Atlantic Oscillation (NAO) index has been performed. The North Atlantic Oscillation is the dominant large scale atmospheric feature in the North Atlantic region (see e.g. Hurrell, 1996 , Dickson et al., 1996), and the NAO index is defined as the difference of normalized sea level pressures between the Azores and Iceland. Besides a large quantity of other frequencies the spectrum of the NAO index time series contains oscillation periods of 7.8 to 9.0 months, of 5.8 months, 4.5 months, and a band of frequencies corresponding to periods of 2.2 to 3.2 months. These oscillation modes can be found primarily in the wind fields, but furthermore many of them are also contained in the sea surface height time series.

Summary and Conclusions

In the presented work we have described variations of the near surface circulation as seen in a time series of the sea surface temperature measured by the ATSR. The study of the ATSR measured SST data and complementary sea surface heights and wind fields in the North Atlantic ocean showed that dominant time scales in this area can be found on the seasonal (i.e. annual and semi-annual) scales and also on time scales of around 160d (i.e. 5.3 months). The area of the central North Atlantic around the Mid-Atlantic Ridge (MAR) is dominated by a slower oscillation of 21.3 months. Intraseasonal oscillations with time scales of around 2-3 months are predominant in the Gulf Stream area, representing the strong eddy field around the Newfoundland Banks and the Flemish Cap. Most of these prevailing temporal structures are equally well found in Fourier spectral analysis and in the statistical analysis using empirical orthogonal functions and principal oscillation patterns. The EOF/POP method additionally yields the spatial patterns connected with the oscillation periods and the influence of the topography for example becomes clearly visible. Furthermore, the partition of the North Atlantic into areas of different spatial scales (smaller west of the MAR, larger east of it) can be seen in the POP patterns. A large fraction of the variability seen in the surface data (SST and SSH) of the North Atlantic is wind driven. Furthermore, several oscillation periods found in the sea surface data sets are also found as modes of the NAO index time series. It should be kept in mind that the analysis methods used here are based on a simplified model of the dynamic processes and that they are strongly limited by temporal as well as spatial boundary conditions. Nevertheless, the results indicate that a large fraction of the oceanic variability found in the surface data can be described.

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