Geodetic aspects of long term sea level variations in European seas from altimetry and tide gauge data

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Abstract

The classical method for monitoring the sea level variations at continental margins, using tide gauge records, gives the relative sea level changes with respect to the earth crust. Absolute sea level measurements are possible from tide gauge records when the geocentric coordinates of the station are known. The altimetry data allow the monitoring of the absolute sea level changes. We investigate the seasonal, annual and interannual variations from satellite altimetry data of the ERS-1, ERS-2 and Topex-Poseidon missions. The altimetry data used cover a time interval of five years, from 1992 to 1996, the secular trend cannot be evidenced on this short interval of time. The regions considered are the European semi-closed basins: the Mediterranean Sea, the North Sea and the Baltic Sea. The agreement with the absolute sea level variations obtained from tide gauge data, as well as the correlation with air temperature and air pressure at the tide gauge stations are investigated. *Keywords: Sea level variation, mean sea level, altimetry, tide gauge.*

Introduction

Absolute sea surface height (SSH) variations are measured today by satellite altimetry with a great accuracy, thanks to the accuracy of the altimeter instrument, of the environmental corrections and of the orbit determination [Scharroo et al., 1996], [Tapley et al., 1994]. The altimetric technique can therefore be considered as a complement to the classical method based on tide gauge stations data. The main advantages of the altimetric method are the global coverage and the absolute character of the observations, which are given with respect to a reference ellipsoid. The observations of the SSHs at the tide gauge stations are relative to the earth crust and, as a consequence, do not allow to distinguish between a sea level increase and an earth subsidence phenomena [Woodworth et al, 1990], [Emery and Aubrey, 1991]. Therefore, the determination of absolute sea level variations requires, in addition to the sea level records, repeated measurements of the absolute geocentric coordinates of a reference point. This paper is part of a study having as objective the determination in the European seas of the absolute MSL heights above a reference ellipsoid and of their long-term variations in time from combined altimetry and tide gauge data [Fenoglio-Marc, 1996]. In addition to geodetic applications, as the monitoring of land uplift and the unification of vertical datums [Groten and Müller, 1990], [Kakkuri, 1994], the combined use of the altimetry technique, of the tide gauge network and of the geodetic system allows the establishment of a long-period climate monitoring system. Tide gauge stations and altimetry data from different satellite missions are used. The SSHs, at a selected location, are sampled by the various satellite altimetry missions and by the tide gauge stations with different time intervals. A necessary step is the investigation and comparison of the seasonal, annual and interannual SSHs time series obtained from each data type in each basin.

Data Analysis

Altimetry data from the three altimetry missions ERS-1, ERS-2 and Topex-Poseidon (T-P) have been analysed. The ERS-1 data used belong to the 35-day and to the 168-day repeat cycles of the missions, i.e. to phases C,E,F and G, covering the intervals from April 1992 through December 1993 and from April 1994 to July 1995. The gap between the intervals corresponds to the 3-day repeat cycles of the phase D, which have not been used, the coverage being too poor over each sea to estimate the mean SSH. The ERS-2 data cover the periods from May 1995 to September 1996 and the T-P data from September 1992 to May 1996. The data are used at 1-s interval. Environmental and other types of corrections have been applied to the data distributed by the respective centres (F-PAF for ERS-1 and ERS-2 [ESA, 1993], [CERSAT, 1996], AVISO for T-P [AVISO, 1994]). The type of study calls for homogeneity in the computation of the corrections, e.g. same orbit determination software for a given mission and same tide model for all missions. This was not always possible, as this condition is not met in the original data. We have applied the corrections available in the original data or computed improved corrections, when possible. Corrections for instrumental drifts, which are particular important for the study, have been applied. Table 1 summarizes the applied corrections for each mission and phase. The criterium we used in the selection of the tide gauge stations is the availability of *absolute* SSHs measurements from January 1991 to December 1995. The selected stations belong to one of the european projects aiming at the determination of the geocentric coordinates of tide gauge stations, as the Baltic Sea Level Project (BSLP), the Sea Level Fluctuation Project (SELF), the West European Tide Gauge Monitoring Project (EUROGAUGE) and the UK Tide Gauge Monitoring Project (UKGAUGE). Moreover, the selected stations are part of the Permanent Mean Sea Level Service (PSMSL) or of the World Ocean Circulation Experiment (WOCE) program, where the monthly and annual averages of the relative SSHs are collected. Only a few stations along the European coasts satisfy the given criterium: one station in the Mediterranean Sea (Trieste), three stations in the North Sea (Lerwick, Aberdeen, Lowestoft), six stations in the Baltic Sea (Spikarna, Ratan, Furugrund, Klagsham, Oland, Stockolm). Lerwick, common to the WOCE and to the PSMSL datasets is the only WOCE tide gauge station we could select. Air pressure and air temperature data every 3 hours were provided for the years 1993-1995 by the German Weather Service for three stations in North Sea (Cuxhaven, List and Helgoland) and for one station in Baltic Sea (Rostock-Warnemuende). Hourly air pressure and air temperature data for the years 1992-1993 were provided by the turkish Military Command of Mapping for stations in Mediterranean Sea (Antalya, Bodrum and Mentes), together with the corresponding SSHs.

Correction	E_1: C,E,F	E_1:G/ E_2	T-P
orbit	DGM-E04	GFZ	JGM-2
SSB	-5.5%swh, Ref.11	-5.5%swh	BM4, Ref.12
inv.bar.	standard	standard	standard
ocean tide	Schw.	FES95.2	Schw./C-R
ocean load	Schw.	FES95.2	Schw./C-R
earth tide	opr02	opr02	aviso
pole tide	not applied	not applied	aviso

dry tropo	opr02	opr02	aviso
wet tropo	radiometer	radiometer	radiometer
time bias	1.5 ms	1.5/1.3 ms.	
SPTR	tab. ESRIN	tab. ESRIN	
USO drift	tab. ESRIN	tab. ESRIN	tab.NASA
CAL drift			tab.NASA

Table 1: Correction applied

At each altimeter measurement location we have computed the difference between the corrected SSHs and a selected reference surface. The free-tide geoid corresponding to the geopotential model EGM96 [Lemoine et al., 1996] is the adopted reference surface. The choice of the reference surface does not influence the results, as it is constant in time. The differences are interpolated to points fixed along the track, also called *normal* points. The spacing of the points is selected as 0.1 degree in latitude, the nearest 6 points, within a window of 1 degree in latitude, are used for the interpolation. This procedure allows the reduction of the number of data and the use of points at the same geographical location for each cycle. For each sea and each satellite we have computed a mean over each cycle for the ERS-1 phases C and G, for ERS-2 and for T-P, and a mean over each sub-cycle of 37 days for the ERS-1 phases E and F. The mean SSH anomalies for each cycle or subcycle have been computed subtracting the mean over all the cycles from the cycle/subcycle mean. They are not sensitive to the latitude-spacing selected for the normal points. The monthly variability is evident in the T-P SSH anomaly cycle-mean, as shown in Figure 1 for the Mediterranean Sea. The T-P data have been averaged over 40 days, to obtain cycle-means comparable to the ERS-1 cycle-means, as the ERS-1 data are averaged over cycles of 35 or 37 days. The tide gauges monthly mean SSH anomalies have been computed subtracting the mean over all the available months in the years from January 1992 to December 1995 from the monthly means provided by the PSMSL and by WOCE. Variations in the geocentric coordinates of the reference points have not been taken into account. The tide gauges monthly mean air temperature and air pressure anomalies have been computed subtracting the global mean over all the available measurements from the monthly means.

Results

Figure 2 shows the mean SSH anomalies obtained from ERS-1, ERS-2 and T-P data over the three regions of investigation. The patterns of the satellites agree fairly well over each area. Comparing the patterns corresponding to the three areas, we note some differences. In the Mediterranean Sea the annual cycle is dominant, with maxima occurring in October except for 1995, when the maximum occurs in December. In the North Sea and in the Baltic Sea the annual signal is still present, but it is less stable from year to year. Other strong features appear. The smallest amplitude of the signal occurs in the Mediterranean Sea, with values in the range +/- 100 mm, the biggest amplitude in the Baltic Sea with values in the range +/- 300 mm, in the North Sea the values are in the range +/- 200 mm. The annual and semiannual components have been estimated by a least square procedure from the ERS-1 and T-P SSH anomaly time series. The ERS-2 data have not been taken into account as they correspond to the Tandem part of the mission, when also ERS-1 data are available. A linear trend has been estimated from the residuals obtained after elimination of these components. Table 2 gives the amplitudes and the phase of the annual and semiannual signals and the estimated annual drift.

	Annual A(mm) phase (y)	Semiannual A(mm) phase (y)	Drift (mm/y)
E_1 Med	75.53 0.78	7.06 0.38	14.34 +/- 3.92
T-P Med	74.28 0.78	20.96 0.38	1.67 +/- 4.19
E-1 Nsea	71.28 0.87	27.04 0.46	-6.47 +/- 4.84
T-P Nsea	65.30 0.86	20.00 0.34	-10.47 +/- 8.75
E-1 Baltic	32.08 0.99	45.94 0.09	-11.17 +/- 16.88
T-P Baltic	37.51 0.98	34.04 0.06	-32.48 +/- 21.99

Table 2: Amplitude and phase of annual and semiannual signals and estimated drift

A good agreement exists between the results from both satellites. The residuals and the linear trend are shown in Figure 3. The residuals are relatively small in the Mediterranean Sea, were the annual signal dominates, as shown in Figure 2. They are bigger in the other two seas. The amplitude spectra of the T-P mean SSH anomalies have been computed using a Fast Fourier Transform (FFT) method and are shown in Figure 4.

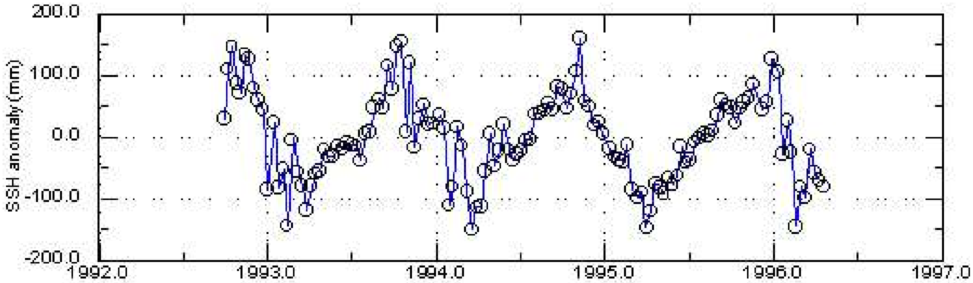

Figure 1: Mean SSH anomalies per cycle from Topex-Poseidon

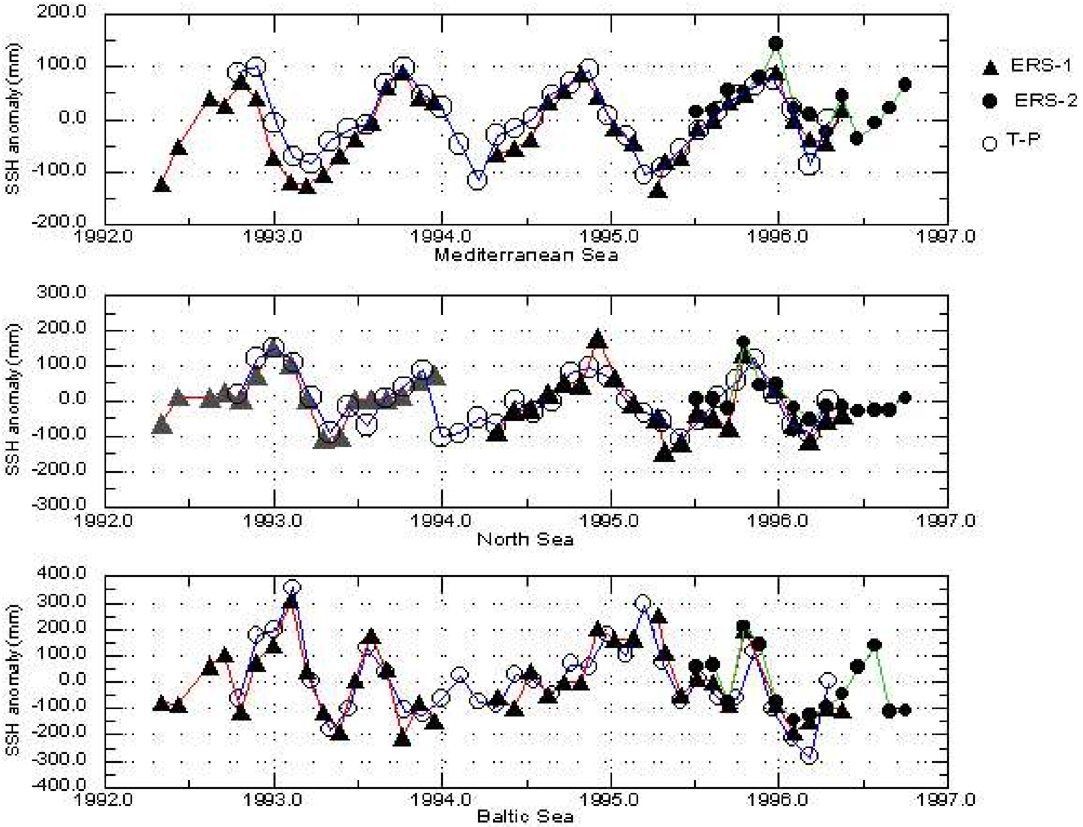

Figure 2: Mean SSH anomalies per cycle/subcycle from ERS-1, ERS-2 and 40-day mean SSH anomalies from Topex-Poseidon

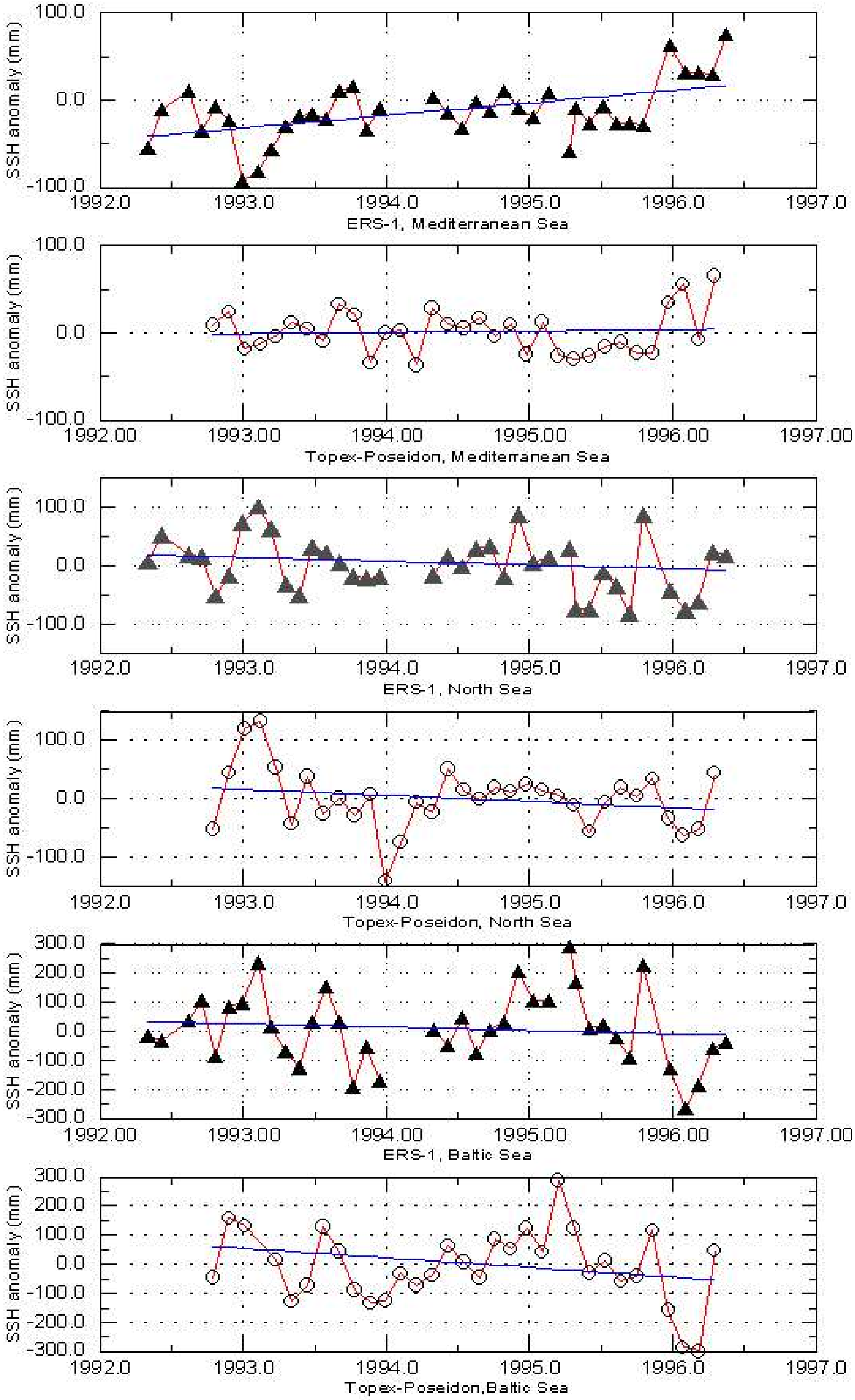

Figure 3: Residuals and linear drifts of cycle-mean SSH anomalies from ERS-1 and of 40-day mean SSH anomalies from T-P

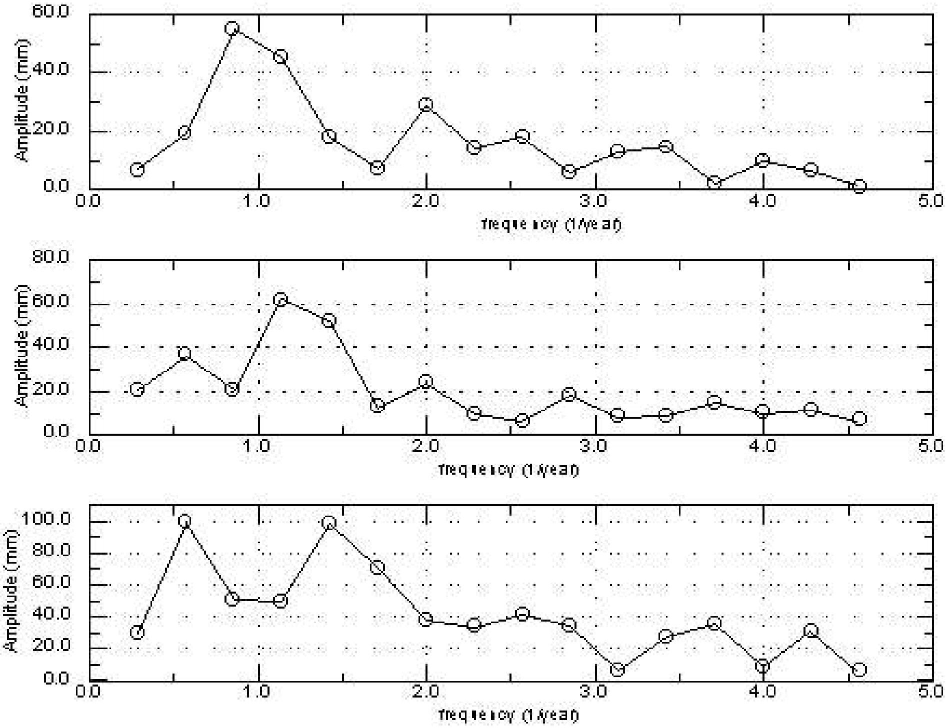

Figure 4: Amplitude spectra of 40-day mean SSH anomalies from T-P in Mediterranean Sea (top), North Sea (centre) and Baltic Sea (bottom)

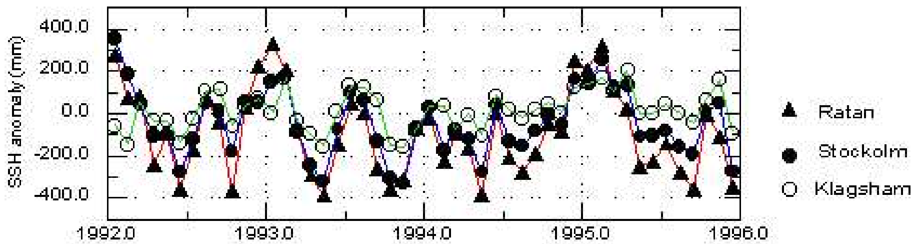

Figure5: Monthly mean SSH anomalies at tide gauge stations in Baltic Sea

In the Mediterranean Sea the biggest amplitudes are found at the frequencies of once and twice per year, in North Sea and Baltic Sea they occur at other frequencies. The altimetric mean SSH anomalies give a global mean over the sea, while the monthly mean SSH anomalies from tide gauge stations provide local information. Data from three stations in North Sea and in Baltic Sea show that the monthly mean corresponding to stations in the same sea have similar shapes, but different amplitudes. The local effects are strong and the smallest variations are found in the southern part of regions. Figure 5 shows the results in the Baltic Sea. The correlation of the monthly mean anomalies of SSH, of air temperature and of air pressure has been analysed. Figure 6 shows the air temperature and air pressure anomalies for two or three years at one station in each of the three basins. In the Mediterranean Sea both temperature and pressure present a dominant annual cycle and SSH, temperature and pressure anomalies appear to be correlated. In North Sea and Baltic Sea the temperature follows an annual cycle, while the pressure variations are more irregular, no significant correlation between SSHs, pressure and temperature anomalies are found.

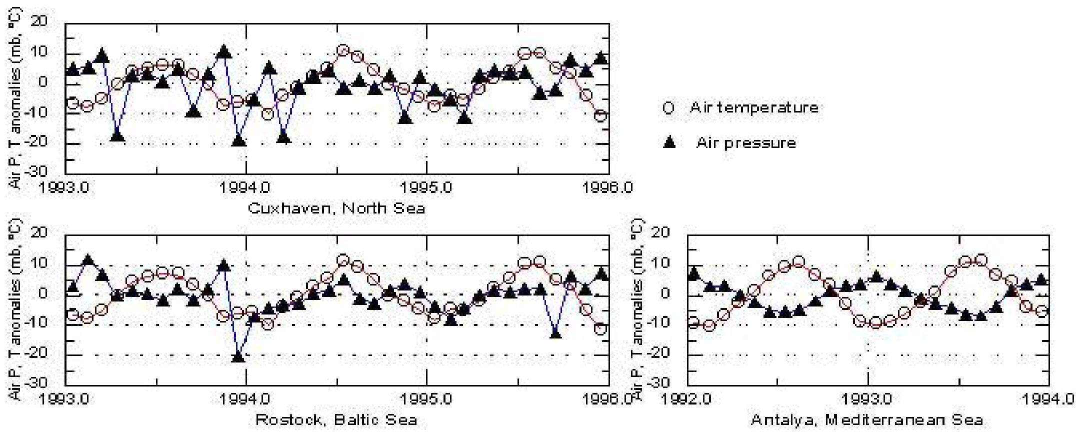

Figure6: Air temperature and air pressure monthly mean anomalies at tide gauge stations

The dominant annual cycle and the strong correlation with temperature in the Mediterranean Sea suggest that the SSH variations in the Mediterranean Sea are mainly of steric origin. In North and Baltic Sea other phenomena play a dominant role, causing sea level variations having maxima of the amplitude at higher and lower frequencies. For the high frequencies, the correlation with wind speed, atmospheric pressure and sea surface temperature patterns is under investigation. For the low frequencies, a correlation with low frequencies atmospheric phenomena [Hurrell, 1995] is possible. Altimeter data over decades are necessary for that analysis.

Conclusions

ERS-1, ERS-2 and T-P radar observations are contributing towards an accurate analysis of absolute sea level variations. The annual and semiannual components of the SSHs variations obtained from each satellite over each area of investigation agree quite well both in amplitude and phase. The annual drift estimated from the residuals cannot be interpreted as long term sea level changes, due to the short time interval analysed. Differences appear between the SSH variations in Mediterranean Sea and in the other two seas. Strong annual and semi-annual signals are found in the Mediterranean Sea but not in the North Sea and Baltic Sea. The biggest residuals, obtained after elimination of these periodic components, correspond to the northern seas. This residual signal is partly due to the non homogenous and inaccurate corrections applied to the altimetry measurements, partly to the different physical characteristics of the seas. A strong correlation with air temperature of the SSHs pattern in Mediterranean Sea, suggests that SSHs variations are of steric origin in this sea. The different general conditions of the seas, in terms of wave heights, wind speeds, sea surface temperature play a role. The study of the mean values of hydro-meteorological parameters, as waves heights, wind speed, sea surface temperature and atmospheric pressure variations, looking at their periodic behaviour and drift is of interest. Local SSH variations should also be investigated and compared with SSH variations at tide gauge locations, to analyse local characteristics. A combined analysis of the ERS, T-P and tide gauge stations datasets can be performed. Altimetry data over several years will allow the estimation of long period SSH changes.

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