

On the variability of Mean Sea Level

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Published in *Allgemeine Vermessungs-Nachrichten* 2/2003, pp.55-59

Abstract

The long-term sea level change during 1985-2001 is investigated in the Mediterranean Sea from satellite altimetry data of the Geosat, Topex-Poseidon (T/P), ERS-1 and ERS-2 missions and from tide gauge data. Discrepancies in the linear change observed between T/P and ERS-1/2 and between T/P and Geosat are reduced by fitting the ERS and Geosat data to T/P, as T/P time-series show the higher agreement with tide gauge data. A model of sea level variability constructed using sea surface temperature data is used in case of the non-contemporaneous Geosat and T-P missions. The regional mean sea level (RMSL) linear change is spatially not uniform. During the first eight years of the T/P mission the average linear sea level change over the entire Mediterranean Sea is 2.2 mm/yr, in agreement with the global mean sea level (GMSL) change, in the western Mediterranean Sea the change is small (0.4 mm/yr), while it is higher in the eastern Mediterranean and in the Ionian Sea, 9.3 mm/yr and -11.9 mm/yr respectively. The tide gauge data analysis shows agreement with altimetry data during 1985-2001. During 1990-2000 an increase in sea level rise with respect to the previous decade occurs. Sea level rise of almost similar strength was observed in the past from the longer tide gauge records indicating that the rise observed today by altimetry may have interannual or decadal frequencies.

Keywords: mean sea level change, altimetry, tide gauge

1. Introduction

Sea level change variations are monitored globally from altimetry since 1985 with a gap in 1989-1991. In this time-span of almost fifteen years short, seasonal and some interannual components of sea level variability are identified (Chen et al., 2000, Nerem et al., 1999), while the separation between interannual, decadal, low-frequency variability and secular components requires a longer time-span to average out decadal and interannual variations. Mean Sea Surfaces (MSS) have been computed from sets of altimetry data (Yi, 1995, Wang, 2000) averaging out the observed variability. The global mean sea level (GMSL) linear variation measured by T/P during 1993-2000 amounts to 2.5 +/- 0.2 mm/yr (Cabanes et al., 2001). Part of the sea level change is related to decadal changes in heat storage (Levitus et al., 2000), while maps of the altimetric geographic variability of the observed sea level trends are currently dominated by ENSO variations (Nerem et al., 1999). The linear sea level change measured by T/P altimetry includes therefore also those effects. Secular sea level change, also called linear-change or trend, in GMSL is an important indicator of global climate change. For sea level linear change detection at least 50-year records are needed. The record of sea level from tide gauges over the past 70-100 years shows a rise at a rate of 1-2 mm/yr (Douglas 2001), unfortunately long tide gauge records are spatially not uniformly distributed and are affected by vertical motions of the station. Tide gauges and altimetry data have been used together to detect low-frequency variability in global mean sea level (GMSL) time-series with secular trends removed (Chambers et al., 2002). Analysis of the T/P data, which is observing the GMSL since 1992, shows that the sea level change is spatially not uniform.

This study analyses the regional low-frequency variability in the Mediterranean Sea using multi-mission altimetry data from 1985 to 2001. In Section 2 the accuracy of both single- and multi-mission unified data is discussed. In Section 3 maps of regional monthly mean sea level (MSL) are computed and low-frequency variability of RMSL analysed. In Section 4 linear changes obtained by the short altimetric time-series are compared to longer tide gauge records results.

2. Construction of a regional unified multi-mission altimetry dataset

A regional multi-mission altimeter data set is constructed from the Geosat, T/P, ERS-1 and ERS-2 missions. Geosat data of the Geodetic Mission (GM) and of the Exact Repeat Mission (ERM) cover the two intervals from March 1985 to September 1986 and from November 1986 to October 1989. T/P data are analysed from September 1992 to August 2001 (cycles 1-333), ERS-1 data during the two 35-day repeat phases (phases c from April 1992 to December 1993 and phase g from April 1995 to Mai 1996), ERS-2 data from May 1995 to April 2001 (cycles 1-66). Geosat data come from the revised JGM-3 geophysical data records (GDR), T/P altimeter data come from the Merged Geophysical Data Records (MGDR-C), ERS data from the precise ocean products (OPR). Orbit and geophysical corrections have been applied to the data, including ocean tide FES95.2, loading tide, earth tide, pole tide and sea state bias. For ERS the orbital heights from the DGM-E04 orbits (Scharroo and Visser, 1998) have been used and the corrections for the ultra stable oscillator (USO) bias drift and for the bias jumps as characterised by the single point target response (SPTR) are applied. The inverted barometer (IB) correction, that accounts for the inverted barometer sea level response to atmospheric loading, is not applied in the comparison with tide gauge stations as it is also not applied in tide gauge data pre-processing. For each of the satellite missions the average over each cycle and over the entire Mediterranean Sea of the corrected sea surface heights (SSH) above the mean sea surface model MSSH95 (Yi, 1995) is computed and a simple regression model is fitted to the results (Figure 1). Geosat data after November 1988 are not considered as they are less accurate than Geosat data before that date. Relative biases and drifts are evaluated by dual crossover (DXO) differences between the lower (ERS and Geosat) and the higher (T/P) missions (Table 1). For contemporaneous ERS and T/P missions, a DXO time-difference of less than 10 days is used to be able to neglect the sea level variability (Figure 2). In case of the

non-contemporaneous Geosat and T/P missions the effect of the sea level variability is reduced considering DXO in corresponding months or correcting both Geosat and T/P observations for a statistical sea level variability model constructed by Canonical Correlation Analysis from sea surface temperature data of time-span 1985-2001 and T/P sea level height data of time-span 1992-2001 (Fenoglio-Marc, 2001). Geosat results are less accurate than ERS results due both to the lower accuracy of the data and to the residual sea level variability. A constant and a variable part of the discrepancy are distinguished, the constant part causes a bias between the satellites, while in the variable part both a trend and an annual cycle are present also for contemporaneous missions. The relative trend causes a different value for the linear sea-level change estimated from different satellites and has therefore to be eliminated before sea level change studies. The linear change in sea level estimated from monthly time-series at tide gauge stations and at the nearest altimeter node (Section 3) agrees better with T/P that with ERS-2 (Fenoglio-Marc, 2002). The ERS-2 and Geosat data are therefore corrected for relative bias and linear drift wrt T/P using the correction per cycle described above.

Table 1. Relative bias and drift between altimetric missions

Missions (low - high)	Time-Interval	Relative bias (cm)	Relative drift (mm/yr)
ERS-1 phase c - T/P	1992.7 - 1993.9	4	15.3 +/- 9.4
ERS-1 phase g - T/P	1995.3 - 1996.3	5	13.1 +/- 11.5
ERS-2 phase a - T/P	1995.4 - 1998.5	9	-3.7 +/- 1.4
ERS-2 phase a - T/P	1998.7 - 2001.7	6	-15.2 +/- 5.8
Geosat - T/P	1986.9 - 1988.7	-8	5.9 +/- 12.1

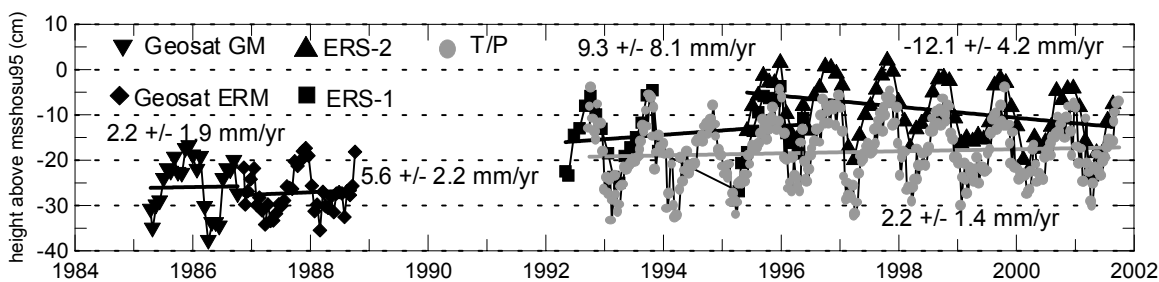


Figure 1. Average over each cycle of sea surface heights above mean sea surface MSSHOSU95

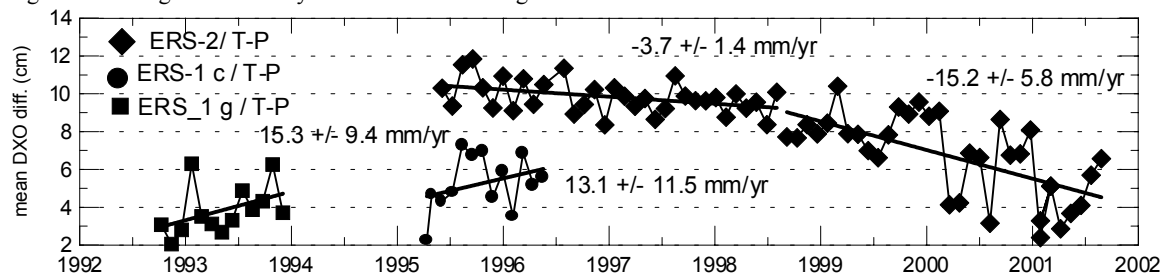


Figure 2. Average over each ERS cycle of dual crossover differences between ERS and T/P

3. Monthly maps of RMSL from multi-mission altimetry

For a 2-dimensional study, each corrected altimetry data set is gridded with a monthly interval and a grid spacing of 0.5 degrees using a Gaussian weighted average method. The half-weight parameter is chosen to be equal to 1 and the search radius equal to 3° to ensure that a pair of ascending and descending T/P arcs contributes to each node value. A multi-mission gridded dataset is constructed merging the T/P and the Geosat data. Monthly values of sea level heights at the tide gauge stations are available from the Permanent Service of the Mean Sea Level, the distribution of the stations is not uniform and the reliable stations are concentrated in the northern part of the Mediterranean Sea. Few stations have data over several decades, as Marseille since 1886, Venezia and Trieste since 1900, Dubrovnik since 1965. More stations have data since 1970, as Alicante, Kalamai, Soudhas. In general the data are available until the end of 1999. A few tide gauge stations are selected for their location and for the relatively small data gaps (Fenoglio-Marc, 2002), the monthly time series at those tide gauge stations and at the nearest node of the multi-mission altimeter fields are selected and the corresponding linear sea level changes compared during the overlapping time-span computing the correlation coefficient between the time series and comparing their long-term trend (Table 2). The agreement between the tide gauge and T/P altimetry is quite good at Soudhas, Estartit and Crotona.

4. Low-frequency variability of RMSL

The regional mean sea level (RMSL) linear change is spatially not uniform. During the first eight years of the T/P mission the average linear sea level change over the entire Mediterranean Sea is 2.2 mm/yr, in agreement with the global mean sea level (GMSL) change, in the western Mediterranean Sea the change is small (0.4 mm/yr), while it is higher in the eastern Mediterranean and in the Ionian Sea, 9.3 mm/yr and -11.9 mm/yr respectively. Due to the short altimetric time-series available, the linear sea level change depends on the time-interval selected if we choose subsets of the altimeter data. Tide gauge stations data in the Mediterranean Sea are analysed to evaluate low-frequency and secular variability over longer intervals and are compared to the variability obtained over the shorter intervals

corresponding to the altimeter data. To investigate the effect of the length of the time-span, intervals of different lengths are considered keeping fixed the end of the time interval and shortening the interval of 0.2 years at each computation-step. Relevant differences in linear change in sea level are observed with intervals of less than 20 years (Figure 3). Results for the intervals 1970-1999 and 1993-1999 show a bigger sea level change in the last seven years than in the longer time-span (Table 2). To investigate if an acceleration in the sea level change is observed on recent data, intervals of constant lengths for 10 and 20 years were analysed. The procedure corresponds to a smoothing of the original series. Results from the long data records of Marseille and Trieste show a positive sea level rate of change since 1990. High values have been reached also in the past (Figure 4).

Table 2. Linear sea level change (mm/yr) from monthly averages at tide gauge stations (TG) and at the nearest node of the T/P gridded field. Correlation of TG and T/P time-series with (r1) and without (r2) inverse barometric correction applied to T/P

Station	1970-1999 TG monthly	1993-1999 TG monthly	1993-1999 TG smoothed	1993-1999 T/P (IBC)	1993-1999 r1	1993-1999 T/P (no IBC)	1993-1999 r2
Estartit		4.2 +/- 2.9	5.3 +/- 1.1	5.3 +/- 1.6	0.79	6.1 +/- 2.7	0.90
Marseille	0.8 +/- 0.4	5.6 +/- 2.9	4.2 +/- 1.6	5.02 +/- 0.4	0.55	5.5 +/- 2.6	0.58
Venezia	-0.2 +/- 0.4	10.9 +/- 2.9	9.6 +/- 0.7	10.7 +/- 2.5	0.79	11.6 +/- 3.6	0.81
Trieste	-0.1 +/- 0.5	10.8 +/- 2.9	7.8 +/- 0.7	10.6 +/- 3.3	0.69	11.9 +/- 4.2	0.73
Dubrovnik	0.1 +/- 0.4	12.9 +/- 2.5	10.5 +/- 0.5	8.1 +/- 1.7	0.81	8.7 +/- 2.3	0.84
Soudhas	1.6 +/- 0.46	9.7 +/- 2.4	8.5 +/- 0.6	16.0 +/- 1.9	0.79	16.2 +/- 2.5	0.86
Anthalia		17.9 +/- 5.0	28.9 +/- 0.9	10.1 +/- 2.1	0.57	10.2 +/- 2.5	0.59

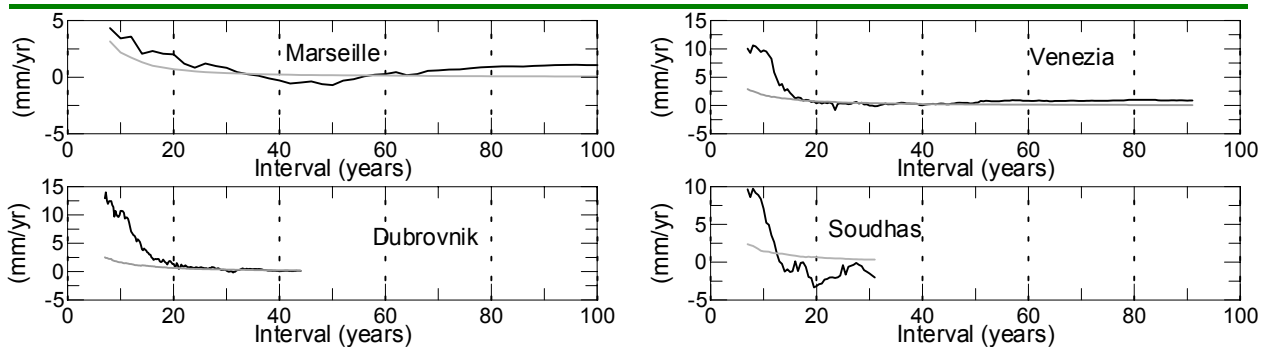


Figure 3. Linear sea level change (mm/yr) for increasing length of the data interval over the last n years before 2000.

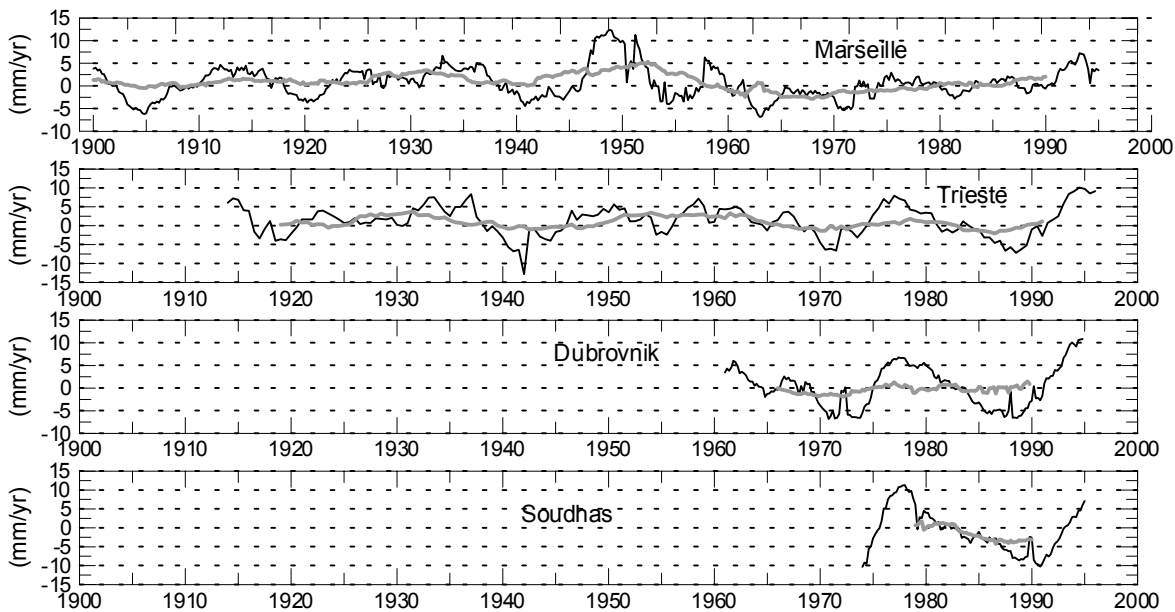


Figure 4. Linear sea level change (mm/yr) estimated over intervals of 10 years (black) and 20 years (grey).

Conclusions

During the last fifteen years satellite altimetry has provided a great amount of measurements of the instantaneous sea surface of high accuracy and spatial resolution that greatly contributes to our knowledge of mean sea level and temporal variations of the ocean. For this purpose, the merging of the multi-mission altimetry increases the time series lengths and the spatial resolution of the data. The increase in the time-series length is of particular importance for long-term sea level changes, as the altimeter satellite lifetime is too short for long-term, decadal and interannual studies.

For our regional analysis we have selected the Mediterranean Sea, because of its peculiar characteristics, such as the small sea level variability and the small ocean tides, that should allow an accurate computation of the MSL. Residual errors present in the altimeter data have been checked by the dual-crossover technique, that identifies the discrepancy

between two satellites. They are due to residual orbit errors, relative offset of co-ordinate frames, errors in media and in model corrections. In the case of the DXO between Geosat and T/P part of the discrepancy observed in the DXO differences comes from errors in the sea level variability model being used to correct for the variability. Two parts of the discrepancy have been distinguished: a constant and a variable part. The constant part produces a bias between the satellites, in the variable part both a trend and an annual cycle are present in the ERS-T/P DXO differences, the trend produces a different value for the linear sea-level change estimated from different satellites and has therefore to be carefully eliminated before sea level change studies are done. The reliability of the linear sea level change estimated by the different satellites has been checked by comparing sea level monthly averages estimated from tide gauge stations and from altimetry over the same time interval at a close location. Tide gauge station data agree well with T/P altimetry during 1993-2000 showing a positive sea level change in the eastern Mediterranean, a negative in the Ionian and a very small change in the western Mediterranean. The higher agreement of tide gauge data with T/P than with ERS confirms the stability of T/P, that is therefore used as reference altimeter dataset to build a multi-mission set. Due to the short altimetric time-series available, the linear sea level change depends strongly on the time-interval selected if we choose subsets of the altimeter data. Tide gauge data during 1990-2000 show an increase in sea level rise with respect to the previous decade. Sea level rise of almost similar strength is observed in the past from the longer tide gauge records indicating that the rise observed today by altimetry may have interannual or decadal frequencies. The good correlation between the linear changes in sea surface temperature and sea level during 1992-2000 shows that a great part of the observed sea level change is due to the thermosteric expansion of the ocean. The remaining part of the sea level change is due to mass exchange between the basins, caused, for example, by river run-off, density change, climatic variations in atmospheric forces that can drive substantial changes in the basin-wide large scale currents.

The observed variation in MSL shows that MSL is time-dependent. A specification of the corrections to be applied to the data before computing the “mean” and an estimation of the errors left is required. In theory, one approach would be to eliminate tidal periodic signals up to 18.6 years and non-tidal periodic seasonal and annual signals. In practice, the altimeter data are corrected for ocean tide models (LeProvost et al., 1994) and several periodic signals are averaged out when the mean is computed over an integer number of years, but longer period tidal and non-tidal effects are not. The deviation of long-period tides from equilibrium phase and amplitude is, for example, not completely known, also thermal variability has seasonal and annual periods that can be averaged out, but longer term signals are superimposed. Interannual and decadal effects linked to global sea-air interactions are also to be taken into account, such as El-Nino and NAO, whose signature appears also in the Mediterranean Sea level records. All these unsolved questions concerning the type of reduction and elimination of specific periodic and quasi-periodic effects lead to uncertainties in the definition and practical implementation of MSL. The determination of long-term variation of MSL is linked to long-term variation of the gravity field. The accuracy of altimetry allows then to detect long-term temporal changes of the gravity field, after accounting for the long-term thermosteric expansion of the ocean.

Acknowledgements

This study was supported by the Deutsche Forschungsgemeinschaft (DFG).

References

- Cabanes C., Cazenave A. and Le Provost C. (2001), Sea level rise during past 40 years determined from satellite and in situ observations, *Science*, 294, 840-842
- Chambers D.P., Mehlhaff C.A., Urban T.J. and Fujii D. (2002), Low-frequency variations in global mean sea level: 1950-2000, *JGR*, 107 (C4), 10.1029/2001JC001089
- Chen J.L., Shum C.K., Wilson C.R., Chambers D.P. and Tapley B.D. (2000): Seasonal sea level change from Topex/Poseidon observation and thermal contribution, *J. of Geodesy*, 73, 638-647
- Douglas B.C. (2001) Sea level change in the era of the recording tide gauge, in *Sea Level Rise, history and consequences*, International Geophysics Series Volume 75, Academic Press, pp. 37-64
- Fenoglio-Marc L. (2001), Analysis and representation of regional sea-level variability from altimetry and atmospheric oceanic data, *Geophys. J. Int.*, 145, 1-18
- Fenoglio-Marc L. (2002): Long-term sea level change in the Mediterranean Sea from multi-mission satellite altimetry and tide gauges, in press in *Physics and Chemistry of the Earth*
- Levitus S., Antonov J., Boyer T.P. and Stephens C. (2000) : Warming of the World Ocean, *Science*, 287, 2225-2229
- Nerem R.S., Haines B.J., Hendricks J., Minster J.F., Mitchum G.T. and White W.B. (1997): Improved determination of global mean sea level variations using Topex/Poseidon altimeter data, *Geophys. Res. Lett.*, 24 (11), 1331-1334
- Nerem R.S., Chambers D.P., Leuliette E., Mitchum G. and Giese B.S. (1999): Variations in global mean sea level during the 1997-1998 ENSO event, *Geophys. Res. Lett.*, 26, 3005-3008
- Yi Y. (1995), Determination of gridded mean sea surface from Topex, ERS-1 and Geosat altimeter data, Report N. 434, Department of Geodetic Science and Surveying, The Ohio State University, Columbus, Ohio
- Wang Y.M. (2000) The satellite altimeter data derived Mean Sea Surface GSFC98, *Geophys. Res. Lett.*, Vol.27, N.5, 701-704