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Investigation of sea level around the island of Gavdos from ten years of TOPEX/POSEIDON satellite altimetry data

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Abstract

The European Union project 'GAVDOS' (MERTIKAS & PAVLIS, 1999) has been designed to lead to the establishment of a calibration and sea level monitoring site for the JASON-1 and ENVISAT satellites as well as the GLObal Sea level monitoring System (GLOSS). Within the context of this project, nearly ten years of TOPEX/POSEIDON satellite altimetry data (cycle 1 to 364) from the vicinity of the Gavdos Island (Crete, Greece) have been processed and analysed. The results presented here are from the application of a method that incorporates the calculation of a corrected sea surface height from the altimetry data, along-track and cross-track data interpolation because of orbital drift, near coastal error filtering, and the use of a new geoid for the area. This method was applied in order to create ten year time series of sea level and associated parameters for the area around Gavdos island. The results reveal the pattern of sea level and local seasonal cycle around Gavdos over the last ten years.

Keywords: Satellite altimetry; Calibration; Sea-level; Sea surface height; Seasonal cycle; TOPEX/POSEIDON.

Introduction

Long term sea level change monitoring has historically only been possible through estimations from tide gauge data. However, tide gauges measure sea level change relative to crustal reference points, which can move vertically at rates comparable to the true sea level signals (DOUGLAS, 1995). Furthermore, these measurements are at high temporal resolution and low spatial resolution which provides a poor representation of the open ocean. Satellite altimetry, on the other hand, is at a lower temporal resolution but can provide much higher spatial resolution which is more representative of the open ocean. Furthermore, the time series available now are long enough to play an important complementary role.

The inception of satellite altimetry can be traced back to the early 1970's when the scanning of the lunar surface was undertaken using a laser altimeter on Apollo 14 (KAULA *et al.*, 1974) and the scanning of the Earth's surface was carried out by the experimental S-193 radar altimeter on Skylab (MCGOOGAN *et al.*, 1974). However, the utility of satellite radar altimetry for oceanography did not become apparent until the launch of GEOS-3 in 1975 and Seasat in 1978. In particular, Seasat demonstrated that data with an appropriate accuracy for global and regional oceanography might be possible as it was able to measure the distance between the satellite and the sea surface below it to within 10cm (ROBINSON, 1985). One and a half decades later, TOPEX/POSEIDON was the first altimetry system in history designed specifically to describe the general circulation of the oceans and has been providing sea level data accurate to 3-4 cm for the past 10 years. A good review of the TOPEX/POSEIDON mission can be found in FU *et al.* (1994). Nevertheless, it is worth mentioning that it was originally designed to have a lifespan of 5 years. The extended dataset of more than twelve years (at the time of publication) continues to be useful to regional oceanographic studies such as this one, global oceanographic studies, and the understanding of the relationship between ocean circulation and the Earth's climate.

TOPEX/POSEIDON's successor, JASON-1, was launched in December 2001 and has recently finished its validation phase and started providing operational data. The potential of this radar altimeter and the RA-2 on ENVISAT (launched in March 2002) to maintain accuracies of a few cm in sea level measurements from space, requires accurate calibration strategies. This is crucial for determining the accuracy of individual altimeter measurements and for combining data from separate instruments. Altimetry missions, including the TOPEX/POSEIDON mission, generally employ three methods of calibration:

i) Onboard internal instrument calibration to monitor any degradation of the electronics.

ii) Independent ground based verification sites, e.g. Harvest Oil Platform off the coast of California and Corsica Island in the Mediterranean (MENARD *et al.*, 1994, BONNEFOND *et al.*, 1997)

iii) The use of selected tide gauges from the global network of tide gauges (MITCHUM, 1998).

The main objective of the European Union project 'GAVDOS' is to establish a European radar altimeter calibration and sea level monitoring site for JASON-1, ENVISAT and the GLObal Sea level monitoring System (GLOSS). This can be considered to be similar to methods (i) and (ii) listed above and is in the process of providing a ground based verification site for these satellite altimeters that includes permanent tide gauges. As can be seen in Figure 1 the choice of site was determined by the fact that the Gavdos island is under one of the crossing areas of two ground tracks of the TOPEX/POSEIDON orbit up until August 2003 (moved to an adjacent orbit) and two ground tracks of the JASON-1 orbit since its launch in 2001. This means that calibration activities can potentially be carried out twice per cycle (approximately every five days) using ascending and descending tracks and direction dependent biases can be removed. Furthermore, as a calibration site for sea level the island benefits from being far from the mainland surrounded by deep ocean with relatively simple circulation and small local tides. The purposes of this site can therefore be considered for the following:

i) To conduct comparative laser distance measurements between the facility and satellite radar altimeters such as TOPEX/POSEIDON, JASON-1, and ENVISAT RA-2.

ii) To ensure the unbiased establishment of the mean sea level, as realised by the globally distributed altimeter measurements.

iii) To monitor, consistently and reliably, any radar altimeter errors (systematic or random).

iv) To cross-calibrate different satellite altimeter missions and, for each one of them, use a common and long-term calibration basis (MERTIKAS *et al.*, 2002).

The rationale for the research presented in this paper is within this framework. A ten-year time series of satellite altimetry derived sea level from TOPEX/POSEIDON and investigation of its seasonal cycle should contribute to a better understanding of the oceanography of the area. This in turn will allow preliminary analysis and interpretation of the tide gauge data and will be incorporated into the ongoing and future calibration work of the GAVDOS project.

Method

The methods detailed in the TOPEX/POSEIDON handooks (BENADA, 1994, 1997, AVISO, 1996) and the MIT processing method (STAMMER, 1998) were adapted to process and geophysically correct the altimetry data and produce a ten year, monthly averaged, time series for any required oceanographic area of interest. For the work presented here the methods were applied to the 3° by 2° (22.25° to 25.25° longitude, 33.25° to 35.25° latitude) area of interest around Gavdos (Figure 1).

Initially binary data were extracted for the orbit tracks of interest from the AVISO CD-ROMS and the required parts of the file headers and geophysical data records were written out as ordered ASCII files. Further computer programs were written and utilised to implement the main part of the method

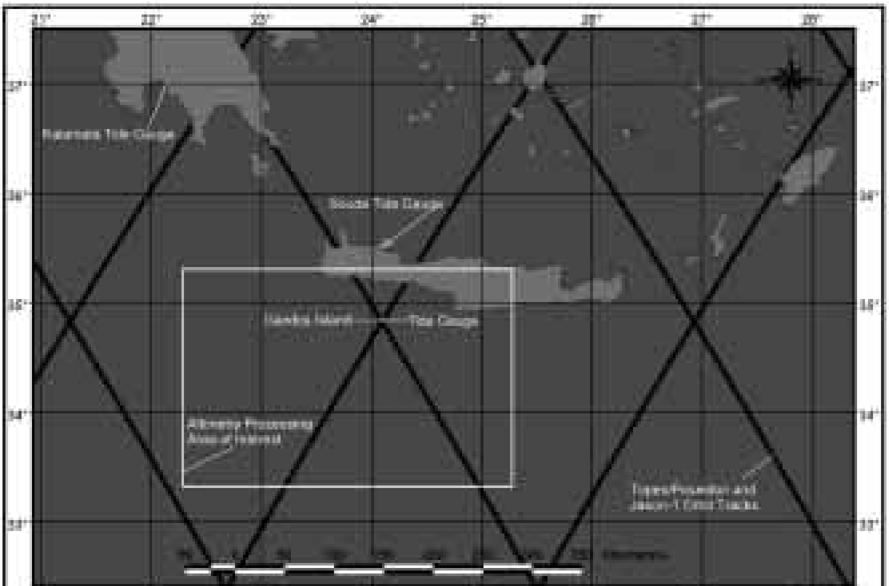

Fig. 1: Gavdos location map showing TOPEX/POSEIDON altimetry orbit tracks and area of interest.

which can be divided into the following procedural elements:

i) Calculation of the month and year of each TOPEX/POSEIDON orbital cycle, allowing for leap years, from the time of day of the extracted records and the julian days and year from the file headers.

ii) Calculation of the number of non-land, 'good' points (error filtered) per TOPEX/POSEIDON orbital cycle within the area of interest using the provided data flags, expected ranges and default values of the altimetry measurements. There are twenty seven error/information flags provided with the TOPEX/POSEIDON raw data and many of these were used in the filtering. However, the main filtering used a combination of the following: a check to see which altimeter was switched on (TOPEX or POSEIDON) in order to use the correct flags; a check to only accept measurements where the one per second altimeter range to the sea surface was positive and between a pre-defined possible minimum and possible maximum for the area; a check of the provided error flags (Alt_Bad_1 and Alt_Bad_2) which give an indication of the validity of each altimeter measurement and if the measurement conditions and corrections were acceptable; and rejection of measurements where default values of the measurements and/or the geophysical corrections occurred. The number of valid points per pass was also taken into account and orbits that contained less than a pre-determined threshold North or South of Gavdos, were not included in the subsequent analysis. The high level and detail of the filtering was the main adaptation of the aforementioned 'global' method and was necessary because of the near coastal nature of the study and high number of invalid points repeating through the datasets (track 018 appx. 20% of measurements were rejected North of Gavdos and appx. 6% South of Gavdos, for track 109 appx. 9% were rejected North of Gavdos and appx. 4% South of Gavdos).

iii) Geophysical correction of the altimetry data for the affecting factors that can mask the underlying ocean circulation. For this work the corrected sea surface height residual (sshr) was calculated as:

$$sshr = (h - \varrho) - (io + dtr + wtr + eb + sot + eot + pt + cgs + ib) \qquad [1]$$

where h is the altitude of the satellite above the reference ellipsoid, ϱ is the one per second altimeter range, io is the ionospheric correction, dtr is the dry tropospheric correction, wtr is the wet tropospheric correction, eb is the electromagnetic bias correction, sot is the solid ocean tide correction, eot is the elastic ocean tide correction (the sum of the ocean tide and the loading tide), pt is the pole tide correction, cg is the centre of gravity shift correction, and ib is the inverse barometer effect correction.

All parameters except the inverse barometer correction are supplied with each data record and this was calculated from Benada (1997) as:

$$ib = -9.948\,(P - 1013.3) \qquad [2]$$

where P (atmospheric pressure) = $dtr\,/\,(-2.277(1+(0.0026*\cos(latitude*1.10^{-6} * pi/180.0))))$, -9.948 is a scale factor based on the theoretical value of the static inverted barometer at mid latitudes, and 1013.3 is the nominal value of mid latitude average atmospheric pressure.

iv) Interpolation of the sea surface heights to nominal mid-track positions where there were enough good points per cycle to allow this. The orbit of the TOPEX/POSEIDON satellite deteriorates due to air drag, and has some variability because of the inhomogenous gravity field of the Earth, solar radiation pressure, and other minor forces. Small maneuvers are performed every 40 to 200 days, depending primarily on the solar flux as it affects the Earth's atmosphere, to correct the orbit so that cross-track drift does not exceed +/- 1km. The effects of this orbital variability with an approximate ten-year track width of 2km and the necessity for interpolation to mid-track reference points can be seen in Figure 2.

In addition to cross-track drift there are along-track measurement position differences due to slight altimetry measurement time differences related to satellite height above the surface.

Inverse distance weighting interpolation of the difference between measurements and the underlying geoid at the measurement points to reference points was applied. When these interpolated differences are added back to the geoid at the reference points this then accounts for along-track and cross-track measurement repeat variability and orbit drift and any geoid gradient. The geoid used was the 5min by 5min high resolution geoid from the Aristotle University of Thessaloniki produced as part of the GAVDOS project. The reference points used were from cycle 018 of TOPEX/POSEIDON which are positioned approximately in the centre of all the tracks (BENADA, 1994, 1997, STAMMER, 1998).

v) Calculation of a monthly average. All interpolated data were averaged to give first one average sea surface height per cycle and then averaged again to combine cycles that fall within the same month. The data were split into North of Gavdos, i.e. between Gavdos and Crete, and South of Gavdos as the two areas represent different oceanographic conditions.

vi) Calculation of sea surface topography per month. All interpolated data were combined into datasets representing all January data, all February data etc. at each reference point. These were then averaged per

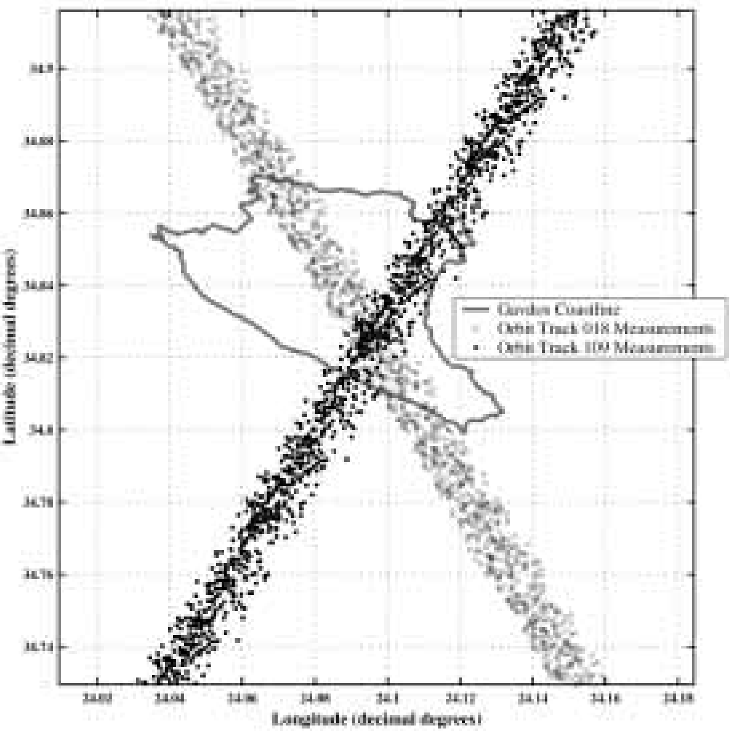

Fig. 2: Positional variability in TOPEX/POSEIDON measurmens around Gavdos (all cycles).

reference point and the geoid was removed for each of these points.

vii) Estimation of the seasonal cycle. A stable estimate of the seasonal cycle requires at least 5 years of data (TSIMPLIS & WOODWORTH, 1994). Three time series of nearly ten years of data were used: the TOPEX/POSEIDON data North of Gavdos; the TOPEX/POSEIDON data South of Gavdos; and for comparison purposes a time series from a tide-gauge at Souda bay, Crete. Also for comparison purposes the seasonal cycle analysis of a time series from a tide gauge at Kalamata in the Peloponnese is included. Data from the tide gauge on Gavdos was not included in the analysis because it has only been operational since August 2002.

The seasonal cycle has been estimated in two ways. Firstly, using a simple way of estimating the mean seasonal cycle by finding the mean monthly value for each month and secondly by fitting an annual and a semi-annual component.

Results

Figure 3 shows the main results of the analysis of the TOPEX/POSEIDON time series and a comparison with Souda tide gauge, the closest tide gauge with long term measurements to the area under question. Figure 3(a) shows the TOPEX/POSEIDON time series of sea level (monthly mean sea surface heights graphed against their long term means) for South and North of Gavdos and for the tide gauge at Souda for the same duration. The best fitting seasonal cycle function is included for each of these time series in Figures 3(d), (e) and (f). Figure 3(b) shows the mean sea level for each month of the year for the duration of the time series and Figure 3(c) shows the residual differences between the fitted seasonal cycle and the original time series of sea level.

Table 1 shows the main characteristics of the seasonal cycle functions fitted to the sea level time series shown in Figure 3 .

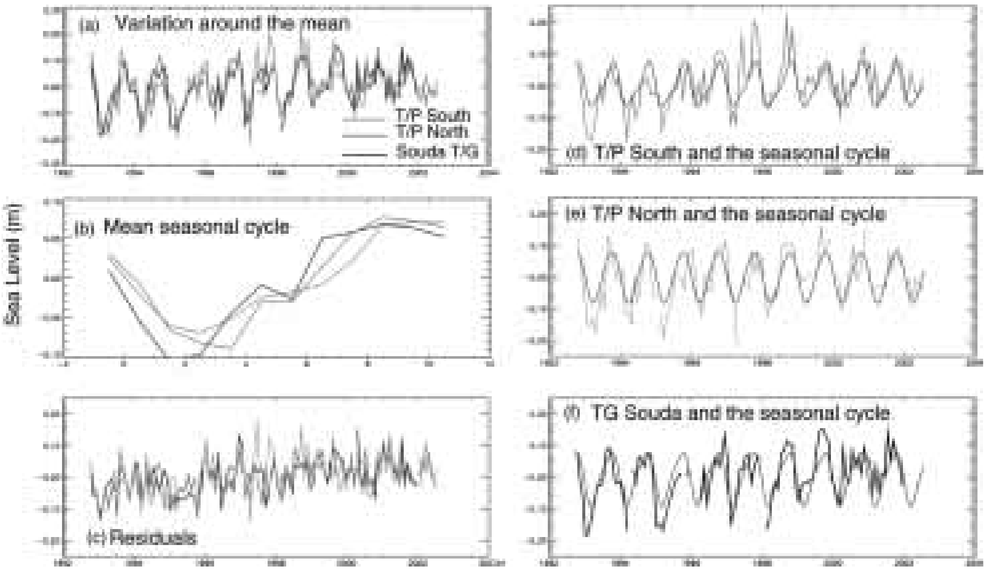

Fig. 3: Sea level around Gavdos against Time (Year for a and c to F and Month to b) and the Seasonal Cycle (T/P=TOPEX / POSEIDON and TG = Tide Gauge).

Table 1
The Harmonics of the Seasonal Cycle (S = amplitude, P = phase, a = annual, sa = semi-annual).

	Sa (cm)	Pa (˚)	Ssa (cm)	Psa (˚)
T/P South	6.5	-54	2.0	-45
T/P North	8.1	-57	0.7	5
TG Souda	8.1	-78	1.7	-34
TG Kalamata	8.2	-56	0.2	0.

Discussion

The results presented form a preliminary analysis and are part of an ongoing effort to utilise the historical TOPEX/POSEIDON dataset for the GAVDOS project. Nevertheless, there are some general points that can be made about these results and their contribution to understanding certain aspects of the sea level of the area.

Firstly, it can be noted that there is a seasonal cycle to the sea level around Gavdos which is also seen in the Souda tide gauge data (Figure 3). However, the annual cycle phase of the altimetric data appears more consistent with the Kalamata tide gauge (Table 1) rather than the one at Souda. This may be fortuitous but it could be related to the fact that the sea surface temperature isotherms move northwards west of Crete. The semi-annual cycle is not well resolved and the estimates are inconsistent.

Secondly, there is a correlation between the sea level values of the different time series. The correlation coefficients between the two T/P time series is 0.77. The T/P North time series correlates slightly better with the tide gauge data at Souda (0.8). The T/P South correlate somewhat less with the tide-gauge data at Souda (0.74). Part of this correlation is due to the seasonal cycle and after its removal the residuals correlate less well: The correlation between T/P North and T/P South is 0.45 while the correlation of the T/P South with Souda and Kalamata reduces to 0.54. Nevertheless, one should note that there are discrepancies in excess of 5 cm between the mean monthly values of the time series.

Finally, there is a general agreement between the data presented here and recent previous work on sea level changes in the Eastern Mediterranean over the last decade. In particular it is worth noting that between 1993 and 1998 the sea level appears to have been increasing rapidly, at least for T/P South (CAZENAVE *et al.* 2001; Tsimplis and Rixen, 2002), and after 1998 it appears to have levelled off.

The adaptation of the altimetry processing methods previously detailed was based on extensive use of the provided error flags and extensive filtering to use only valid points. This was an issue because parts of the area of interest are very close to coastal regions. Without this extra filtering the data were too noisy. Furthermore, the size of the area used around Gavdos was carefully selected in order to ensure that enough valid points were available to calculate consistent reliable monthly means of sea level and minimize the impact of near-coastal noisy or invalid data. However, there are limitations to the methodologies employed and the results gained here as well as possibilities for further work stemming from these limitations, some of which have already been envisaged by the GAVDOS project:

i) The time series will be extended to include the new satellite altimetry data from Jason-1 and RA-2 on ENVISAT.

ii) Potentially more accurate interpolation schemes will be investigated employing the latest and most accurate geoid solutions.

iii) The results and further analysis will be utilized to contribute to an accurate sea surface topography of the area.

iv) A combination of GAVDOS and other tide gauge measurements, oceanographic observations, and the satellite altimetry results will be used to contribute to the overall calibration process of satellite altimeters using the GAVDOS site.

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