Estimating mean dynamic topography in the tropical Pacific Ocean from gravity and altimetry satellites

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[1] A new geoid model, combining the CHAMP satellite gravity data and an accurate altimetric mean sea surface, was used to investigate the 1993–1999 mean dynamic topography in the tropical Pacific Ocean. The mean dynamic topography, represented by a spherical harmonic expansion to degree 60 appear to be consistent with our knowledge of the tropical circulation, notably the South Equatorial Counter Current which is clearly visible in the western Pacific. This satellite solution, validated with in-situ data, is independent from any climatology and has a resolution similar to other classical mean dynamic topographies. Altimetry combined with geodesy can thus provide an absolute sea level which will be useful for data assimilation and tropical oceanography. *INDEX TERMS:* 4231 Oceanography: General: Equatorial oceanography; 0920 Exploration Geophysics: Gravity methods; 1243 Geodesy and Gravity: Space geodetic surveys; 4223 Oceanography: General: Descriptive and regional oceanography; 4512 Oceanography: Physical: Currents. **Citation:** Gourdeau, L., J. M. Lemoine, M. H. Rio, and F. Hernandez, Estimating mean dynamic topography in the tropical Pacific Ocean from gravity and altimetry satellites, *Geophys. Res. Lett.*, *30*(20), 2062, doi:10.1029/2003GL018200, 2003.

1. Introduction

[2] Because of geoid uncertainties, altimetric applications have concentrated on ocean variability, using sea level anomalies. Several satellite gravity missions such as CHAMP, GRACE and GOCE have been devised to provide high resolution, highly accurate geoids, in order to improve our knowledge of the absolute circulation of the ocean. Motivated by improvements in the geoid due to the CHAMP mission, a mean dynamic topography for the 1993–1999 period was computed from satellite altimetric and geodetic data, providing an estimate of the absolute sea level over that period. We focused on the tropical Pacific Ocean which has been intensively surveyed since the Tropical Ocean Global Atmosphere (TOGA) programme began in an attempt to understand and predict the climatic ENSO (El Niño-Southern Oscillation) phenomenon. The satellite solution was compared with climatology, model simulations, and synthetic solutions in terms of dynamic topography and geostrophic circulation. Its contribution to absolute sea level is quantified with independent in-situ data, such as those from the Tropical Atmosphere Ocean TAO/TRITON mooring arrays, and XBTs.

2. Satellite Estimation of Mean Dynamic Topography

[3] The geoid used in this study was computed from the EIGEN-2 Earth gravity field model, based on 6 months of data from the CHAMP satellite gravity mission in 2000 and 2001 [*Reigber et al.*, 2003]. The formal, cumulated geoid error of EIGEN-2, obtained from the full covariance matrix of spherical harmonic coefficients, is 7 cm at harmonic degree 36 (i.e., a resolution of 550 km) and 46 cm at degree 60 (i.e., a resolution of 333 km) in the tropics. The shape of this error, common to all 'satellite-only' gravity field models, mostly reveals an excessive attenuation of the geoid undulations, increasing with the harmonic degree. The improvement in spectral content made possible by the very low flight altitude of CHAMP is however clearly visible in Figure 1: EIGEN-2 has a spectral power comparable to that of the 'combined' field EGM96 up to about degree 53, while the spectral power of the 'satellite-only' part of EGM96 (EGM96-S) already starts to decrease around degree 25.

[4] The mean sea surface used here corresponds to a 7-year mean (1993–1999) based on the most recently processed TOPEX/POSEIDON, ERS1-2 and GEOSAT altimetric satellite data (SMO CLS01, *Hernandez et al.* [2001]). Formal errors are about 2–3 cm rms for most ocean regions.

[5] The mean dynamic topography was then computed by subtracting the satellite-only, derived geoid from the mean sea surface. A problem to be overcome at this stage was the non-compatibility of the spectral contents of both surfaces: unlike the geoid, the spectral power of the mean sea surface tends to remain complete up to very high

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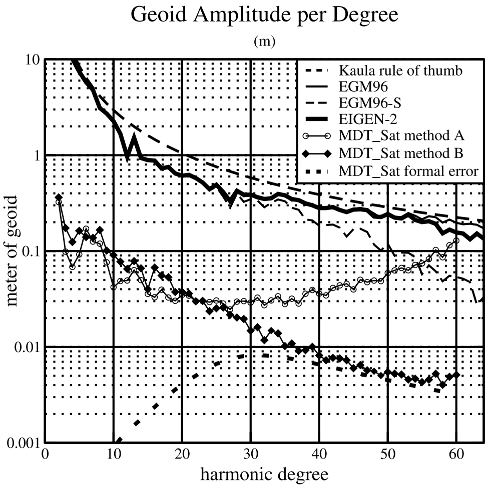

Figure 1. Comparison of spectral power (amplitude per degree) for the EIGEN-2, EGM96 and EGM96-S (the 'satellite-only' solution of EGM96) geoids. Comparison of spectral power for the mean dynamic topography when limiting the solution to the longest wavelengths (method A), and when controlling the decrease of the power to follow the geoid accuracy (method B). In dot, the formal error estimation for the method B solution. Units are in meters.

degrees and its error curve is rather flat. We decided that a crude solution (Figure 1, method A) – simply differentiating the two surfaces and solving for the mean sea surface spherical harmonic coefficients without constraints, – was not satisfactory. We thus chose a more refined solution (Figure 1, method B) in which a constraint is added in the inversion process to ensure that the solution spectrum follows an a-priori, geophysically consistent, law. This led to a significant improvement of both the spectra of the mean dynamic topography and of its associated error (see Figure 1). While the method A solution would have had to be truncated at degree ~27, it is possible to use the method B solution up to degree 60. The formal cumulated error of the mean dynamic topography reaches 4 cm at degree 36 and 5 cm at degree 60.

[6] The mean dynamic topography thus obtained was mapped on a 1° resolution grid, and was filtered spatially in accordance with the mainly zonal currents (i.e., 3° in the zonal direction).

3. Satellite Mean Dynamic Topography Versus Climatology, Synthetic, and Modelled Solutions

[7] A climatological mean dynamic topography has been estimated from the *Levitus et al.* [1998] surface dynamic height field referenced to 1500 dbar. It suffers from a lack of circulation data below 1500 m. A modelled mean dynamic topography has been provided by the LODYC OGCM (Ocean General Circulation Model). The simulation, using interannual atmospheric state-of-the-art products, covers the 1993–1999 period [*Durand et al.*, 2003]. The simulation suffered from unresolved physics, errors in the forcing fields and model parameters. A new synthetic mean dynamic topography from *Rio* [2003] integrates all the information available from in-situ, altimetric, and gravimetric data, and has been computed for the 1993–1999 period. Note that the gravimetric data does not influence this solution in the tropical band. Except for the satellite solution, both the modelled and synthetic solutions are conditioned by Levitus data.

[8] The global rms differences between the solutions are in the 14–24 cm range. In the tropical Pacific Ocean, the rms differences are much lower in the 4–8 rms cm range. The lowest differences are between the climatology and synthetic solutions, which illustrates the climatological constraint in the synthetic solution. The highest differences were obtained with the modelled solution, illustrating errors in the mean model state. The differences between the satellite and synthetic solutions (5.6 cm rms) were located in the central and eastern part of the basin along 5°N, and in the south west (Figure 2). Actual errors in the satellite mean dynamic topography seem to be coherent with their formal estimation. The satellite solution may provide a realistic solution in the tropics independently of any climatology.

3.1. Mean Surface Geostrophic Currents

[9] Tropical oceans exhibit mainly zonal circulation. Computation of zonal geostrophic currents is very sensitive to the latitudinal gradient of the dynamic topography, particularly towards the equator, where the Coriolis force vanishes. Therefore, estimating the equatorial currents is a stringent test for validating the satellite dynamic topography.

[10] The classical surface geostrophic currents are clearly visible both in the satellite and synthetic solutions (Figure 3): the North Equatorial Current (NEC, [10°N–17°N]), the North Equatorial Counter Current (NECC, [5°N–10°N]), the northern and southern branches of the South Equatorial Current (SEC, [7°S–4°N]), and also the South Equatorial Counter Current (SECC) at 10°S in the western Pacific.

[11] In Figure 2, the satellite and synthetic currents differ in the NECC and the SECC. The synthetic solution is in accordance with the geostrophic currents deduced from the 0/1500 dbar dynamic height field from *Levitus et al.* [1998]. The NECC crosses the basin with a maximum amplitude in the central Pacific reaching 30 cm/s, and its eastern part shifts southward. The SECC is located around 10°S. For the satellite solution, in contrast, the NECC is maximum in the extreme west, and vanishes at 110°W as in the model (not

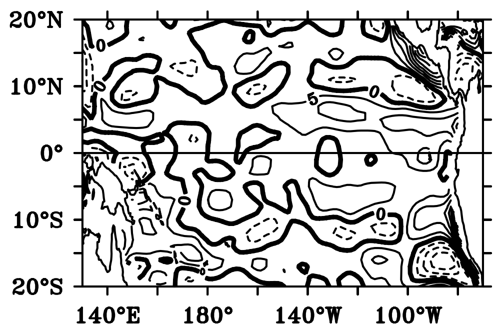

Figure 2. Differences of mean dynamic topography in the tropical Pacific basin between the satellite and synthetic solutions. Iso-contours are every 5 cm.

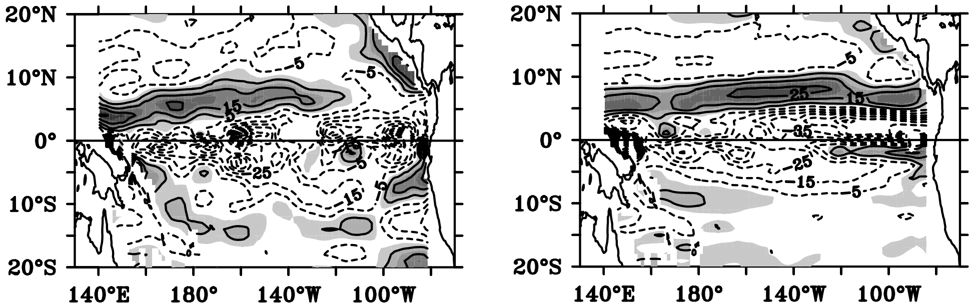

Figure 3. Mean zonal geostrophic circulation in the tropical Pacific associated with the satellite solution (left) and the synthetic solution (right). Iso-contours are every 5 cm/s.

shown). Its magnitude is around 15–20 cm/s. The SECC is located more to the south, extending south-east from 5°S to 15°S until 180°W before turning eastward. For both solutions, the SECC vanishes at around 150°W, and its magnitude reaches 5–10 cm/s.

4. Altimetric Sea Level Data Versus Independent In-Situ Data

[12] The ocean is constantly changing, so the absolute circulation is time dependant. To get absolute sea level, the satellite mean dynamic topography was added to the TOPEX/Poseidon sea level anomalies, referenced to the 1993–1999 period. Sea level and corresponding surface geostrophic currents were mapped onto a 1° * 1° resolution grid, and sampled every 5 days over the 1993–2001 period. They were compared in time and space with in-situ data. The tropical Pacific is continuously observed through the XBT Ship Opportunity Programme (upper ocean temperature measurements), and the TAO/TRITON moorings array which are key elements of the ENSO survey. The 70 TAO/TRITON moorings are in the 8°N–8°S equatorial band where the ocean exhibits a dominant baroclinic signature.

4.1. Sea Level

[13] The 0–500 dbar daily TAO dynamic heights are low pass filtered with a 10-day Hanning filter. The dynamic height calculation is limited by the 500-dbar reference level which would result in an error of about 1–2 dyn. cm, and the use of mean TS curves which would result in a 4 cm error [*Delcroix et al.*, 1994]. Nevertheless, rms differences (Figure 4) between dynamic height and sea level, which integrate the differences both in term of mean and variability, are in the 4–8 cm range. The rms of the average difference between the sea level and the TAO dynamic height is around 4 cm, similar to the rms of the variability difference. It is around 3 cm, 2.3 cm, and 6.6 cm when using the synthetic, the climatology, and the modelled mean dynamic topographies, respectively, to estimate sea level.

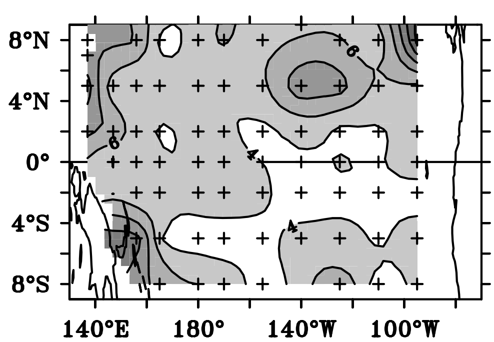

Figure 4. RMS differences at the TAO moorings (crosses) between 0–500 dynamic height and the corresponding sea level signal. Iso contours are every 2 cm.

[14] To extend the validation in latitude, the 1996–1997 mean of the 0–700 dbar dynamic height determined along the Fiji-Japan XBT line by *Delcroix et al.* [1998] was compared with the corresponding mean sea level (Figure 5). Both curves are highly correlated except in the south where the SECC shifted 3° to the south in the satellite solution. The location of the SECC (13°S at 175°E) may appear to be suspect. At 165°E, the SECC is located at around 9°S as in *Delcroix et al.* [1987]. At 150°W, *Eldin* [1983] described a SECC, highly variable in time, with two thin branches at 9°S, and 12°S. When using the synthetic solution instead of the satellite solution, to estimate sea level, the shift of the SECC is no longer observed. This is not surprising as the synthetic solution incorporates most of these in-situ data.

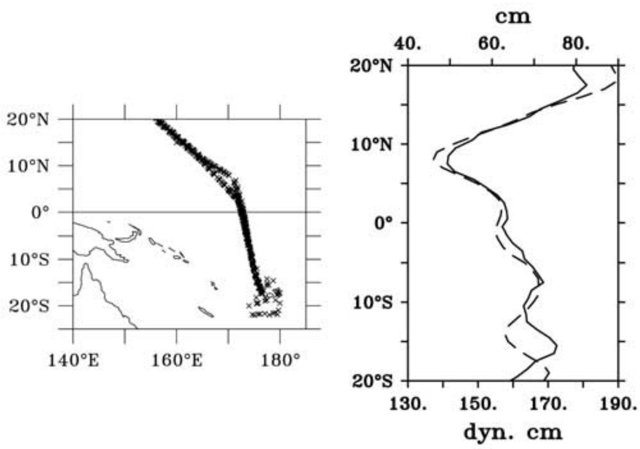

Figure 5. Left: Location of the XBT derived measurements along the Fiji-Japan shipping track. Right: Mean 1996–1997 dynamic topography along the shipping track from *Delcroix et al.* [1998] (continuous line), and from sea level (dash line), units are in dyn. cm and cm respectively.

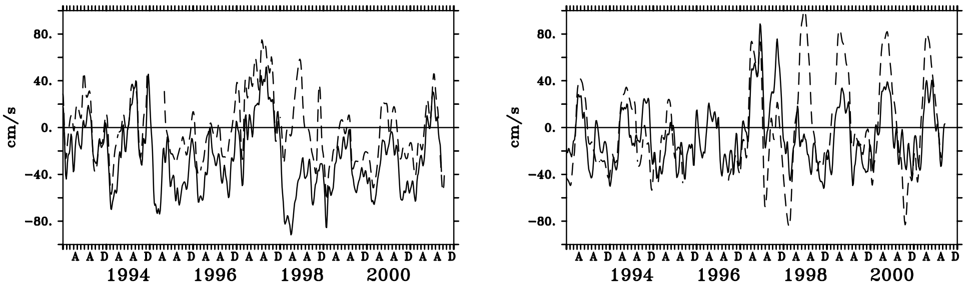

Figure 6. Time evolution at the 165°E (left), 140°W (right) TAO equatorial moorings of surface zonal currents observed (dash line), and of the sea level-derived geostrophic currents (continuous line). Units are in cm/s.

[15] Error estimation for absolute sea level is in the same range as error for the sea level anomaly, but sea level errors cannot be defined by a simple white noise, as is classically done when using anomalies, because of correlated geoid errors.

4.2. Zonal Current

[16] Monitoring the surface currents in the tropical Pacific is crucial for climate studies. In-situ comparisons of sea level-derived zonal currents are performed from currents measured at the 3 TAO equatorial moorings (110°W, 140°W, 165°E) fitted with current meters and ADCP (Acoustic Doppler Current Profile). The ADCP current data at depth of 50 m, 35 m, and 30 m were selected for 165°E, 140°W, and 110°W, respectively, to take advantage of quasi-continuous time series. Their mean values were adjusted to the mean value at the surface provided by the current meter data (biases of 0 cm/s, 20 cm/s, and 40 cm/s were removed at 165°E, 140°W, and 110°W, respectively). To suppress most of the ageostrophic currents, the time series were filtered with a 35-day Hanning filter. The rms differences between the time series of sea level-derived zonal current and in-situ measurements are 31, 32, and 40 cm/s at 165°E, 140°W, and 110°W respectively, compared with the 27, 40, and 44 cm/s rms of the observed currents, with corresponding correlation coefficients of 0.77, 0.63, and 0.44. The same results were obtained when using the synthetic solution to estimate the sea level-derived zonal current.

[17] At 165°E (Figure 6), the rms difference was attributed to a mean difference around 25 cm/s. The westward shift of the satellite current may be attributed to some errors at the equator in the curvature of the mean dynamic topography. At 140°W (Figure 6), and at 110°W, the mean satellite current is close to the mean observed current, in a 5 cm/s range, and the rms difference has been attributed to a higher seasonal variation in the observed current than in the satellite current from 1998 to 2001. The peculiar physics of the equatorial oceans makes the zonal current very sensitive to the balance between the trade winds, and the zonal pressure gradient. Looking at TAO wind measurements, the westward wind relaxes in March–April on a seasonal time scale as observed since 1999, therefore the zonal pressure gradient may tend to accelerate the zonal current towards the east.

5. Discussion and Conclusion

[18] Improved knowledge of the geoid due to the CHAMP mission, and the great accuracy of altimetric data are capable of providing mean dynamic topography up to degree 60 for the global ocean, independent from any in-situ data. This satellite solution seems to match the reality for the tropical Pacific. It has been used to reference altimetric sea level without introducing dramatic errors (errors are less than 5 cm rms). Part of this error, due to the altimetry, corresponds to white noise; another part, due to the geoid, is correlated in space and time. The resolution and accuracy of sea level and its associated geostrophic circulation are compatible with oceanographic studies in the tropics. This now offers a new perspective for using altimetry.

[19] The time/latitudinal section of sea level-derived geostrophic current at 175°E (Figure 7) clearly shows the strong seasonal variability of the SECC, at a maximum in February–March with a 15 cm/s magnitude and minimum in October, in phase opposition with the NECC which reaches a 30 cm/s magnitude. When the SECC grows, it migrates to the north from 15°S to 5°S, similarly the NECC migrates to the south. The El Niño conditions are clearly visible in 1993, 1994, 1997 and 2001 with equatorial eastward currents centred in July–August. The NECC is intensified during El Niño (reaching 70 cm/s in 1997), whereas the SECC disappears during the extreme 1997 El Niño, and the SEC reverses. During La Niña conditions, as in 1998, the NECC disappears, and both the SEC and the SECC intensify.

[20] This satellite surface information, when assimilated in numerical models, may prove very useful for improving simulations of the tropical oceans. In the future, the GRACE and GOCE missions will provide new information in terms of geoid resolution and variations which will improve our knowledge of the absolute circulation.

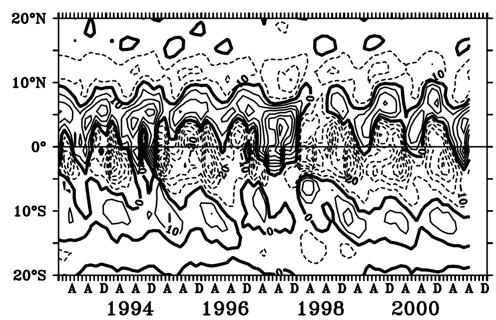

Figure 7. Time-latitude plot at 175°E for the sea level-derived zonal geostrophic currents. Iso contours are every 10 cm/s.

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