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A high resolution satellite-only GRACE-based mean dynamic topography of the South Atlantic Ocean

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[1] A new filtering method based on Singular Spectrum Analysis has been devised to extract high resolution (0.25° × 0.25° grid) satellite-only Mean Dynamic Ocean Topography(MDT) constructed by differencing of the GGM02 GRACE Gravity Model from the GSFCMSS00 Mean Sea Surface. This data-adaptive interpolation-type filter is adequate for the finite domain MDT processing since it minimizes smoothing and does not lose boundary points. It is applied to the computation of two new MDTs and MDT-derived mean geostrophic circulation maps of the South Atlantic region from 15°S to 50°S. Advantages of these new maps are clarified when contrasted with the Rio-2005, Chambers-Zlotnicki-2004 and ADCP cruise transect data. Citation: Vianna, M. L., V. V. Menezes, and D. P. Chambers (2007), A high resolution satellite-only GRACE-based mean dynamic topography of the South Atlantic Ocean, Geophys. Res. Lett., 34, L24604, doi:10.1029/2007GL031912.

1. Introduction

[2] There is a present-day interest in the construction of a good surface time-mean absolute MDT of the global ocean, with a precision of a few centimeters on a scale of 100 km. This is related to the need of a best possible upper-layer mean geostrophic circulation field, from which one can derive more precise mesoscale circulation structures by satellite altimetry and numerical modeling. The need seems to be more pressing for the South Atlantic. Some authors recognize that the observed current system in this ocean is still not reproduced in high resolution general circulation models [Stramma et al., 2005].

[3] In a recent important paper, Vossepoel [2007] presents a first in-depth assessment of almost all the presently available MDTs of the global ocean. His results suggest that the best MDT is Rio05 [Rio and Hernandez 2004], due to its finest resolution and its inclusion of oceanic in situ data. This MDT exhibits more mesoscale features and agrees with other observational MDTs in large scales.

[4] Vossepoel correctly mentions that the smaller scales could be either semipermanent features or the result of aliasing signals with a temporal resolution which is not resolved. We add here that such aliasing could be also a result from the finite time averaging interval used for the MSS computation. His assessment points out that the observational MDTs are superior to the non-assimilative GCM-MDTs to date.

[5] There is one detail in common between the computations of all the observational MDTs studied by Vossepoel: the use of traditional spatial gaussian or Hamming filters for the suppression of the noise caused by the smoother geoid as compared to the MSS. This filter has well-known difficulties near boundary points, which means difficulties with the MSS discontinuities near continental boundaries. Due to this problem, the satellite-only MDTs do not behave well on western boundary current regions before separation from the continent. Another problem is that these filters smooth out both small-scale noises and signals alike, with the consequence that known quasi-permanent subgyre recirculation cells may not become apparent in the maps.

[6] The present work describes an efficient procedure which can be applied for filtering noise in bounded regions by using standard Singular Spectrum Analysis (SSA) methodologies [see, e.g., Ghil et al., 2002]. It may extract colored noise without attenuation of peak signal amplitudes and does not miss boundary points, which makes this filter behave more like an efficient interpolator than a smoother. This procedure is applied here to compute a higher resolution satellite-only GRACE-based MDT for the South Atlantic region by using the same MSS and geoid model data of Chambers-Zlotnicki (CZ04) [Chambers and Zlotnicki, 2004].

[7] Our best MDT-derived mean geostrophic circulation (MGC) field is contrasted to those obtained from the Rio05 and the CZ04. Additionally, we use ADCP current profile data from one zonal and one meridional transect to compare with the absolute geostrophic velocities derived from high resolution objective mappings of 3-satellite altimetric surface height anomalies summed to the different MGCs.

2. The MDT Grid

[8] The high resolution MDT was constructed by differencing of the GRACE Gravity Model 02, GGM02C [Tapley et al., 2005], based on 363 days of data (April 2002–December 2003), from the multi-satellite MSS field GSFCMSS00 (1993–1998) [Wang, 2001]. This raw MDT was mapped into a 0.25° × 0.25° grid between 15°N–50°S; 60°W–20°E.

[9] The MDT so obtained (not shown) has a very complex noise pattern dominated by meridional non-continuous striations, due in part to the insensitivity of GRACE K-Band ranging system to cross-track signals in the gravity field measurements made by the GRACE system. Additionally, tidal model residual errors are generated in the extraction of the tidal potential signal from the

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gravity measurements used to generate the model Geoid [Ray et al., 2003].

There are also other geoid signatures as expected, e.g. fracture zones, island and seamounts. These are caused by the fact that they are resolved in the MSS but not in the geoid models. All such signatures are spurious as related to the MDT signal, and should be filtered out with the minimum possible signal attenuation. Some details on these noises have been discussed by Jayne [2006] for the North Atlantic.

3. Adaptive Filtering

Since MDTs are not defined on land, the use of traditional filters to remove the peculiar MDT noises require appending land data or missing real MDT data near boundaries [Jayne, 2006]. It seems clear to us that adaptative filters, based on principal component analysis techniques, as in the Singular Spectrum Analysis (SSA) expansions [see, e.g., Ghil et al., 2002], should be more efficient in removing noise in such cases. The main advantages of this kind of filter are: it does not have problems with domain boundaries; it uses the space covariance structure of the data; it works well with short data sets; it does not lose boundary points; it does not smooth out large isolated peaks; and it is able to efficiently separate the signal from noise in a automatic and controlled manner.

The SSA expansion is based on a extended lag covariance matrix, and a free windowing parameter $M$. It is used here in the standard way to expand each of the zonal (meridional) longitude (latitude) sequences at constant latitudes (longitudes), with the basic lag covariance unbiased estimator. Formally, the $M \times M$ lag covariance matrix is given by

$$c_{ij} = \frac{1}{N - |i - j|} \sum_{l=1}^{N-|i-j|} X_l X_{l+j} \quad 0 \leq i, j \leq M - 1$$

where $X_l$ is a constant latitude (longitude) sequence of N points, and $M$ is chosen here as $M = N/3$, which gives the maximum information-carrying matrix dimension [Ghil et al., 2002] and is a safe value against computational instabilities dictated by practice. Eigenvalues $\lambda_k$ and eigenvectors $E_k^p$ of this matrix are obtained and sorted in descending order of energy $\lambda_k$ with $j, k$ from 1 to $M$. The $k$ Principal Components $p_k^p$ (PC’s) are obtained from

$$p_k^p = \sum_{j=1}^{M} X_{i+j} E_k^p \quad 0 \leq i \leq N - M$$

and the Reconstructed Components (RC) sequences $R_k^p$ of adaptive filters by

$$R_k^p = \frac{1}{M} \sum_{j=1}^{M} p_{i+j}^k E_j^p \quad M \leq i \leq N - M + 1$$

$$R_k^p = \frac{1}{i} \sum_{j=1}^{i} p_{i+j}^k E_j^p \quad 1 \leq i \leq M - 1$$

$$R_k^p = \frac{1}{N - i + 1} \sum_{j=i-N+M}^{M} p_{i-j}^k E_j^p \quad N - M + 2 \leq i \leq N$$

The RCs constitute data-adaptive $M$-dependent filtered versions of the signal, each characterized by a dominant wavelength, obtained here by the Maximum Entropy Method. Nonlinear trend components, possibly including isolated peaks, appear as RCs with infinite wavelength. A filter can be constructed by partial sums of RCs which increasingly converge into the original series. These RCs are chosen by their dominant wavelength, to obtain a bandpass-type filter.

The noise-free MDT was obtained by a filtering procedure which consists of two steps. First we remove the meridional striations, and next we remove other noises from the striation-free data. In both steps we use the same kind of filter as described above, always applying the filter twice.

It should be noted that the signals appear in RCs containing few sharp spatial peaks a few hundred km across, characterized by much larger spectral wavelength maxima, including nonlinear trends. The striations, on the other hand, are contained in RCs characterized by shorter spectral wavelengths due to quasi-periodicity. This is why the method can, in contrast with Fourier-based filtering, separate a non-periodic signal with sharp features from a background of colored noise of larger wavelengths than the length of those signal peaks.

To remove the striations we made RC expansions of the data at each latitude. The different $N$ points for each latitude makes $M$ also vary as a function of latitude, but the wavelength band analysis makes this procedure largely independent of $M$ since the RC selection is made by maximum spectral peaks of each RC. The striation-free data at each latitude is constructed by excluding from the RC sum (reconstruction) those that fall within a band interval $[L_{\text{min}} \text{ km}, L_{\text{max}} \text{ km}]$. After several tests (not shown) with different spectral band limits, we found that with $L_{\text{min}} = 300$ km as the lower limit, and $L_{\text{max}} = 600$ as the upper limit, we could get rid of the striae almost entirely.

The second step consists of the removal of remaining noises in the striation-free data by a 2D filter. After several tests with 2D isotropic filters using all RCs with spectral indices larger than $L_{\text{max}}$ km, we found that different solutions offer good compromises between noise elimination and preservation of mesoscale features. We show this in the next section by contrasting two solutions, with $L_{\text{max}} = 350$ (VM350) and 500 km (VM500). We stress again that this does not mean that features with much less than 500 km are washed out.

4. Comparing MDTs Through Derived Mean Geostrophic Currents

In this section we compare the VM350 and VM500 MDTs with the Rio05 and CZ04. It should be noted that the VM MDTs have higher resolution ($0.25^\circ \times 0.25^\circ$) than Rio05 and CZ04, both with $0.5^\circ$ regular grids. Since the Rio05 MDT has an offset of 1.23 m with ours, and 1.17 m with CZ04, it is best to use the MGCs in the comparisons. This offset is caused by the use of the Levitus1998 data referred to the depth of 1500 m in the Rio05, as discussed by Yossepoel [2007].

Figures 1 and 2 show the MGCs of VM500 and Rio05 (the other MGCs are omitted due to space limita-
Qualitatively, there is good agreement between all the MGCs in large scales away from boundaries. However, Rio05 is more noisy and lacks some mean closed loop currents known to exist, e.g., the recirculation subgyre centered at 24°S; 33°W, first studied by Tsuchiya [1985].

Other notable difference between the MGCs is on western boundary currents. In Rio05 the widths are smaller, and intensities are about twice as compared to the others. Examples are the cases of the Brazil Current (21 cm/s from Rio05, 11 cm/s from VM500 and VM350, and 8 cm/s from CZ04), and the retroflected (southeastward) North Brazil Current (NBC) (70 cm/s from Rio05, 32 cm/s from VM500, 38 cm/s from VM350 and 25 cm/s from CZ04). The NBC and its retroreflection between 5°N and 8°N are clearly present in Rio05 and VM500, very noisy in VM350, but absent in CZ04. It is important to note here that altimeter-derived geostrophic currents correlate with currents below the mixed layer, which means that the MGC should be related to currents at depths of 50 m or more. However, the annual means obtained from current meter moorings in the NBC and its retroreflection, as reviewed by Johns et al. [1998], is 50 cm/s at 60 m depth or less at deeper depths. This means that Rio05 overestimates the intensities of the mean boundary currents, which suggests more consistency of these with VM500.

VM500, VM350 and Rio05 show the same intensity (30 cm/s) for the mean North Equatorial Countercurrent (NECC) centered at 5°N, but the width is smaller in VM350 and Rio05. It is very broad in CZ04, with intensity of 20 cm/s.

The current amplitudes in CZ04 are always smaller and with more spread than the other MGCs. The mesoscale features in the VMs are always better defined than in Rio05 and CZ04, especially south of 2°S. As an example, the double-gyre structure for the South Atlantic Subtropical Gyre, with a northern subgyre centered around 24°S and a long almost zonal one centered at 32°S, consistent with the geopotential anomaly maps of the Atlantic Ocean presented by Reid [1989] and Tsuchiya [1985], where Tsuchiya suggests that these structures might be semi-permanent.

In all MGCs the major large scale currents are present, and away from western boundaries all major flows are well represented. To illustrate this, we plot the zonal velocity transect (Figure 3) from 50°S–15°N along 20°W obtained from all four MGCs. All MGCs exhibit a clear Brazil Front current at 35°S and a different current at 40°S; a very weak westward flow between 30°S–12°S, which pertains to the SEC as described in by Stramma [1991]; a eastward flow at 7°S; the strong (25 cm/s) westward cSEC at 4°S; a NECC (20 cm/s).

Although the RMS difference of VM350 to VM500 is only 4.4 cm/s, in the NBC region VM350 is corrupted by spurious eddies due to remaining noise not effectively filtered out. Summing up, we may suggest that VM500 is the best choice between the two VM MDTs.

One interesting idea to (indirectly) compare different MGCs and measured currents is by deriving the velocities obtained from altimetric Sea Surface Height Anomalies (SSHAs) and different MGCs. This has been done by some authors [Rio and Hernandez, 2004; Jayne, 2006] using drifter data. We did this by use of VM Oceanica high resolution (1/8° × 1/8°) multi-satellite (Jason1, GFO and ERS2/Envisat) gridded daily SSHA summed to each of the MDTs to be assessed. The SSHA gridded product uses SSA filtered collinear data and space-time objective mapping with correlation scales of 150 km × 150 km × 15 days. Each of the derived MGC velocities are compared to two contemporaneous ship mounted ADCP transect data, where we used one zonal data set from a Mirai cruise (30°S,
Acknowledgments. We are grateful to the S-ADCP/U. Hawaii corresponding to the Gordon and Bosley\[1991\]. The general pattern away from the boundary is consistent with Rio05, except that the BF is not clearly represented, and as mentioned above the flow patterns are very noisy. The Brazil Current merges with the Malvinas Current at 40°S with intensity of 35 cm/s, while in VM500 these flows do not merge, and the Brazil Current turns eastward at 35°S with a speed of 8 cm/s offshore of the weak overshoot to the south.

5. Summary and Conclusions

The use of the SSA method shows advantages over standard smoothing filters. Contrasting the derived VM MGCs large and mesoscale flow structures for the South Atlantic Ocean with the Rio05, we showed that the former has all the known current structures, is less noisy and show subgyres not seen in latter. In Rio05 the western boundary currents are more slender and with twice the intensity, which is too large as compared to the measured mean annual cycle in the NBC retroreflection region. Since vigorous meandering and large eddies are known to be related to these currents, it is natural to expect that the mean currents should be less intense. VM500 is consistent with CZ04, but the currents are better defined and more intense than in CZ04, and present structures in the subgyre scale not seen in the other MGCs. We can finally state that the SSA filter is an efficient tool that should be used in future global MDT computations.

References


Figure 3. Contrast between zonal currents at 20°W obtained from VM350 (dash-dotted), VM500 (solid), Rio05 (dotted) and CZ04 (dashed).
