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Large Scale Ocean Circulation from the GRACE GGM01 Geoid

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[1] The GRACE Gravity Model 01 (GGM01), computed from 111 days of GRACE K-band ranging (KBR) data, is differenced from a global mean sea surface (MSS) computed from a decade of satellite altimetry to determine a mean dynamic ocean topography (DOT). As a test of the GGM01 gravity model, large-scale zonal and meridional surface geostrophic currents are computed from the topography and are compared with those derived from a mean hydrographic surface. Reduction in residual RMS between the two by 30–60% (and increased correlation) indicates that the GGM01 geoid represents a dramatic improvement over older geoid models, which were developed from multiple satellite tracking data, altimetry, and surface gravity measurements. For the first time, all major current systems are clearly observed in the DOT from space-based measurements. *INDEX TERMS:* 4532 Oceanography: Physical: General circulation; 1214 Geodesy and Gravity: Geopotential theory and determination; 1294 Geodesy and Gravity: Instruments and techniques; 4594 Oceanography: Physical: Instruments and techniques. **Citation:** Tapley, B. D., D. P. Chambers, S. Bettadpur, and J. C. Ries, Large scale ocean circulation from the GRACE GGM01 Geoid, *Geophys. Res. Lett.*, *30*(22), 2163, doi:10.1029/2003GL018622, 2003.

1. Introduction

[2] An Earth geopotential model that has both high accuracy and spatial resolution is a requirement for a number of contemporary studies in geophysics and oceanography. *Wunsch and Gaposchkin* [1980] (hereafter referred to as WG80) discussed how accurate sea surface height (SSH) measurements from satellite altimetry could be combined with a precise geoid to compute the absolute dynamic topography. If the absolute topography is known, one can derive the total surface geostrophic current from the spatial gradients.

[3] Only a relative dynamic topography can be computed from in situ hydrographic sections [*Wyrtki*, 1974; *Levitus*, 1982]. Generally, it assumed that the currents at some reference level are zero so that the relative topography is identical to the absolute topography. However, WG80 point out that this assumption is often not correct. One specific example is the Antarctic Circumpolar Current (ACC), which extends almost to the ocean floor. Because of this, WG80 suggested that if the absolute topography could be recovered precisely from altimetry and a geoid, then one could combine the absolute and relative topography measurements to map sub-surface geostrophic currents with greater detail than has ever been available.

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[4] Mapping the absolute dynamic topography with radar altimetry was a primary goal of the TOPEX/POSEIDON (T/P) mission, which was launched in August 1992. It was recognized well before the satellite was launched that significant improvements in global gravity field models were necessary to meet this goal both in terms of the geoid as a reference surface and as an input to the orbit determination for the satellite itself. A major effort was undertaken to improve existing gravity models by reprocessing existing satellite tracking data as well as new tracking data [*Nerem et al.*, 1994; *Tapley et al.*, 1996]. The latest such model, the Goddard Earth Gravity Model 1996 (EGM96) [*Lemoine et al.*, 1998], included information from all available surface gravity and ocean altimeter data as well as the satellite tracking data. Although these advances were significant, the estimated errors in the marine geoid models were still at the 20 cm level or worse, at length scales of several hundred km [*Stammer and Wunsch*, 1994; *Tapley et al.*, 1994]. As a consequence, even the largest scale ocean circulation features could not be accurately resolved, even though the T/P altimeter is able to measure SSH to an accuracy approaching 2 cm at the same scale for a period of over a decade.

2. The Grace Gravity Model

[5] The Gravity Recovery and Climate Experiment Mission (GRACE) was designed to help unravel global climatic issues by enabling a better understanding of ocean surface currents and heat transport, measuring changes in sea-floor pressure, observing mass of changes in the oceans, and by monitoring changes in the storage of water and snow on the continents. The GRACE mission was funded under the NASA Earth System Science Pathfinder (ESSP) Project, and is a joint project between the U.S. and Germany. GRACE consists of two satellites, which, in flight formation, can be considered to be the effective mission instrument. The principle data are the high accuracy inter-satellite ranging system, consisting of K-band dual-one-way range measurements of the distance between the two GRACE satellites. Space limits a complete discussion of the GRACE mission and instrumentation in this article; for more details please see the GRACE web-site (http://www.csr.utexas.edu/grace), *Davis et al.* [1999], *Dunn et al.* [2003], or *Tapley et al.* [2003a]. It is expected that GRACE will provide a minimum of a ten-fold increase in the accuracy of the Earth's gravity model to degree/order 70.

[6] A solution for the Earth's mean gravity field was determined from 111 days of GRACE data spanning the months of April through November 2002 during the commissioning phase of the mission [*Tapley et al.*, 2003b]. An important consideration in the generation of this field is that no other information was included as part

of the solution; no a priori constraint, no other satellite information and no surface gravity information is used. It is especially important to note that no satellite altimeter data was used; the preliminary geoid is free from any sea surface topography signal in the altimeter measurements. This assumption is not satisfied in any of the better earlier geoid models. Errors in previous gravity field models were the result of using data from multiple sources with varying accuracy and incomplete geographic coverage. Various portions of the earth have no gravity measurements and, if the satellite altimeter data is excluded, neither do major areas of the oceans.

[7] This deficiency is removed with the GRACE data. The data set collected by GRACE is global in coverage, homogeneous in distribution and of very high accuracy. For spatial scales as small as 200 km, the GRACE data used to develop the GGM01 model has improved our knowledge of the gravity model by an order of magnitude over the knowledge obtained using over 30 years of tracking to geodetic satellites such as those used in, for example, EGM96. When the geoid developed with the GGM01 model is compared with the geoid from EGM96, there are major differences over the polar regions and over mountainous land areas. Over the oceans, there are 20 cm level differences in the regions of the western boundary currents, the equatorial currents and the Artic Circumpolar Currents.

3. Results and Discussion

[8] The gravity field coefficients from the GGM01 model to degree and order 90 were used to compute a 1° gridded map of geoid height relative to the T/P reference ellipsoid. In order to compute the dynamic topography, a comparable gridded map of SSH from altimetry is also needed. We used a gridded mean sea surface (MSS) model computed from a combination of altimeter satellites, including the Geosat Geodetic and Exact Repeat Missions, ERS-1 and -2 (including 186-day repeat orbits), and TOPEX/POSEIDON [*Tapley and Kim*, 2000]. However, the spatial resolution of the MSS model is equivalent to degree/order 8640 (1/24°), compared to degree/order 90 for the geoid. The MSS therefore contains the geoid signal to degree/order 90, the geoid signal above degree/order 90, and the mean dynamic topography signal. Since the geoid signal above degree/order 90 can be of the order of several meters, especially around seamounts and trenches, one needs to smooth the MSS to a level comparable to the geoid before differencing the two, or the short-wavelength geoid signal will obscure any real topography signal.

[9] In this analysis, we have decomposed the MSS into spherical harmonics to degree/order 90, so as to be comparable to the GRACE geoid. We have found this is a better method of filtering than interpolating the high-resolution MSS to the grid points, then smoothing, because it is less sensitive to the locally large short-wavelength signals in the MSS. However, because the MSS is only defined over the ocean and between latitudes 82°S and 82°N, the missing grid values must be filled with a reasonable proxy in order to compute spherical harmonic coefficients. We have filled in the missing grids over land and poleward of 82° with the geoid computed from EGM96 to degree/order 360. The spherical harmonic coefficients of the MSS model were computed to degree/order 90 and then used to compute the heights at the same 1° grid locations as the GGM01 geoid. Then, the dynamic topography was computed by differencing the gridded values (MSS - geoid) and masking land based on a land/sea database. An identical procedure was used to create the results with the EGM96 geoid.

[10] In order to assess the improvement in topography and ocean circulation due to the GGM01 geoid, we compare the grids with a relative topography computed from data in the World Ocean Atlas 2001 (WOA01) [*Stephens et al.*, 2002] to 3000 m and 4000 m depth by *V. Zlotnicki* [personal communication, 2003]. The temperature and salinity data in this WOA01 are interpolated to a 1° grid using weighted averages where the weights (W_S) are

$$W_S = \exp\left[-4\left(\frac{r}{R_S}\right)^2\right], \quad (1)$$

r is the distance (in km) from the center of the grid for which the average is desired to the nth grid around it and R_S is the averaging radius. For WOA01, the interpolation was done as a 3-step iteration with R_S = 888 km, 666 km, and 444 km. In order that the topography maps from the altimetry and geoid models have comparable smoothness, we have applied the same weighted average (1), but with R_S = 555 km. This will also reduce short-wavelength variations that appear in the altimeter topography maps due to inconsistency between the MSS over the ocean and geoid model over land, as well as residual errors in some high degree/order GGM01 gravity field coefficients.

[11] We compute the zonal and meridional circulation from all the topography maps using forward-backward differences between adjacent grids and accounting for the change in the area of an equi-angle grid away from the equator. Values were computed except within ± 2° of the equator, where values are set to no data. The circulation for the WOA01 maps was first computed relative to 4000 m depth. If no value existed in a grid (because the ocean depth was less than 4000 m), the current from the 3000 m map was used, if available. Circulation maps are very useful to evaluate improvement, since small changes in the geoid can lead to significant changes in the circulation, especially in the tropics. Figure 1 shows the zonal velocities (based on the north-south gradient), while Figure 2 shows the meridional currents (based on the east-west gradient).

[12] The GRACE topography shows all major zonal geostrophic currents (Figure 1), especially those in the tropics. Qualitatively, the locations and magnitudes are very similar to those from the WOA01 maps. The EGM96 topography, however, shows no strong currents in the tropics, and a significantly weaker Kuroshio Extension and Gulf Stream. The ACC in the EGM96 map is also noticeably weaker than that in the GRACE map. The GRACE and Levitus meridional currents, albeit weaker, are also in good agreement. Both show similar drifts toward the equator in the central Pacific and Atlantic, and there are drifts toward the equator in the Indian Ocean and western Pacific. The northward flowing Kuroshio and Gulf Stream are evident in both the GRACE and Levitus maps. However, the GRACE map shows better detail closer to land due to the depth required for the WOA01 maps. Although the EGM96 topography shows similar drifts near the equator

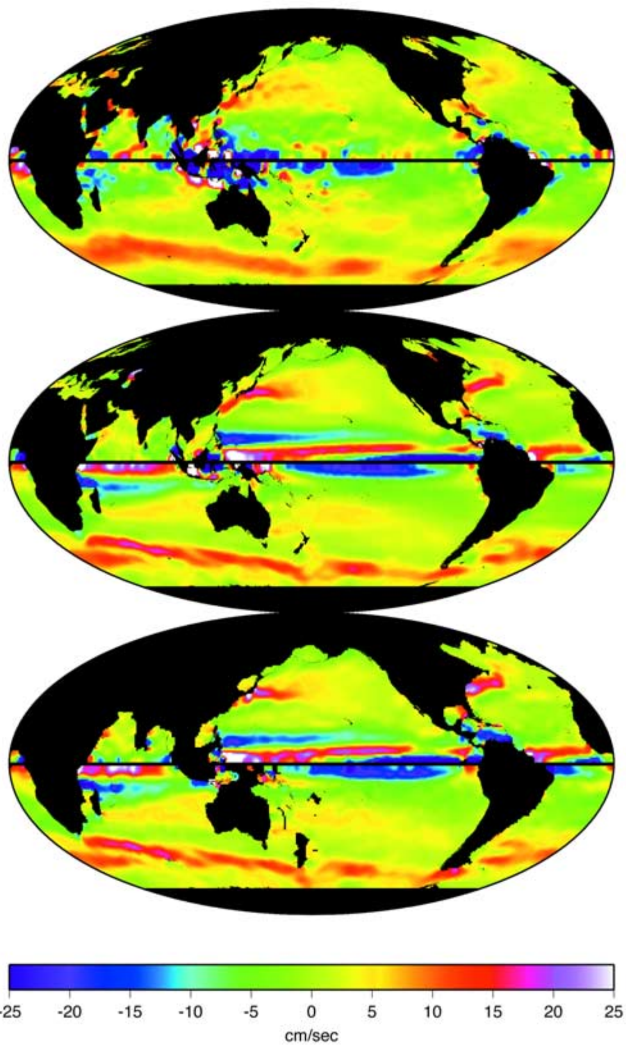

Figure 1. Zonal geostrophic currents determined from the EGM96 geoid (top), a preliminary GRACE geoid (middle), and from the WOA01 hydrographic data (3000–4000 m). Positive currents are toward the east.

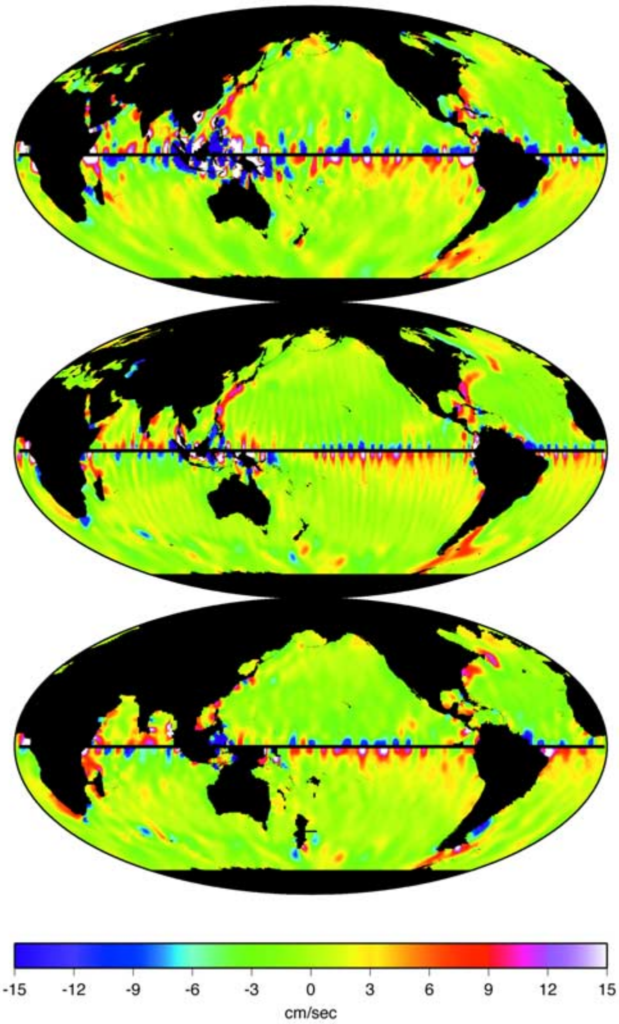

Figure 2. Meridional geostrophic currents determined from the EGM96 geoid (top), a preliminary GRACE geoid (middle), and from the WOA01 hydrographic data (3000–4000 m). Positive currents are toward the north.

and in the Kuroshio, it does not show the meridional motion of the Gulf Stream at all.

[13] Note that there are small, but noticeable vertical tracks in the meridional circulation computed relative to the GRACE geoid (Figure 2). Because of the polar orbit, near-sectorials at the higher degrees are not determined as strongly, and are thus more susceptible to systematic errors in the data and our models. This problem will be reduced when longer spans of GRACE data (greater than 111 days) are used in the computation, and can be reduced now by using a priori constraints on the higher degrees (i.e., from a Kaula power law) or the use of surface gravity information. However, in this report, we wanted to emphasize the results from a GRACE-only solution.

[14] Table 1 lists statistics of a comparison of the GRACE and EGM96 velocity maps with the WOA01 maps. The RMS of the difference between the WOA01 and GRACE maps is significantly lower than when the EGM96 geoid is used for both zonal and meridional currents. Note that the RMS of the total zonal currents using the GRACE geoid is 7.2 cm/sec, which is nearly as high as the RMS difference between EGM96 and WOA01. The RMS difference between the EGM96 and WOA01 maps is higher than the RMS of total meridional current (4.4 cm/sec). The correlation between the WOA01 and GRACE maps is also significantly higher than between the EGM96 and WOA01 maps.

4. Conclusions

[15] At wavelengths of 500 km and longer, the GRACE GGM01 Model produces a significantly better marine geoid

Table 1. Global Statistics of Difference in Velocity Maps Computed With Geoid Models and That Computed With WOA01 to 4000 m Depth

	zonal component			meridional component		
Model	mean	RMS	correlation	mean	RMS	correlation
EGM96	−0.22	6.97	0.45	−0.10	4.91	0.36
GGM01	0.03	2.61	0.93	0.04	3.25	0.48

(mean and RMS in cm/s).

than any previous model. This conclusion follows from evaluating the geostrophic currents determined by combining the model with a mean sea surface from altimetry. The agreement with currents computed from a traditional hydrographic map is very close, which suggests that one of the primary missions of the TOPEX/POSEIDON mission, to determine the absolute dynamic ocean topography, may soon be met.

[16] Because of the filtering necessary when using sparse data, global hydrographic maps will typically not have as fine a spatial resolution as one computed from altimetry and an eventual geoid based on GRACE tracking and surface gravity measurements. Thus, it may soon be possible to study geostrophic circulation on an even finer scale than has been possible with in situ measurements. By combining the absolute topography from altimetry and GRACE with in situ hydrographic data, oceanographers may also be able to map sub-surface currents on a global scale for the first time [e.g., WG80].

[17] The geoid model presented here is based on data available during the commissioning phase of GRACE, with varying degrees of accuracy. A complete re-processing of the data is underway. It is expected that this re-processing will lead to significant improvements over this initial model. The expected accuracy of final GRACE geoids is expected to be a few mm out to degree/order 70. However, the MSS is probably only accurate to a few cm at the same scale. Thus, the limiting factor in precisely determining absolute topography from space may once again be the altimetry measurement. Further research will be required to quantify this error and to reduce it in order to benefit completely from the anticipated accuracy of future GRACE geoids.

[18] **Acknowledgments.** The geoid model behind these results is the work of a large team of GRACE engineers and scientists - their achievement is gratefully acknowledged. GRACE is a joint partnership between the National Aeronautics and Space Administration (NASA) in the United States and the Deutsches Zentrum für Luft und Raumfahrt (DLR) in Germany. The Principal Investigator is from the University of Texas Center for Space Research (UTCSR) and the Co-Principal Investigator is from the GeoForschungsZentrum (GFZ). The Jet Propulsion Laboratory (JPL) has responsibility for the Project Management. The German Space Operations Center is responsible for operating the satellite. We would also like to thank V. Zlotnicki for many useful discussions related to calculating dynamic topography and geostrophic circulation, and for calculating the relative topography maps. This work was supported by NASA's Earth System Science Program.

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