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A comparison of model and GRACE estimates of the large-scale seasonal cycle in ocean bottom pressure

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[1] Seasonal variability in ocean bottom pressure p_b is analyzed using GRACE (Gravity Recovery and Climate Experiment) data products and an optimized model solution obtained by fitting most available ocean data in a least-squares sense. The annual cycle in the spatial mean is a substantial part of the observed seasonal p_b variability; net freshwater input and atmospheric pressure effects are both important. For the residual spatially-varying patterns, GRACE and model results agree well over the Southern Ocean where strongest variability at both annual and semiannual periods is present. Phase patterns tend to match well, although model amplitudes are generally weaker. Considerable uncertainty remains in both GRACE and model p_b fields, judging from the spread among available estimates. Improving the p_b estimates requires removal of data noise from aliasing and leakage of land hydrology signals, and further optimization of the ocean model, including possible use of GRACE data to constrain the solution. **Citation:** Ponte, R. M., K. J. Quinn, C. Wunsch, and P. Heimbach (2007), A comparison of model and GRACE estimates of the large-scale seasonal cycle in ocean bottom pressure, *Geophys. Res. Lett.*, *34*, L09603, doi:10.1029/2007GL029599.

1. Introduction

[2] Fluctuations in ocean bottom pressure (p_b) represent changes in the vertically integrated oceanic and atmospheric mass. These changes can result from horizontal mass redistribution associated with ocean currents, including bottom geostrophic flows themselves in balance with p_b gradients, or from net mass changes related to precipitation, evaporation and river runoff. Changes in the overlying atmospheric pressure can also affect p_b. Although knowledge of p_b is important for determining the variable ocean circulation and heat content, and for assessing freshwater transports between land and ocean and their role in sea level rise, global observations of p_b have been lacking. Partly for this reason, studies of large-scale p_b signals are rare in the oceanographic literature. *Gill and Niiler* [1973] derived an approximate equation for p_b and diagnosed the seasonal cycle in the North Atlantic and Pacific from wind stress estimates, and *Ponte* [1999] provided a first look at the seasonal p_b variability using a general circulation model (see also *Condi and Wunsch* [2004]). Most other studies are regional in scope and limited by the extremely sparse in situ p_b records (see discussion in *Ponte* [1999]).

[3] The launching of the Gravity Recovery and Climate Experiment (GRACE) mission in 2002 brought the capability to observe large-scale p_b signals globally at monthly intervals [*Tapley et al.*, 2004]. *Chambers et al.* [2004] found a good match between GRACE estimates of the seasonal cycle in total oceanic mass, and those obtained by differencing global mean sea level and steric height from altimetry and hydrography data, respectively. On basin scales, *Kanzow et al.* [2005] and *Bingham and Hughes* [2006] report good agreement between GRACE and model estimates of oceanic mass signals over the North Atlantic and North Pacific. However, on sub-basin scales, comparisons between GRACE and in situ p_b measurements have produced mixed results [*Kanzow et al.*, 2005; *Rietbroek et al.*, 2006], and matching GRACE observations and model predictions has been difficult [*Kanzow et al.*, 2005; *Bingham and Hughes*, 2006; *Rietbroek et al.*, 2006; *Chambers*, 2006a], with a mixture of data and model problems probably to blame.

[4] As part of the ECCO-GODAE (Estimating the Circulation and Climate of the Ocean-Global Ocean Data Assimilation Experiment) project [*Wunsch and Heimbach*, 2007], we have been combining most oceanic observations from 1992 to the present (2006; now ~100 million ocean data points) with a general circulation model to produce dynamically rigorous estimates of the oceanic state since 1992. One of the variables that can be estimated is p_b. At the same time, efforts to decrease noise levels in the GRACE data have continued [e.g., *Swenson and Wahr*, 2006] and *Chambers* [2006b] has recently produced GRACE fields particularly tailored for the study of p_b. Here we revisit *Ponte* [1999] and examine the seasonal cycle in p_b using the *Chambers* [2006b] dataset and ECCO estimates. Our intent is to check the consistency of the recent data and ECCO p_b estimates, particularly at sub-basin scales, assess the basic properties of the seasonal cycle in p_b including the relative importance of ocean currents vs. freshwater flux and atmospheric pressure effects, and discuss the prospects for improving our present capabilities to estimate large-scale p_b variability.

2. Data, Model, and Methodology

[5] We use GRACE gravity data over the oceans that have been processed by *Chambers* [2006b] and made available at the GRACE Tellus Web site (http://gracetellus.jpl.nasa.gov/month_ass.html). The atmospheric and (non-tidal) oceanic effects removed from the monthly GRACE solutions during processing have been restored in the fields used here. Analyses are based on the Release-03 dataset

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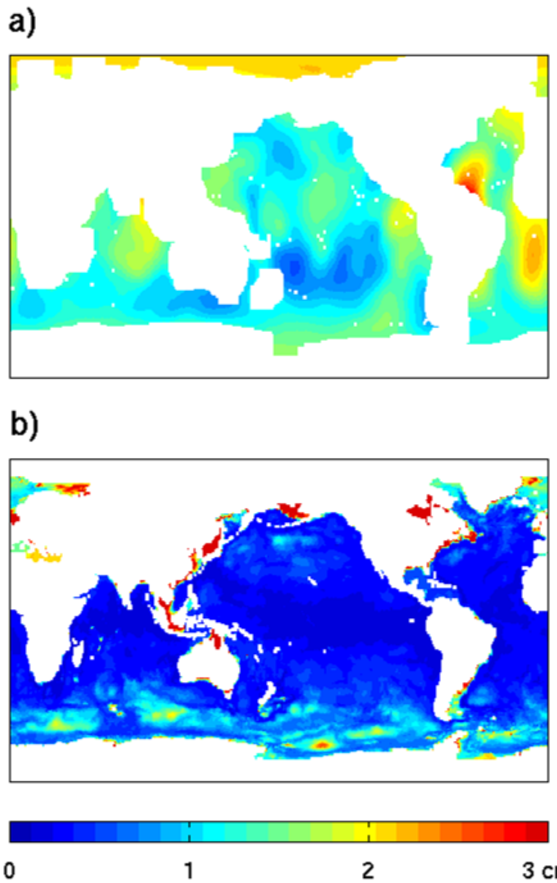

Figure 1. Root-mean-square difference between (a) GFZ and JPL series and (b) ECCO (version 3) p_b estimates and those calculated based on v2.199 for the period 2002–2004. All values given in cm.

from GFZ (GeoForschungsZentrum Potsdam) and the Release-02 dataset from JPL (Jet Propulsion Laboratory). These are monthly solutions available from January 2003 through 2006 for GFZ and from February 2003 to November 2005 for JPL, with the months of June 2003, January 2004, and July–October 2004 missing. *Chambers* [2006b] used a version of the filter proposed by *Swenson and Wahr* [2006] to smooth the short wavelength errors and remove the north-south stripes that appear in unfiltered GRACE gravity grids. The fields produced are equivalent water thickness values on a 1° × 1° grid and are given at various degrees of spatial smoothing. To minimize the noise, we use grids with the largest smoothing radius (750 km); an approximate upper bound for the optimal averaging radius for ocean GRACE fields suggested by *King et al.* [2006] is 2000 km.

[6] Model p_b estimates are from the ECCO optimization products described by *Wunsch and Heimbach* [2007]. The ECCO solutions are continuously evolving, and different versions, each consisting of many iterations, are archived for study. For this work, we use a recently obtained experimental (version 3) solution that extends from 1992 to the end of 2005. For comparison, we also use another solution from version 2, iteration 199 (v2.199 for short), which extends to December 2004 only. Some of the changes introduced in the version 3 solution include the use of a thermodynamic sea-ice model and background forcing fields based on atmospheric state variables (wind speed, specific humidity, air temperature, etc.) instead of flux estimates.

[7] The present ECCO model uses the Boussinesq approximation. To avoid known spurious effects of such approximations on p_b, as discussed by *Ponte* [1999], we calculate the spatial mean of p_b over the model domain and remove it at each grid point. The changes in global mean oceanic mass resulting from net freshwater input ($\overline{\mathcal{F}}$) are calculated directly from the freshwater flux forcing fields, which are adjusted together with other forcing fields and initial conditions as part of the least-squares optimization procedure. For comparison with the ECCO estimate, we also estimate $\overline{\mathcal{F}}$ using the land hydrology model of *Rodell et al.* [2004], available through July 2005.

[8] The ECCO model also does not currently include atmospheric pressure forcing. At monthly and longer scales, however, the oceanic response to pressure loading is approximately isostatic, and the resulting p_b signals are spatially constant and equivalent to the net change in air mass over the global oceans [*Ponte*, 1999]. Thus, the mean surface atmospheric pressure over the ocean ($\overline{P_a}$) is calculated from the reanalysis fields discussed by *Kanamitsu et al.* [2002] and added to the ECCO p_b estimates.

[9] All analyses are done using monthly fields that have had a trend removed (mean + slope) where the trend has been calculated as part of a simultaneous trend + annual + semiannual fit at each grid point over the 28 monthly fields common to all datasets for the period February 2002–November 2005. Each GRACE monthly mean is based on a different number of days, depending on data availability. No effort is made to have an exact match between model and data periods represented in the monthly means, as such differences are expected to be at the noise level of both series.

3. Results

[10] As a crude lower bound measure of uncertainty in the p_b estimates, the root-mean-square (RMS) difference between GFZ and JPL series and between two different ECCO estimates are shown in Figure 1. Model differences are <1 cm over most of the oceans, reaching values of 1–2 cm in the Southern Ocean; higher values occur in shallow regions, but these are not considered in the current analyses. Agreement between JPL and GFZ products is best in the Pacific and worst in the Atlantic, with RMS values ~1 cm and ~2 cm, respectively. Both series are based on the same ranging data and on similar background models [*Chambers*, 2006b]. Thus, their discrepancies result mostly from the different processing algorithms, suggesting disparate errors. Averaging JPL and GFZ series can remove some noise [*Chambers*, 2006b], but we carry each series separately in the analyses to further assess their differences.

[11] Figure 2 examines the variability in the spatial mean of p_b. Net freshwater exchanges with land have been shown [e.g., *Chambers et al.*, 2004] to cause a sizable annual cycle in average p_b. The effects of $\overline{P_a}$, estimated in Figure 2, are equally important and amount to a water mass equivalent peak-to-peak annual oscillation of ~1 cm. (Changes in $\overline{P_a}$ result mostly from the seasonal shift of air mass between

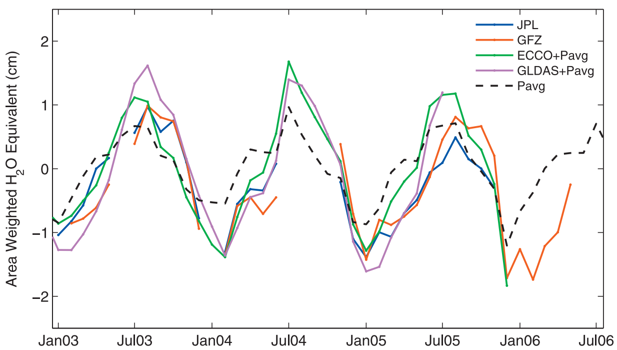

Figure 2. Monthly time series of the area integral of the JPL and GFZ GRACE fields in equivalent cm of water, and two estimates of the average p_b change over the oceans based on the sum of $\overline{P_a}$ from reanalysis fields of *Kanamitsu et al.* [2002] and the net freshwater input from either the ECCO flux fields or the model of *Rodell et al.* [2004]. Variability in $\overline{P_a}$ (dashed line) is a considerable part of the total p_b change.

land and ocean, with contributions from the net change in atmospheric water vapor amounting to ∼0.3cm [*Trenberth and Smith*, 2005].) The average p_b based on the sum of $\overline{P_a}$ and the ECCO estimate of $\overline{\mathcal{F}}$ shows an annual cycle of ∼2 cm peak-to-peak and maximum in boreal summer, which is very similar to the observed annual cycle in the spatial mean of the GRACE data (Figure 2). The correlation between ECCO and both GRACE series is >0.8 and comparable to those obtained using an $\overline{\mathcal{F}}$ estimate from the hydrology model of *Rodell et al.* [2004], also shown in Figure 2.

[12] Superposed on the annual net mass variability, there are large (basin) scale p_b anomalies that arise from ocean dynamic signals and related mass redistribution within the ocean. In what follows, we remove the spatial mean from the GRACE data and concentrate on comparisons of the spatially varying, dynamically relevant p_b signals in both data and ECCO solution.

[13] The annual cycle in ECCO, shown in Figure 3, has amplitudes ∼1 cm, and a large-scale phase structure, with strongest variability along the Southern Ocean and in western parts of most oceanic basins. Results are similar to those of *Gill and Niiler* [1973], *Ponte* [1999], and *Condi and Wunsch* [2004]. The annual variability is generally weak compared to the uncertainties suggested in Figure 1. For most regions, agreement between ECCO and GRACE is only qualitative. GRACE series have amplitudes substantially larger, but do tend to show enhanced variability in most regions indicated by the model (e.g., Southern Ocean). In addition, the zonally-banded, broad phase structure in the Pacific and Southern oceans is similar for the most part. Analysis of the semiannual cycle, also shown in Figure 3, yields similar results, although GRACE and ECCO amplitudes are generally more comparable. There are regions of

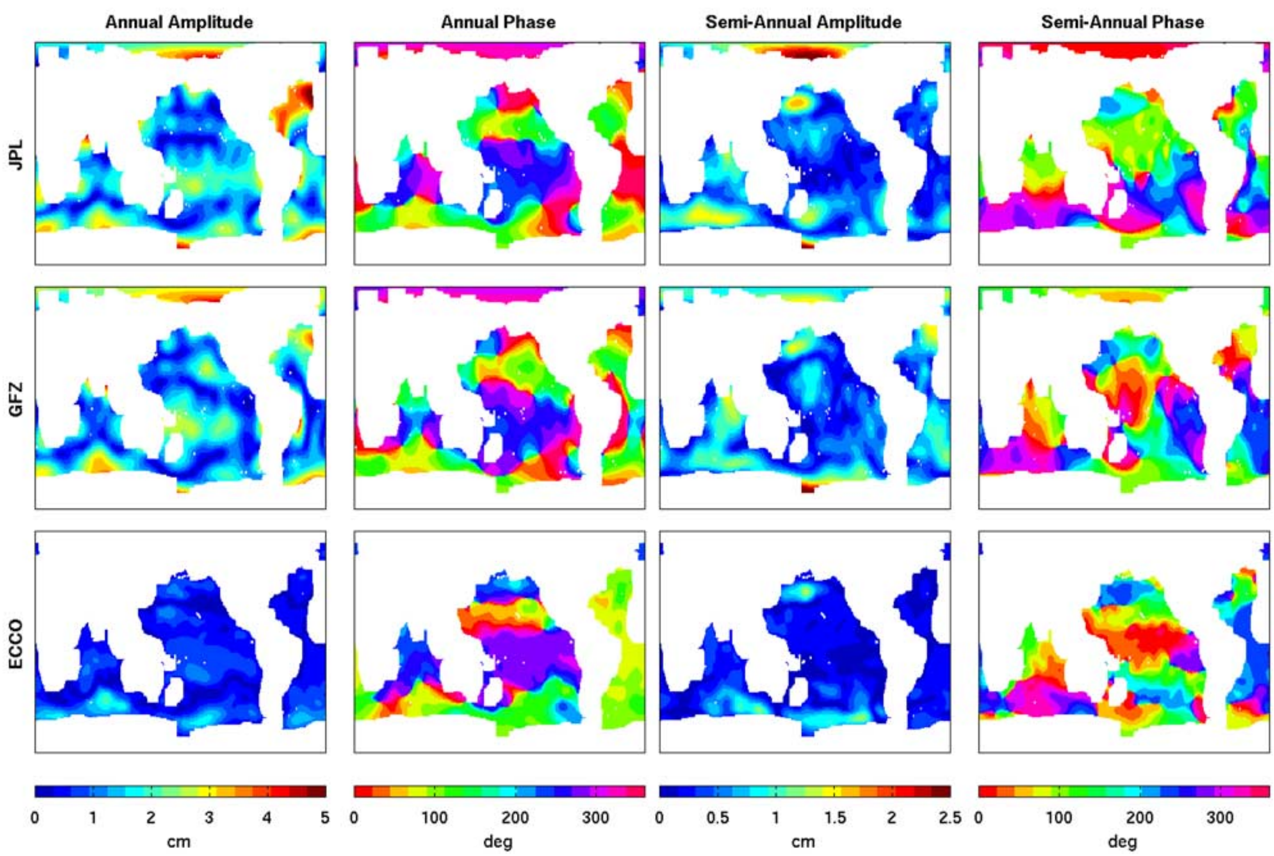

Figure 3. Amplitude A (cm) and phase θ (degrees) of the annual and semiannual cycle for JPL, GFZ, and ECCO series, calculated as $A \sin(\omega t + \theta)$ where ω is the frequency and $t = 0$ at January 1. Spatial means have been removed from all fields.

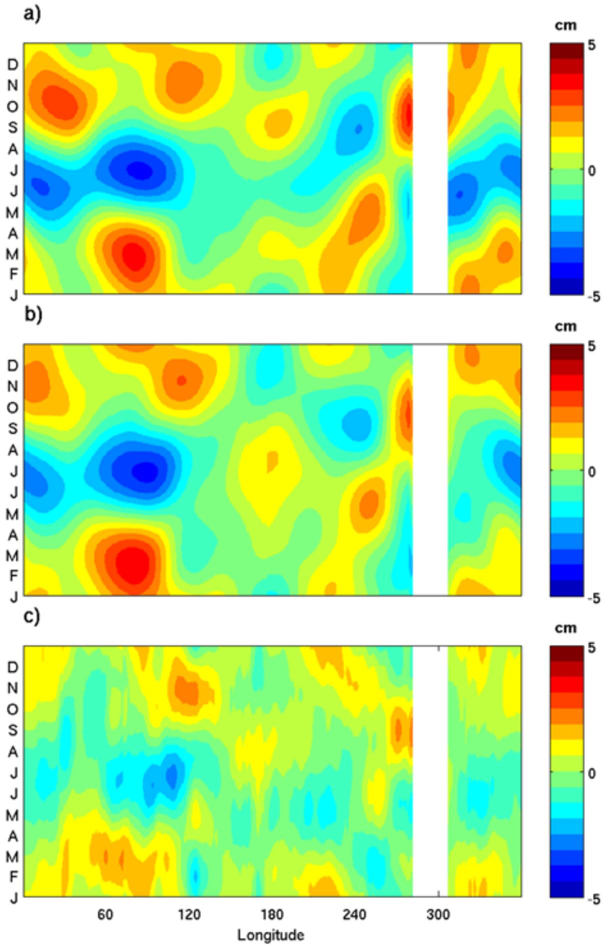

Figure 4. Longitude-time plot of the seasonal (annual + semiannual) cycle for (a) JPL, (b) GFZ, and (c) ECCO series averaged over 50°S–60°S latitude. Spatial and time means have been removed from all fields. ECCO series are plotted at full 1° resolution, to indicate some of the details that can be lost when using smoothing over 750 km, as with the GRACE data.

enhanced amplitudes in the data (e.g., tropical Indian Ocean) that are absent in ECCO. However, in regions of strongest modeled semiannual amplitudes (southwest of Australia, Pacific sector of the Southern Ocean, and the northwest corner of the North Pacific), GRACE shows qualitatively similar amplitudes and phase structure.

[14] From the ECCO estimates in Figure 3, the largest expected seasonal p_b variability occurs in the Southern Ocean and in the North Pacific. The latter basin has been considered in some detail by *Bingham and Hughes* [2006] and we focus here on seasonal p_b fluctuations in the Southern Ocean. The combined annual and semiannual variability from averages over 50°S–60°S is shown in Figure 4 as a function of longitude for GFZ, JPL and ECCO series. Apart from ECCO amplitudes being generally weaker than those inferred from GRACE, most longitudes show good agreement between the seasonal evolution of p_b field in ECCO and data. The correlations between ECCO and the GFZ and JPL patterns in Figure 4 are 0.69 and 0.63, respectively (compared to 0.89 for GFZ/JPL pair). One can begin to see the tendency for zonal coherence of the seasonal cycle over large sectors of the Southern Ocean, with minimum p_b in the JJA season, and the important mixture of annual and semiannual cycles in the Indian sector (50°E–100°E), which also shows the largest variability at these latitudes.

4. Concluding Remarks

[15] From the joint analysis of GRACE data and ECCO p_b estimates, the annual net mass change (~1 cm) emerges as a significant contributor to the seasonal p_b variability in many deep ocean regions, and in fact comparable to the effects of mass redistribution within the ocean (cf. Figures 2 and 3). Both $\overline{\mathcal{F}}$ and $\overline{P_a}$ effects are important. Note that, apart from possible self-gravitation effects, the surface loading by freshwater and atmospheric pressure results in truly spatially-constant p_b signals of amplitude $\overline{P_a} + \overline{\mathcal{F}}$ over the global ocean, because at the seasonal timescale the oceanic response to such loading is approximately isostatic [*Ponte*, 2006]. The good agreement between GRACE and ECCO series in Figure 2 suggests that such signals, of little dynamic relevance, can be effectively estimated and removed from local p_b records if needed.

[16] The spatially varying, dynamically relevant p_b signals have typical amplitudes of order 1 cm at scales of several thousand kilometers. With the possible exception of the North Pacific results by *Bingham and Hughes* [2006], finding agreement between p_b estimates at sub-basin scales from ocean models and GRACE data has been difficult. The good correlation between the seasonal evolution of p_b features in the ECCO and GRACE estimates found for the Southern Ocean is, thus, quite encouraging, and consistent with the findings of *Rietbroek et al.* [2006] on the ability of GRACE to measure p_b signals in the Crozet-Kerguelen region based on comparisons with in situ p_b data. The results in Figure 4 suggest that constraining ECCO solutions with the information provided by GRACE, at least on seasonal timescales and on the largest spatial scales, might be beneficial in places like the Southern Ocean. Most efficient use of the data, however, requires a good understanding of the data and model uncertainties.

[17] Preliminary estimates of errors in GRACE data have been discussed [*Wahr et al.*, 2006]. Two factors affecting the quality of the data over the ocean are the leakage of land hydrology signals, particularly at the annual period, and the aliasing of unresolved rapid p_b fluctuations. Both of these effects can contribute to the observed tendency for larger variability in the GRACE data relative to the ECCO estimates. Leakage at semi-annual period should be less of a problem, and we note that discrepancies between ECCO and GRACE amplitudes are stronger for annual than for semi-annual period. Tide dealiasing procedures can cause typical errors of 1 cm over most of the oceans [*Ray and Luthcke*, 2006], and similar errors may be involved in the use of non-tidal dealiasing schemes [*Kanzow et al.*, 2005]. Such errors are of the same magnitude of the expected seasonal fluctuations in p_b over many ocean regions. Removal of land signals, either using models or GRACE data inversions, and improving the dealiasing models, might be especially useful. There are, however, indications that GRACE instrument noise might still dom-

inate [e.g., *Ray and Luthcke*, 2006] and that ultimately one will need to address those hardware limitations.

[18] Errors in the ECCO solutions, which are not trivial to estimate [*Wunsch and Heimbach*, 2007], can result from incomplete knowledge of the forcing fields and initial conditions or model deficiencies (missing physics, inadequate spatial resolution, inaccurate topography, etc.). Results from *Losch et al.* [2004] indicate that the Boussinesq and hydrostatic approximations, used in the ECCO and most other ocean models, can induce millimeter to centimeter level errors in p_b. Similar errors arise in approximations made to the equation of state [*Dewar et al.*, 1998], and a long list of other errors contributing at the same level could probably be made, including inherent numerical noise [*Losch et al.*, 2004]. While model developments will certainly continue, one powerful tool for error mitigation is the optimization procedure used in the ECCO solutions analyzed here. In this regard, continuing improvements in the ECCO p_b estimates are also expected, as more data is included and further iterations are able to reduce the misfits to the data.

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