Large-scale mass redistribution in the oceans, 1993–2001

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[1] A recent study of satellite laser ranging measurements by *Cox and Chao* [2002] indicates that large-scale mass redistribution has caused a rapid change in Earth's dynamic oblateness (J2) since 1998. Using satellite altimeter observations and two runs of an ocean general circulation models (OGCM), we examine mass variations in the oceans and their estimated effect on J2. Combined altimeter and OGCM results indicate variations similar to the J2 changes in 1998, and predict considerably larger oceanic effects on the J2 anomaly than purely OGCM estimates, suggesting that the oceans should not be ruled out by any means as a significant source of this interesting geodetic anomaly, until they have been studied further. *INDEX TERMS:* 1214 Geodesy and Gravity: Geopotential theory and determination; 1223 Geodesy and Gravity: Ocean/Earth/atmosphere interactions (3339); 1227 Geodesy and Gravity: Planetary geodesy and gravity (5420, 5714, 6019); 4283 Oceanography: General: Water masses; 4556 Oceanography: Physical: Sea level variations; *KEYWORDS:* Gravity, OGCM, SLR, Altimeter, J2. **Citation:** Chen, J. L., C. R. Wilson, X. G. Hu, and B. D. Tapley, Large-scale mass redistribution in the oceans, 1993–2001, *Geophys. Res. Lett.*, *30*(20), 2024, doi:10.1029/2003GL018048, 2003.

1. Introduction

[2] Satellite laser ranging (SLR) has been successful in measuring temporal variations in low degree spherical harmonic components of the Earth gravity field, [e.g., *Yoder et al.*, 1983; *Rubincam*, 1984; *Cheng et al.*, 1997]. Changes in the degree 2 zonal variation (J2), Earth's dynamic oblateness, are believed to be well determined from SLR, and show variability over a broad range of periods. Previous studies have confirmed a J2 decrease at a rate of -2.5 to -3×10^{-11} per year [e.g., *Yoder et al.*, 1983; *Rubincam*, 1984; *Cheng et al.*, 1997; *Devoti et al.*, 2001]. This decrease is understood to be primarily controlled by post-glacial rebound (PGR), plus secondary effects from climatic changes [e.g., *Rubincam*, 1984; *Mitrovica and Peltier*, 1993].

[3] A recent study by *Cox and Chao* [2002] shows that the secular decrease in J2 reversed around 1998, roughly coincident with the 1997/1998 El Nino event, but lasting much longer. *Cox and Chao* [2002] examined possible error sources including data analysis methods and the 9.6- and 18.6-year in-phase tide model, but concluded that the reversal was real. Given the rapid time scale of the reversal, mass redistributions within the atmosphere, ocean, continental water cycle, or snow/ice sheets are the most likely causes. *Cox and Chao* [2002] demonstrated, using National Center for Environmental Prediction (NCEP) reanalysis data, that the atmosphere is apparently not the main cause. Therefore, the oceans, continental water storage, and snow/ice sheets remain the likely candidates.

[4] *Dickey et al.* [2002] estimated oceanic effects on J2 using the data-assimilating ocean general circulation model (OGCM) [*Fukumori et al.*, 2000], developed at NASA's Jet Propulsion Laboratory (JPL), a partner in the Estimating the Circulation and Climate of the Ocean (ECCO) program. This model is denoted as ECCO1 in this study. Their results based on ECCO1 suggest that the oceans account for only a fraction (about 1/3) of the observed J2 anomaly. They suggested, instead, that recent acceleration in subpolar glacial melting was likely to be a more important cause of the J2 anomaly. Others [e.g., *Nerem et al.*, 2002; and *Chao et al.*, 2002] have also estimated oceanic effects using ECCO1.

[5] In this study, we estimate mass redistribution within the oceans by combining OGCM and satellite radar altimetry observations. We compute ocean bottom pressure (OBP) change and predict oceanic effects on J2 using sea surface height (SSH) anomaly observations from the TOPEX/Poseidon (T/P) satellite radar altimeter. These are used in combination with OGCM (ECCO) predictions of steric SSH changes (i.e., the SSH changes that do not alter OBP). We employ both a more recent computation from ECCO1, and a separate calculation (called ECCO2) that does not assimilate altimeter data. The main objective is to re-examine oceanic effects on the J2 anomaly using different approaches and model runs and to understand to what extend we could quantify oceanic mass changes of these spatial and temporal scales from current data resources.

2. Data and Models

2.1. The ECCO Models

[6] The ECCO OGCM is based on the parallel version of the Massachusetts Institute of Technology (MIT) general circulation model [*Fukumori et al.*, 2000]. The model coverage is nearly global ($-79.5°$S to $78.5°$N) with a telescoping meridional grid at a 1/3-degree resolution in the tropics ($-20°$S to $20°$N), gradually increasing to 1-degree resolution away from the equator. The resolution in longitude is 1 degree. There are 46 vertical levels with 10 m resolution within 150 m of the surface. The model is forced by NCEP reanalysis products (12-hourly wind stress, daily heat and fresh water fluxes) with time-means replaced by those of the Comprehensive Ocean-Atmosphere Data Set (COADS). Temperature and salinity at the model sea surface are relaxed towards observed values. Model fields are available at 10-day intervals (as 10-day averages). SSH and OBP are also available as instantaneous values every 12 hours.

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[7] ECCO1 is driven by wind and surface heat fluxes, and assimilates SSH anomaly observations from T/P, but ECCO2 is driven only by winds and surface heat fluxes. ECCO1 and ECCO2 10-day averaged temperature (T) and salinity (S), from January 1993 to November 2002, are used to compute steric SSH (SSH_{steric}) change (The 1993 data of ECCO1 are replaced by an earlier run (kf038a) because of irregular jumps in T and S data). To calculate OBP change, proportional to ocean mass redistribution, SSH_{steric} is subtracted from SSH. We use either model calculations of SSH, or observed (T/P) SSH. At a given grid point (latitude φ, longitude λ, time t), OBP change represents the integral of mass change in the water column and can be approximately treated as mass load change, $q(\varphi, \lambda, t)$. Therefore, fluctuations in J2, called ΔJ2, can be computed as [e.g., *Chao et al.*, 1987],

$$\Delta J2 = -\frac{\left(1 + k_2'\right) \cdot R_e^2}{\sqrt{5} \cdot M_e} \int q(\varphi, \lambda, t) \cdot P_2(\sin\varphi) \cdot ds \qquad (1)$$

in which, R_e and M_e are the Earth's mean radius and mass; k_2' is degree 2 load Love number (-0.31); $P_2(\sin\varphi)$ is the degree 2 associated Legendre polynomial; and ds is the surface area element.

[8] Both ECCO1 and ECCO2 have applied the Boussinesq approximation to conserve the total ocean volume (for mathematical convenience). This will result in artificial changes of total mass of the oceans unrelated to any real oceanographic effect. To correct this, we explicitly force ECCO1 and ECCO2 to conserve mass by removing the geographical mean of OBP at each time step [*Greatbatch*, 1994]. However, this correction is not required for T/P derived OBP change because T/P measures real sea level change, which includes mass changes caused by water exchange between the oceans and other parts of the Earth system [e.g., *Chen et al.*, 1998; *Minster et al.*, 1999].

2.2. OBP Computation from T/P Observations

[9] T/P SSH changes include two effects, SSH_{steric} changes caused by density variation, that do not alter OBP, and mass flux effects, that directly affect OBP. SSH_{steric} change could be as large as observed SSH change and could even show a negative phase, depending on temporal and spatial scales [e.g., *Chen et al.*, 2000]. Therefore, the steric effects must be removed from T/P SSH data. OBP variations can be represented as $\Delta OBP = g{\cdot}\rho_0{\cdot}(SSH - SSH_{steric})$, where

$$SSH_{steric} = -\frac{1}{\rho_0} \cdot \int_{-h}^{0} \Delta\rho \cdot dz \qquad (2)$$

in which ρ_0 is the mean density of sea water (1.028 g/cm^3), and $\Delta\rho$ the density change as a function of T, S, and pressure (P). The integral is from the ocean bottom to the surface (h = 0). Atmospheric pressure loading over the ocean is treated separately through an inverted barometer (IB) assumption (see 2.3).

[10] Based on equation 2, we compute SSH_{steric} using T, S, P (at model layer depths) from ECCO1 and ECCO2. SSH_{steric} results are then combined with T/P altimeter SSH observations to estimate OBP variations. T/P SSH data are from the JPL World Ocean Circulation Experiment (WOCE), in which the IB correction has been applied using NCEP surface pressure data (for details, see http://podaac.jpl.nasa.gov/woce). We form four estimates of OBP change and associated ΔJ2 using the combinations, T/P + ECCO1, T/P + ECCO2, ECCO1 alone, and ECCO2 alone.

2.3. SLR J2 Observations and Atmospheric Effects

[11] J2 variations determined from SLR observations were provided by the NASA/GSFC group, as published by *Cox and Chao* [2002]. The J2 time series spans February 1979 to January 2002. We interpolated earlier values to form a uniform J2 series at 30-day intervals. Atmospheric contributions to J2 were computed from NCEP reanalysis daily atmospheric surface pressure fields, in a manner similar to that of *Cox and Chao* [2002]. Atmospheric IB correction is applied, in a consistent way as used in T/P SSH data (i.e., spatial average of barometric pressure over the oceans is applied to all ocean areas). Averaged at 30-days time intervals, the predicted atmospheric effect is subtracted from the J2 series. We further remove the estimated PGR trend, -2.8×10^{-11} [*Cox and Chao*, 2002] from the time series. The residual (in Figure 1a) represents non-atmospheric, non-tidal, and non-PGR contributions, including oceanic, hydrological, and other effects.

3. Results

[12] Figure 1a shows the 4 estimated oceanic contributions to ΔJ2: T/P + ECCO1 (green curve), T/P + ECCO2 (blue curve), ECCO1 alone (red curve), and ECCO2 alone (cyan curve). The residual ΔJ2 from SLR is in black. Seasonal variability in ΔJ2 is not well-accounted for by any of the 4 predictions, although the predictions is generally in phase with the observed. Seasonal variation in ΔJ2 may be dominated by effects of water storage changes on land that are not considered in the four predictions. Longer period variations in all four estimates follow the general pattern of the ΔJ2 anomaly that begins around 1997/1998. To clarify this, we remove annual and semiannual signals from all time series by a least square fit, and then smooth the residuals with a sliding 6-month window. We refer to these smoothed series as 'non-seasonal' and show them in Figure 1b.

[13] Figure 1b shows that the two estimates T/P + ECCO1 and T/P + ECCO2 predict significantly larger oceanic effects (green and blue curves) than the two estimates from ECCO1 alone or from ECCO2 alone. T/P + ECCO1 accounts for over half the observed J2 anomaly (since 1997/1998), while T/P + ECCO2 predicts a ΔJ2 larger than observed. In contrast, ECCO1 accounts for about 1/3 of the observed anomaly, consistent with the earlier results of *Dickey et al.* [2002]. The ECCO2 prediction shows a smaller anomaly. In addition, T/P + ECCO1 and T/P + ECCO2 show better agreement with J2 observations in the period between 1993–1997, relative to predictions based on ECCO1 or ECCO2 alone.

[14] We now consider a few key questions. Why does the use of T/P SSH with ECCO1 steric SSH predict a significant change in ΔJ2 given that ECCO1 also assimilates T/P data? Why does the combination of T/P and ECCO2 predict such a large effect? To address these questions prompted by

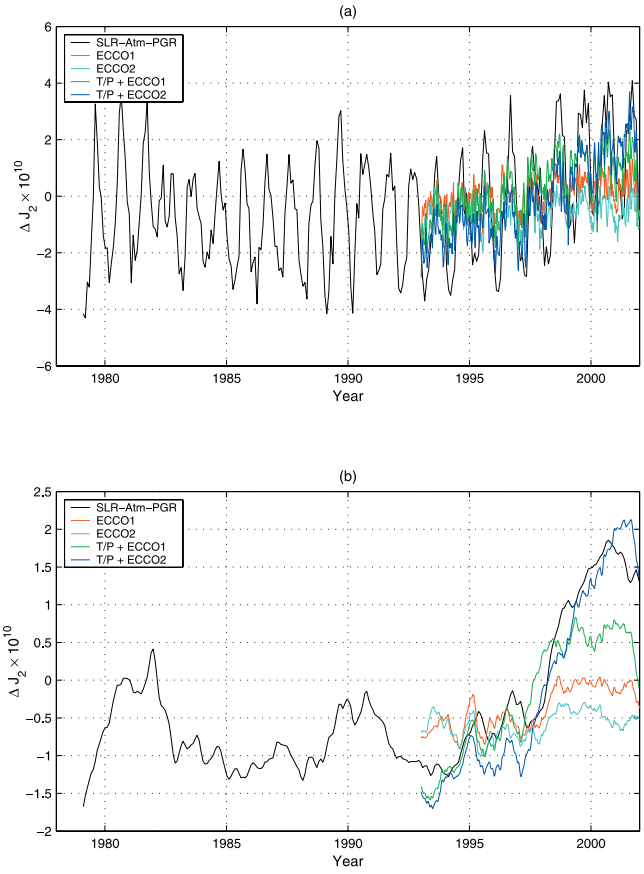

Figure 1. (a) Oceanic contribution to ΔJ2 computed from T/P + ECCO1 (green), T/P + ECCO2 (blue), ECCO1 (red), ECCO2 (cyan), and ΔJ2 residuals (black) = ΔJ2 SLR-Atmosphere-PGR. (b) Comparison of non-seasonal oceanic contributions – seasonal subtracted smoothed time series from (a).

Figure 1b, we show in Figure 2 non-seasonal time series of separate contributions from SSH and SSH_{steric}. Figure 2 shows SSH effects from T/P (green curve), ECCO1 (black curve), and ECCO2 (cyan curve). The dashed curves are SSH_{steric} effects from ECCO1 (red curve) and ECCO2 (blue curve).

[15] T/P SSH observations differ greatly from ECCO2 SSH, as might be expected considering that ECCO2 has not assimilated T/P data. However, T/P SSH does differ from ECCO1 SSH, despite the fact that ECCO1 had assimilated the T/P SSH data. Clearly, the larger J2 effect from combining T/P SSH with ECCO1 or ECCO2 is due to the difference between T/P observed SSH and calculated SSH (either ECCO1 or ECCO2). For ECCO1 SSH and ECCO2 SSH, there is a clear correlation with SSH_{steric} change, consistent with simple hydrostatic equilibrium. ECCO2 predicts a considerably larger decrease of steric effect around 1998 than ECCO1. This explains the significantly larger J2 effect from T/P + ECCO2 than that from T/P + ECCO1.

[16] In addition, Figure 2 shows that the assimilation of T/P data does greatly improve SSH estimates when compared with T/P observation and pure simulation, though large discrepancies still exist at non-seasonal time scales. At seasonal or shorter time scales, both ECCO1 and ECCO2 agree well with T/P observations (Figure 1a). Detailed examination and discussion of improvements from assimilating T/P data are beyond the scope of this study.

4. Discussion

[17] We cannot prove that the estimates T/P + ECCO1 or T/P + ECCO2 are superior to those derived from ECCO1 or ECCO2 alone. However, we claim that these estimates are still physically plausible. While beyond the scope of this paper, it is possible to verify the model derived density data in certain regions, in which reasonable number of Expendable Bathythermograph (XBT) observations are available. Thus, our main conclusion is that the oceans should not be ruled out by any means as a significant source of this interesting geodetic anomaly anomaly, until they have been studied further. Of course only one (or none!) is closer to truth than others, but the insight provided by the comparison in this study is important, and provocative, as these differences point right to the heart of the attempts to explain the J2 anomaly.

[18] The observed J2 anomaly began near the time of 1997/1998 El Nino, but persisted far beyond the period usually identified as an El Nino event. This geodetic evidence suggests that mass redistribution triggered by El Nino may persist longer than the recognized climate and sea surface temperature effects. *Chao et al.* [2002] reported evidences that such phenomenon occurred in the extra-tropic Pacific basins. Density changes in the deep ocean, with presumably long relaxation time scales, would be consistent with this observation.

[19] It is feasible to combine the model density estimates with T/P SSH data. OBP is proportional to the non-steric SSH change, the difference between two quantities (SSH and SSH_{steric}) that tend to be comparable in size, and temporally correlated, as noted above. This magnifies the effects of errors in contaminating the estimates. This is one of the main reasons that current OGCMs might reasonably capture SSH and steric SSH changes, but probably not OBP

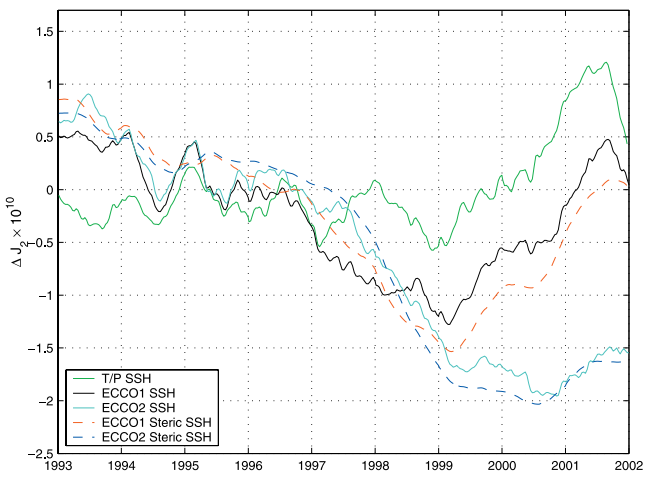

Figure 2. Non-seasonal oceanic effects on J2 change from T/P SSH (green), ECCO1 SSH (black), ECCO2 SSH (cyan), ECCO1 steric SSH (red dashed), and ECCO2 steric SSH (blue dashed).

(or non-steric SSH) change. The OBP estimates are relatively less accurate than either SSH and steric SSH change. There are presently no independent observations of SSH_{steric} on a global basis. Poor sampling of temperature and salinity observations over the volume of the global oceans thus requires OGCM calculations as a proxy for SSH_{steric}.

[20] A recent study by *Chen et al.* [2003] also demonstrated that the combination of model derived density change and T/P SSH data could be a useful and successful approach to study large scale oceanic mass changes. *Chen et al.* [2003] shows that oceanic excitations computed from T/P SSH and model density data agree reasonably better with polar motion observations (when atmospheric effects are removed) than those from the ECCO1 model OBP data alone, although ECCO1 shows considerable improvements in modeling large scale mass variations than previous OGCMs.

[21] Many factors could affect the estimates of oceanic effects on $\Delta J2$, which include the expected large errors in T and S from the model, in particular at deep layers, the errors in T/P observations, the non-global coverage of both ECCO models and T/P measurements, the lack of dynamic coherence between T/P SSH and ECCO T and S data, and the conventional mass conservation adjustments (considering the non-global coverage of ECCO models). A full treatment of the global water cycle (land, oceans, and atmosphere) would be desirable.

[22] Some other factors could also contribute to the observed J2 anomaly, including land hydrological change, snow/ice change over Antarctica and Greenland, subpolar glacial melting [e.g., *Dickey et al.*, 2002], and the ways to treat atmospheric IB effects [e.g., *Nerem et al.*, 2002]. It's interesting to notice that both the ECCO models and T/P altimeter predictions show early signs of the fall back of the J2 anomaly in early 2002, which is consistent with SLR observations [*Chao et al.*, 2002]. This could be an indication that the observed J2 anomaly is part of an interannual or decadal change and is likely driven by changes in the ocean and land hydrology. A more comprehensive assessment of oceanic mass variations and effects on $\Delta J2$ and other geodetic variables can be expected from future advanced OGCMs assimilating satellite gravity measurements, such as those from the Gravity Recovery and Climate Experiment.

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