Comparison of Oceanographic Signals with SLR-Derived Gravity Observations

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1 Introduction

The recent results of Cox and Chao (2002) identified a significant departure from the otherwise linear post-glacial rebound (PGR) dominated drift in the Earth's J_2 zonal harmonic. That study considered a number of potential causes, however it was not possible to firmly identify the source of the change. That analysis included Satellite Laser Ranging (SLR) data from a total of 10 different satellites, covering the period from 1979 up to 2002. That data series has since been extended through May of 2002. Figure 1 shows the complete data series. With the exception of the additional data in 2002, it is similar to Figure 2 of Cox and Chao (2002). In addition to the J_2 zonal, time series for J_3 was also estimated. The J_3 zonal, which describes north-south mass distribution does not show any significant anomalies corresponding to the timing of the J_2 event. Provided this result is accurate, it implies that whatever is causing the J_2 anomaly is symmetric around the Equator. So far the most consistent explanation is for an oceanic cause, which will be further investigated here. Further considerations about the other potential causes are also provided below.

2 Possible Causes

Several possible causes for the J_2 anomaly have been investigated, including the cryosphere, atmosphere, reservoirs, core, and oceans. A reasonable first guess as to the cause is accelerated melting of ice mass. The melt water must be transported from the high latitude regions to the equator to produce an effect such as the J_2 anomaly. As a hypothetical example of the magnitude of the event, Greenland would have to shed about 400 Gt of ice mass annually, with a net *additional* global sea level (GSL) rate of >1 mm/yr. However, Greenland and West Antarctica radar altimeter derived ice height changes for the 1992–1998 period show an equivalent GSL change of –0.22 mm/yr for Greenland, and –0.08 mm/yr for West Antarctica (based on preliminary results provided by J. Zwally and described in Zwally and Brenner, 2001). The green curve in Figure 1 shows the implied J_2 change caused by the ice height changes in Greenland and West Antarctica. East Antarctica, while generally considered to be in mass balance, is an unknown, but it would need to contribute ~1–2 mm/yr to GSL, depending on the scenario. Using relations based on the Meier (1984) estimates, mountain glaciers have a smaller effect on J_2 per unit mass than Greenland. The mass loss required to explain the observed J_2 changes would result a sea level contribution of ~2 mm/yr over the pre-1998 rate. All of these accelerated ice melt scenarios require huge GSL changes that simply have not been seen in the TOPEX/POSEIDON (T/P) GSL data. If the ice melt is going into the oceans, it must be accompanied by a significant cooling event in order to conserve GSL. Also, there is the remote possibility that the residual melt water is accumulating on land. In any case, the turn around of the J_2 anomaly in 2001 implies an ice mass accumulation.

The atmospheric gravity correction applied to the data in Figure 1 was computed from the monthly NCEP reanalysis pressure grids assuming a two-dimensional approximation. While the atmosphere explains a good portion of the variation from the monthly to annual periods, it does not explain the anomaly. Consideration has also been given to the effects of the two-dimensional assumptions. In this case the maximum difference between the two-dimensional and three-dimensional computations amounts to ~0.5x10^{-10} change in the annual amplitude, with no significant effect on the interannual variation.

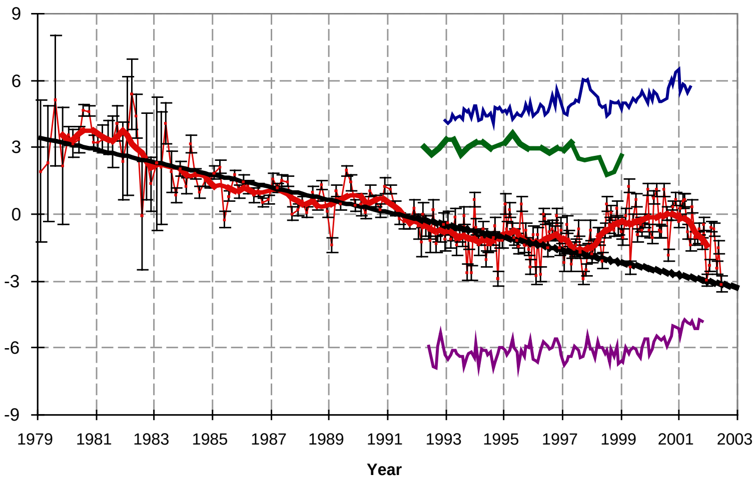


Fig. 1 Observed ΔJ_2, after subtraction of the IB corrected atmospheric signal and an empirical annual term, before (thin red line with error bars) and after an annual filter has been applied (heavy red line). Error bars are the observed J_2, uncertainties. The heavy black line is a weighted fit to the (unfiltered) pre-1997 data. The slope is –2.8x10^{-11} year^{-1}. The offset green line (second from top) is the J_2 implied by the Greenland + W. Antarctic ice heights derived from ERS-1/2 altimetry data. Also shown are the J_2 implied by the T/P uniform GSL change (blue, offset, top), and that considering the geographic distribution of the sea height changes (purple, offset, bottom). Neither sea height derived estimate includes steric effects. Sampling intervals are 90-days in 1979, 60-days from 1980 through 1991, and 30-day afterwards. No detrending of rates has been performed. Units are 10^{-10}. (For a colour version of this Figure see http://www.iers.org/iers/publications/tn/tn30/.)

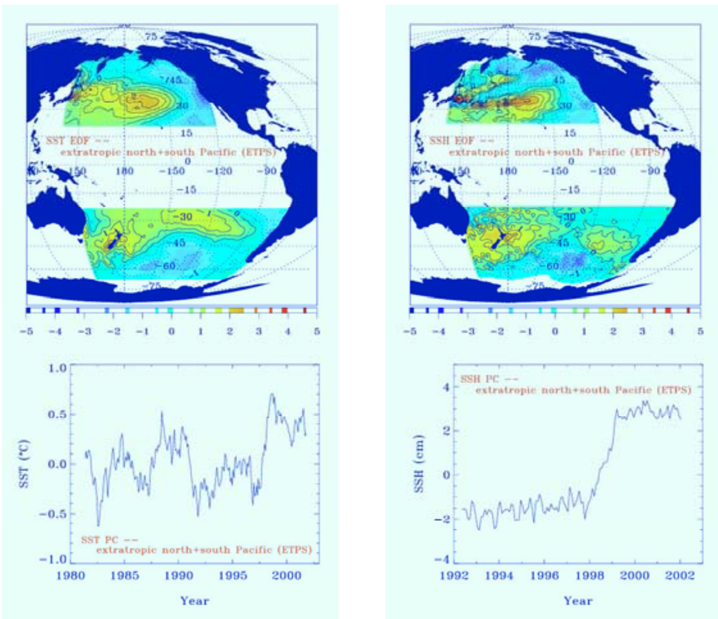
Terrestrial water impoundment is another possible factor. Large dams can individually cause a jump of ~0.2x10^{-10} in J_2, however, the cumulative effect since 1998 is far too small to explain the observed J_2 changes (Chao, 1995). Regrettably there is insufficient reliable data at the moment to make any assessment about the role of hydrology.

Changes in the Earth's mantle – specifically post-glacial rebound – result in the largest known interannual variation in the low degree gravity field. Such changes in the mantle occur over very long time constants due to the viscosities involved, so a mantle-originating cause for the post 1998 J_2 changes is unlikely. A more dynamic source of solid Earth variation is the core, which has generally been assumed to not be a contributor to gravity field changes. W. Kuang, (now at NASA GSFC, private communication, 2002), reviewed his geodynamo models and found that under some assumptions rates as large as ~0.5–1.0x10^{-11} per year are possible. While the core signal may be larger than previously assumed, it still does not explain the J_2 anomaly.

3 The Contribution of the Ocean

The timing of the J_2 anomaly onset corresponds to the last big El Niño event, raising the possibility of an oceanographic cause. If the T/P sea surface height (SSH) data is treated as being entirely caused by mass redistribution, the implied change in J_2 is consistent with the SLR results, if not a close match. A large uncertainty exists when interpreting the mass redistribution implications of the SSH data, because thermally driven changes in sea level have no gravity signal. Figure 2 shows the primary mode of an EOF/PC analysis of the Seas Surface Temperature (SST) and T/P SSH for the extratropic regions of the Pacific. Both the SST and SSH modes show a change around 1998. A breakdown of the SSH analysis for each region (not shown) indicates that the Northern pacific is the dominant contributor. The SST mode corresponds to the Pacific Decadal Oscillation (PDO), which is correlated with the observed J_2 data (Cazenave and Nerem, 2002). The implied gravity change associated with the SSH mode is several times too small to explain the observed change in J_2, but it is symmetric about the Equator, satisfying the J_3 constraint.

EOF/PC analyses of the assimilation mode output of the ECCO consortium ocean model (Stammer et al., 1999) yields similar results to those based on the observed SST and SSH data. Figures 3 and 4 show the EOF/PC analyses for the North and South Pacific, respectively. Despite the more abrupt jump in SSH seen in the Northern Pacific, the biggest jump in ocean bottom pressure occurs in the Southern Pacific. A break down of the temperature and salinity data along parallels traversing the northern and southern regions gives some indication as to the cause of this difference in behavior. While the North and South Pacific regions had similar behavior in terms of temperature and SSH, there was a significant difference in the salinity modes. This illustrates the need for care when making mass inferences based on SST and SSH data alone.



(a) (b)

Fig. 2 Primary modes of EOF/PC analyses of the (a) Sea Surface Temperature and (b) Sea Surface Height for the extratropic regions of the Pacific Ocean. The SST data series runs from 1980 through 2001, while the SSH series begins in 1992.

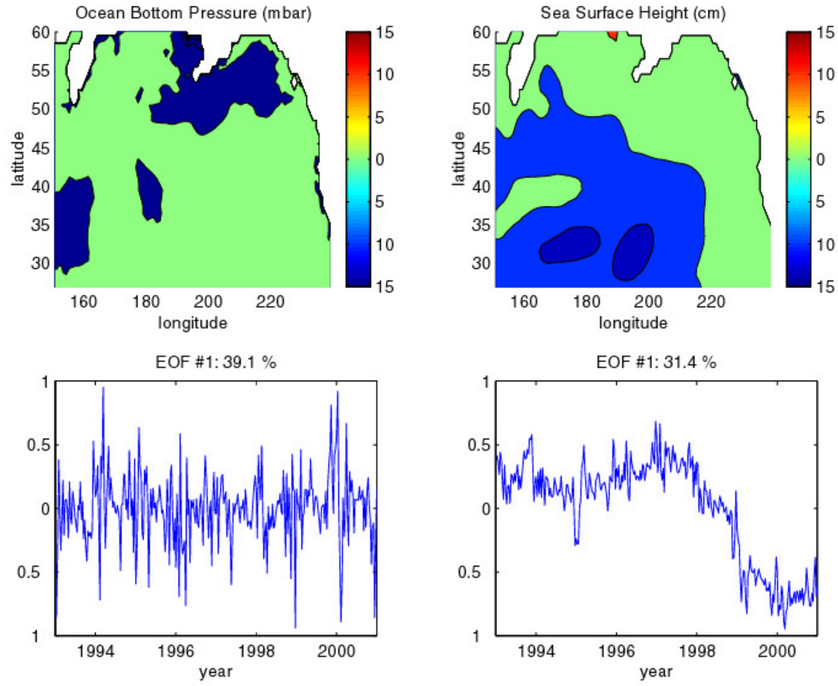


Fig. 3 Principle EOF modes for the ocean bottom pressure and sea surface height from the ECCO assimilation model for the North Pacific

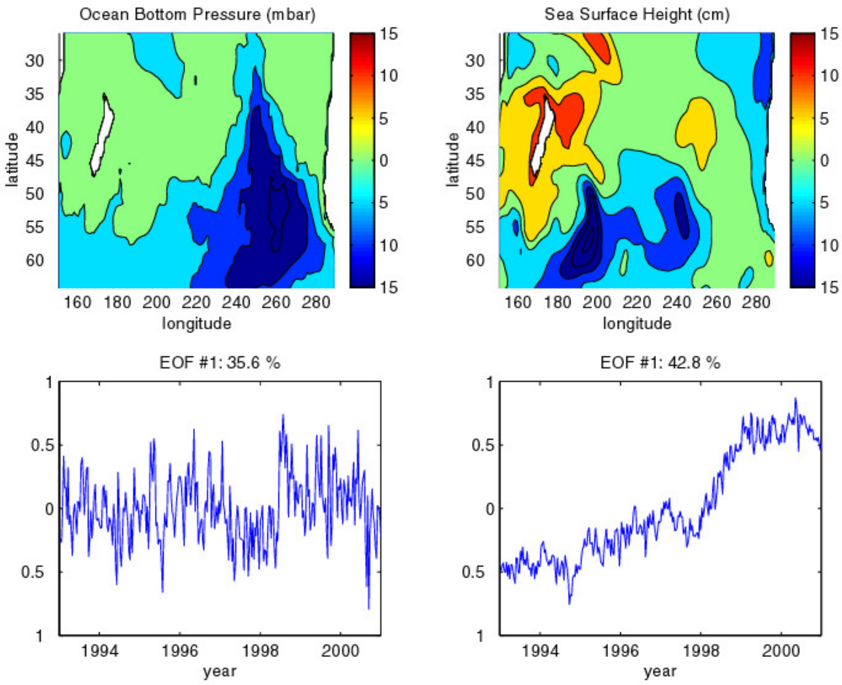


Fig. 4 Principle EOF modes for the ocean bottom pressure and sea surface height from the ECCO assimilation model for the South Pacific

Similar analyses have also been performed for the Indian Ocean, North Atlantic, and South Atlantic. The dominant contributor of the five regions to J_2 is the primary mode for the Southern Pacific, with some small change in slope or offset occurring in the rest of the regions. The net jump in J_2 predicted by the ECCO assimilation model is ~$0.7x10^{-10}$, or only about 25% of the observed anomaly. The correspondence between both the observational SSH and SST data and the ECCO model modes with the J_2 anomaly, as well as the correlation with PDO, supports the hypothesis that the ocean is a major contributor. However, some other source of mass redistribution (possibly driven or related to the ocean changes), or a more accurate accounting, is required to fully explain the anomaly. One early point of concern is the lack of coverage in the arctic sea for both the ECCO model and the radar altimetry data types.

4 Conclusions

First, a large anomaly in J_2 began sometime around 1998, and has persisted until the present time. There are indications that J_2 is returning to the nominal values and long-term trend dictated by post-glacial rebound. Consequently, the deviation may be interannual in nature, and therefore does not necessarily represent a departure from the long-term trend. Ice melting scenarios large enough to explain this deviation produce a large GSL change, which simply has not been observed. Likewise, the apparent recent turn in J_2 would then imply a recent accumulation of ice mass, which, while not impossible, is unlikely.

There is evidence that some component of the cause of the J_2 anomaly lies within the oceans. The timing corresponds to changes in the primary EOF modes for the SST and SSH in the extra-tropic regions. The primary SST EOF mode corresponds to PDO, which is generally correlated with the J_2 series. The timing also corresponds to changes primary EOF modes of the ECCO model bottom pressure. Analysis of that model's output shows that the most influential region is the Southern Pacific, but some effects are also seen in the other regions. However, the ECCO model bottom pressure data can only explain about 25% of the observed magnitude of the J_2 change. Nonetheless, the good overall agreement in the timing and nature of the event with the ocean activity warrants more detailed analysis of the ocean's role.

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