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Hydrological and oceanic excitations to polar motion and length-of-day variation

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SUMMARY

Water mass redistributions in the global hydrosphere, including continental water storage change and non-steric sea level change, introduce variations in the hydrological angular momentum (HAM) and the oceanic angular momentum (OAM). Under the conservation of angular momentum, HAM and OAM variations are significant excitation sources of the Earth rotational variations at a wide range of timescales. In this paper, we estimate HAM and OAM variations and their excitations to polar motion and length-of-day variation using soil moisture and snow estimates and non-steric sea level change determined by TOPEX/Poseidon satellite radar altimeter observations and a simplified steric sea level change model. The results are compared with the variations of polar motion and LOD that are not accounted for by the atmosphere. This study indicates that seasonal continental water storage change provides significant contributions to both polar motion and LOD variation, especially to polar motion X, and the non-steric sea level change is responsible for a major part of the remaining excitations at both seasonal scale and high frequencies, particularly in polar motion Y and LOD. The good correlation between OAM contributions and the remaining excitations shows that large-scale non-tidal mass variation exists in the oceans and can be detected by TOPEX/Poseidon altimeter observations.

Key words: length of day (LOD), ocean, polar motion, TOPEX/Poseidon, water.

1 INTRODUCTION

The Earth's rotation varies slightly with time both in its magnitude and in the orientation of its axis. The magnitude of rotational rate change is conveniently measured by length-of-day (LOD) variation. The orientation of the Earth's rotational axis with respect to the terrestrial reference frame is known as polar motion. The variable rotation of the solid Earth is introduced and maintained by mass redistribution and movement within the earth system, which includes the atmosphere, ocean, hydrosphere/cryosphere and solid earth. The observed polar motion and LOD variation reflects angular momentum variation of the solid earth. Under the conservation of angular momentum of the Earth's system, polar motion and LOD provide important information of mass and angular momentum exchange of the solid Earth with geophysical fluids.

Atmospheric angular momentum (AAM) variations have been demonstrated to be the dominant excitation source for LOD variations and a major excitation for polar motion in a broad frequency band (e.g. Barnes *et al.* 1983; Eubanks *et al.* 1988; Chao & Au 1991; Hide & Dickey 1991). In particular, zonal wind variations in atmospheric general circulation are responsible for about 80–90 per cent of observed LOD variability, indicating a strong dynamical coupling between the atmosphere and the solid Earth (Hide & Dickey 1991). Additional variabilities in polar motion and LOD arise from variations in hydrological angular momentum (HAM) and oceanic angular momentum (OAM).

The determination of HAM and OAM variations is relatively difficult due to inadequate observational data and our lack of knowledge about the hydrosphere (including the cryosphere) and the oceans. Continental water storage variation and its excitation to polar motion are traditionally estimated using precipitation, evapotranspiration and surface run-off based on sparse climatological observations and empirical formulations. Some studies (Van Hylckama 1970; Hinnov & Wilson 1987; Lei & Gao 1992) based on traditional data have indicated that seasonal continental water storage change could provide a significant contribution to polar motion. However, other studies (Chao & O'Connor 1988a; Kuehne & Wilson 1991) came to a different conclusion: continental water storage change plays only a rather minor role in polar motion excitation. A definitive conclusion is not yet available.

Similarly, the role of the oceans in polar motion and LOD excitation is not well understood, mainly due to the difficulties in modelling mass redistribution over the oceans. A few recent studies (Ponte 1990; Johnson 1998; Marcus *et al.* 1998) based on the ocean general circulation models have shown that the oceans may play an important role in accounting for the remaining LOD variation (after the AAM effects of winds and pressure are removed). These studies rely on ocean models, which have very few observational data as input. Here we use an alternative approach by applying different data types (e.g. satellite radar altimeter data) to support this conclusion.

The rapid development of climatological and hydrological assimilation systems has provided new opportunities to investigate HAM variations using assimilated hydrological variables in a global coherent hydrological system. In this study, we will apply a different approach to estimate continental water storage change and corresponding HAM excitation to polar motion and LOD variation using soil moisture and snow accumulation data from the NCEP/NCAR Climate Data Assimilation System I (CDAS-1) (Kalnay *et al.* 1996). The TOPEX/Poseidon (T/P) satellite radar altimeter has been providing global measurements of sea level change every 10 days for over six years with unprecedented accuracy. The T/P-measured sea level change provides a new means to investigate mass redistribution within the oceans. The potential OAM variation due to non-steric sea level change will be estimated by combining T/P sea level anomaly measurements with a steric model based on the climatological ocean temperature model in the World Ocean Atlas 1994 (WOA94) (Levitus & Boyer 1994). We will only focus on the mass-induced HAM and OAM variations. The motion terms, that is, those due to river flow and ocean current, are neglected, mainly because (1) we do not have adequate data to quantify the river flow effects, and these effects are generally believed to be relatively small, and (2) we use T/P altimeter sea surface anomalies to estimate oceanic contributions; these cannot be applied to compute ocean current excitations directly, and the current effects are also relatively small compared to the mass contribution (Ponte 1990; Johnson 1998).

The estimated HAM and OAM variations are then compared with the remaining variabilities in polar motion (X, Y) and LOD after removing the AAM contribution estimated from the NASA GEOS-1 assimilated atmosphere model (Schubert *et al.* 1993). We will discuss possible error sources that may affect this estimation and further improvements needed to better our understanding of the HAM and OAM variations and their role in the global angular momentum budget.

The Earth rotational variation is conventionally expressed as (Munk & MacDonald 1960; Lambeck 1980)

$$\frac{1}{\sigma_c}\dot{\mathbf{m}}+\mathbf{m}=\boldsymbol{\psi},$$

$$m_3=-\psi_3, \tag{1}$$

where $\mathbf{m}=X-i\cdot Y$ is a complex polar motion vector (the negative sign comes from the left-handed coordinate system used in polar motions X and Y), $\sigma_c=2\pi F_c(1+i/2Q)$, F_c is the Chandler frequency (about 0.843 cycle yr^{-1}), $1/Q$ is the associated dissipation factor (Q is the quality factor determined by the Earth's physical properties), $m_3=\Delta\mathrm{LOD}$ per 24 hr, and $\boldsymbol{\psi}=\psi_1+i\cdot\psi_2$ and ψ_3 are the so-called polar motion and LOD excitations. A discrete version of eq. (1) developed by Wilson (1985) will be applied to compute the observed excitations from X, Y and LOD time-series.

The excitations due to surface mass load variations from continental water storage or non-steric sea level changes can be evaluated by

$$\boldsymbol{\psi}=\frac{-1.00R_e^4}{C-A}\int\Delta L(\phi,\lambda)\sin\phi\cos^2\phi\,e^{i\lambda}d\phi d\lambda,$$

$$\psi_3=\frac{0.70R_e^4}{C}\int\Delta L(\phi,\lambda)\cos^3\phi d\phi d\lambda \tag{2}$$

(Barnes *et al.* 1983), where ϕ and λ are latitude and longitude, respectively, $\Delta L(\phi,\lambda)=L(\phi,\lambda)-\bar{L}(\phi,\lambda)$ is the mass load variation as a function of time (in units of mass per unit area) with respect to the mean over time, R_e is the Earth's mean radius, and C and A are the Earth's axial and equatorial moments of inertia [at seasonal scales, we use C and A for the mantle instead of the whole Earth (Barnes *et al.* 1983)]. The key unknown to be evaluated is ΔL. The elastic deformational effects are included in eq. (2), represented by the two numerical factors 1.00 and 0.70 (Barnes *et al.* 1983).

2 DATA AND MODELS

2.1 Hydrological model

CDAS-1 is a near-real-time climate model running from January 1958 to the present. It provides monthly diagnostic and intrinsic fields for surface and pressure level climatological and hydrological parameters (Kalnay *et al.* 1996). The soil moisture and water-equivalent snow accumulation fields used in this study are from CDAS-1 monthly diagnostic fields with a Gaussian scheme grid of 1.875° in longitude (even) and about 1.905° in latitude (uneven). The soil moisture fields include two layers. The first layer includes the top 10 cm of soil, and the second layer is from 10 to 200 cm depth. The soil water content is represented by volumetric fraction. Snow water variations are directly measured by water-equivalent snow accumulations (in units of g cm^{-2}). Continental water storage changes ($\Delta L_{\mathrm{water}}$) are then computed by adding soil water (layers $1+2$) and snow water variations:

$$\Delta L_{\mathrm{water}}=\Delta L_{\mathrm{soil}}+\Delta L_{\mathrm{snow}}, \tag{3}$$

where $\Delta L_{\mathrm{soil}}(\phi,\lambda,t)=\Sigma\,\Delta\eta_i(\phi,\lambda,t)h_i\rho_o$ $(i=1, 2)$ is the water mass load change due to soil moisture variations, $\Delta\eta_i(\phi,\lambda,t)=\eta_i(\phi,\lambda,t)-\bar{\eta}_i(\phi,\lambda,t)$ is the soil moisture change of layer i with respect to the mean (in units of volumetric fraction), h_i is the depth of layer i ($h_1=10$ cm, $h_2=190$ cm) and $\rho_o=1$ g cm^{-3} is the density of water. $\Delta L_{\mathrm{snow}}(\phi,\lambda,t)=\Delta N(\phi,\lambda,t)$ is the mass load changes due to snow variations, and $\Delta N(\phi,\lambda,t)=N(\phi,\lambda,t)-\bar{N}(\phi,\lambda,t)$ is the snow water changes with respect to the mean (in units of g cm^{-2}).

The CDAS-1 soil moisture and snow variations are from model analysis without any *in situ* observations as constraints (H. L. Pan 1998, personal communication), so the results could be quite biased from the real changes in some regions. For example, the snow depth in the Antarctic is set to be a constant during the model run, which is apparently not the case in reality. Another major uncertainty is the soil water below 200 cm depth (including ground water), which is not included in this computation.

2.2 Non-steric sea level change

The T/P data used in this research include cycles 2 to 168, which span the period October 1992 to April 1997. Mass load variations are estimated from sea level anomalies using the T/P Merged Geophysical Data Record B (MGDR-B) with all media, instrument and geophysical corrections (Callahan 1993), including ionosphere delay, wet and dry troposphere delay, electromagnetic bias, tides and a standard inverted barometer (IB) response (that is, assuming a constant reference mean pressure). Several changes have been made to update models and correct errors. The original GDR orbits have been replaced with those computed using the JGM-3 gravity field model (Tapley *et al.* 1996), the diurnal/semi-diurnal ocean tide model has been replaced with the UT/CSR 3.0 model (Eanes & Bettadapur 1995), and an error in the pole tide has been corrected in the new MGDR-B data. Sea level anomalies, which are deviations from a 4 yr mean surface, are computed by interpolating the data to a fixed grid and then removing the mean sea surface height. The sea surface anomalies are then averaged into a uniform $1^\circ \times 1^\circ$ grid for each cycle.

Observed sea level anomalies include two parts: steric and non-steric sea level change. The steric sea level change is due to density variation, which is caused by temperature and salinity variations but is dominated by thermal effects at large spatial scales. The remaining signals after the steric effects have been removed are assumed to be due to mass redistribution within the oceans and water exchange between the oceans, atmosphere and hydrosphere. The steric sea surface height estimate is from a simplified steric model (Chen *et al.* 1998, 2000), which is derived from the top 14 layers (0–500 m depth) of the climatological mean 3-D ocean temperature field in WOA94. Due to inadequate salinity data on a global basis and the relatively minor role of the salinity contribution to large- (continental) scale steric sea level change, salinity effects are neglected in this simplified model. The WOA94 climatological data represent the seasonal temperature variations in the tropical and subtropical regions fairly well, especially in the Northern Hemisphere. However, due to the sparse data samples in the Southern Hemisphere, especially in regions south of 40°, the WOA94 data will be less accurate.

Mass load variations within oceans are thus computed by removing steric sea level changes from T/P observations, i.e.

$$\Delta L_{\mathrm{ocean}} = (\Delta H_{\mathrm{T/P}} - \Delta H_{\mathrm{steric}})\rho_{\mathrm{sw}}\,, \tag{4}$$

where $\Delta L_{\mathrm{ocean}}(\phi, \lambda, t)$ is the oceanic mass load at the grid-point (ϕ, λ) and time t, $\Delta H_{\mathrm{T/P}}(\phi, \lambda, t)$ is the observed sea level change from the T/P altimeter, $\Delta H_{\mathrm{steric}}(\phi, \lambda, t)$ is the steric sea level change estimated from WOA94 (Chen *et al.* 1999) and $\rho_{\mathrm{sw}} = 1.03$ g cm^{-3} is the mean density of sea water.

2.3 Polar motion, LOD and AAM series

Polar motion (X, Y) and LOD time-series used in this study are from SPACE95 (Gross 1996), a combined solution of X, Y and LOD variations from space geodetic observations, including Very Long Baseline Interferometry, Satellite Laser Ranging, the Global Positioning System and the Lunar Laser Ranging based upon a Kalman Earth Orientation Filter (Eubanks 1988). The data cover the period 1976 to 1995 at daily intervals. The excitations of polar motion and LOD variation are derived from eq. (1) and are shown in Fig. 1. The mean and trend are removed from the time-series.

The AAM excitations to polar motion and LOD are computed using surface pressure and wind variations from the NASA GEOS-1 assimilated atmospheric model (Schubert *et al.* 1993). The model ran from March 1980 to May 1995 with a 6-hourly time interval. An IB correction similar to that used in the T/P data, that is, assuming a constant reference pressure over the oceans, was applied to the atmospheric surface pressure data. As long as we apply the same IB model to both the atmosphere and the oceans, we should not see notable differences in the total contribution of the atmosphere and oceans (for each component the results will certainly be different). The AAM contributions are shown in Fig. 1 superimposed on observed excitations derived from SPACE95 X, Y and LOD time-series. Clearly, the AAM plays a dominant role in LOD variation (see Fig. 1c), and provides significant contributions to polar motion, especially the Y component (see Fig. 1b). This is a well-studied conclusion from past studies; here, we simply subtract AAM excitations from observations, and focus on the remaining variations in terms of hydrological and oceanic contributions. Since the upper layer of the GEOS-1 atmospheric model only covers up to 10 hPa, the missing portion (i.e. 10–0 hPa) may introduce some errors in the residuals, especially to LOD due to the strong winds in the upper layers.

3 RESULT AND COMPARI/SON

Hydrological excitations in terms of HAM due to continental water storage change, including soil moisture and snow water variation, are computed using eqs (2) and (3). The results are shown in Fig. 2 superimposed by the remaining non-atmospheric polar motion and LOD variations not accounted for by the atmosphere after AAM effects have been removed. A significant portion of both polar motion (X, Y) and LOD excitations remains unexplained (see Fig. 2). Continental water storage change derived from soil moisture and snow data introduce strong seasonal (annual and semi-annual) excitations to polar motion (X, Y) and LOD. The HAM excitation accounts for much of the remaining seasonal variability in X, although in Y and LOD the phase seems to be opposite. The large seasonal excitations estimated from the model are comparable in magnitude to those of the observed mass associated polar motion and LOD excitations, suggesting that polar motion and LOD observations can provide observational constraints on large-scale mass budgets within the Earth system.

Fig. 3 shows the OAM contributions, that is, the oceanic excitations to polar motion and LOD estimated from non-steric sea level change using T/P observations and the WOA94 steric model (eqs 3 and 6), together with the remaining excitations after both the AAM and the HAM contributions have been removed. At seasonal scales, OAM is less important in X and Y (Figs 3a and b) but appears to be in surprisingly good agreement with LOD residuals in both amplitude and phase (Fig. 3c) after the AAM and HAM excitations have been removed.

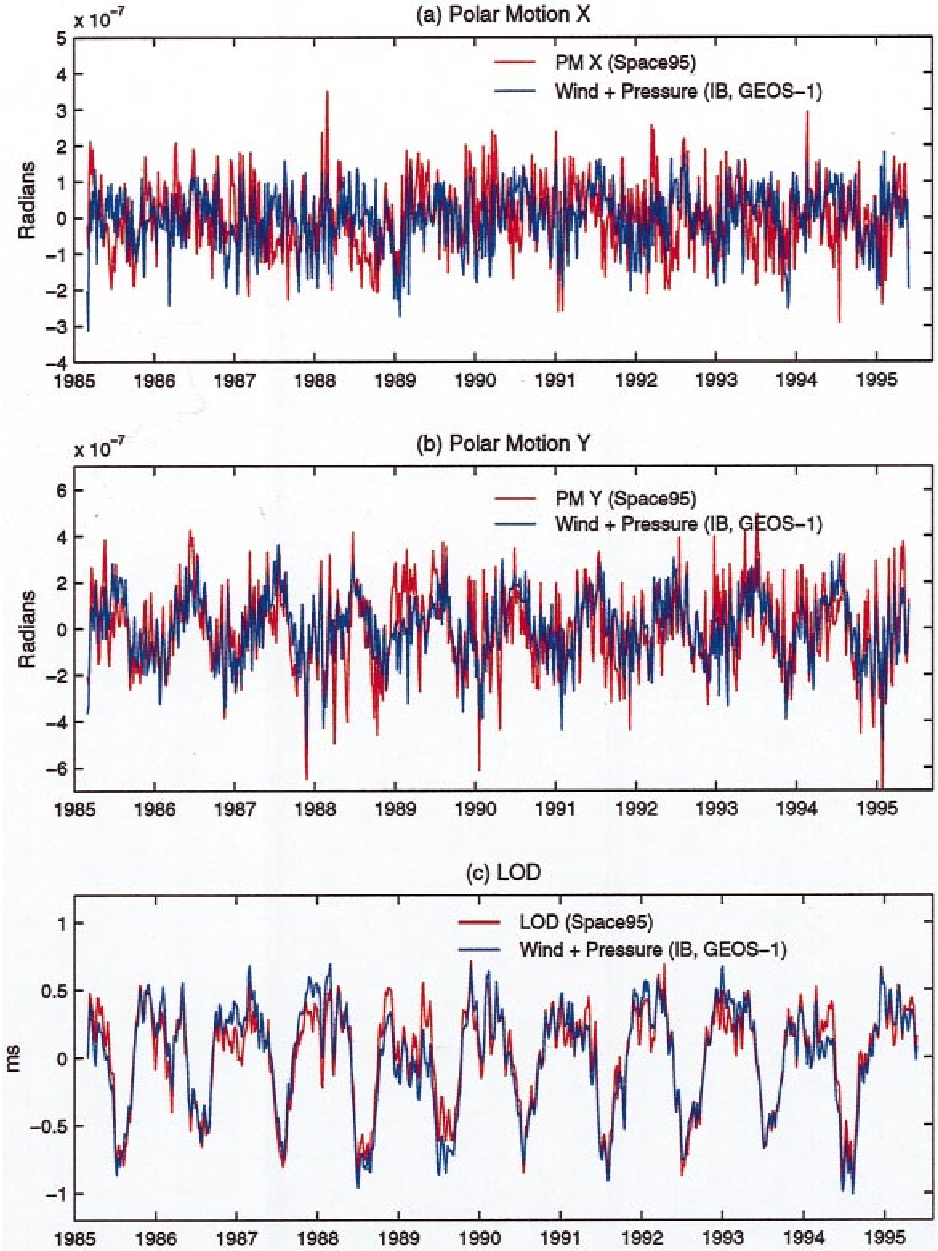

Figure 1. Observed polar motion (X, Y) and LOD excitations from SPACE95 EOP time-series (red curves) and AAM contributions from GEOS-1 (blue curves, IB correction applied). Results for X, Y and LOD are shown in (a), (b) and (c) respectively.

For intraseasonal (shorter than half a year) variabilities, OAM excitations show reasonably good agreement with the remaining signals in both polar motion (X, Y) and LOD, especially in Y and LOD. Fig. 4 shows the broad-band cross-correlation function between OAM excitations and X, Y and LOD residuals after removal of annual and semi-annual signals. Strong correlations well over the 99 per cent confidence level exist at zero phase lag, especially in Y and LOD.

4 DISCUSSION

This investigation shows that both the global hydrological cycle and the ocean mass redistributions play important roles in balancing the global angular momentum budget. The seasonal variability of HAM is of the same magnitude as the atmospheric pressure contribution. The monthly sampled soil moisture and snow depth fields can only provide some very broad features in the global hydrological cycle. Water mass in aquifers and soil water under 2 m depth could be major error sources in water mass calculation, which are practically unknown on a global scale.

This research reveals some encouraging results for oceanic excitations, especially for LOD. The OAM is computed using mass variation only. The relative motion impact from ocean current is not included in this study. Investigations using the ocean general circulation model indicate that the ocean

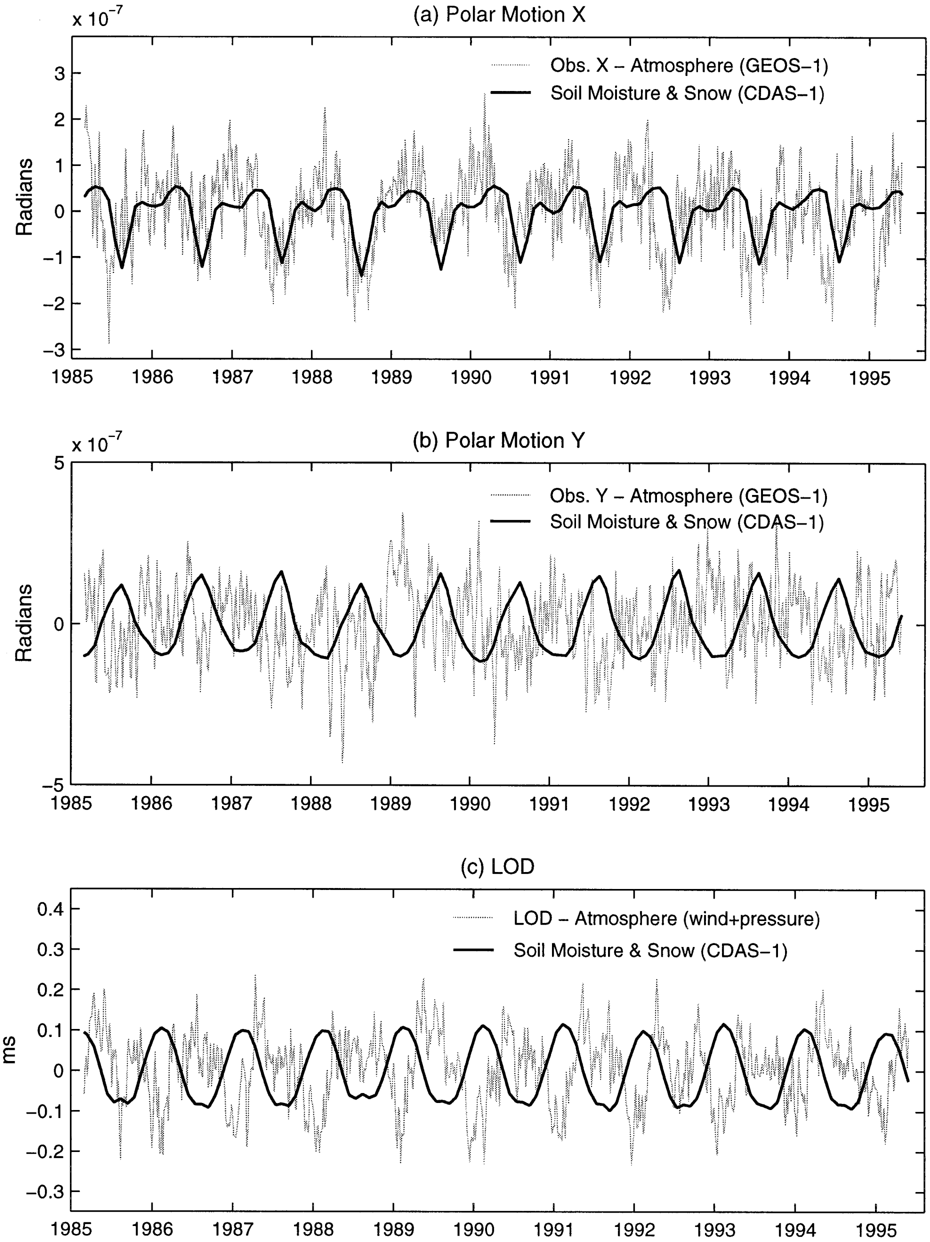

Figure 2. The remaining variations of polar motion (X, Y) and LOD (thin grey curves) not accounted for by the atmosphere compared with hydrological excitations (thick black curves) derived from CDAS-1 soil moisture and snow water variations. Results for X, Y and LOD are shown in (a), (b) and (c) respectively.

current's contribution to the Earth angular momentum budget is considerably smaller than its mass term (Marcus *et al.* 1998; Johnson 1998), but non-negligible. A combined application of satellite altimetry and the ocean general circulation model to study the OAM variability is one of our future tasks.

On seasonal scale, hydrological and oceanic excitations to LOD variations are nearly out-of-phase (see Fig. 5). It seems that there is a cancellation effect between the land and ocean water in driving the Earth rotational rate change. If we look into the details of the LOD excitation computation formulae (eq. 2), this interesting phenomenon is actually evidence that indicates that there is a seasonal mass balance between continental water storage (plus atmospheric water vapour) and the oceans, which was recently identified and reported by Chen *et al.* (1998) and Minster *et al.* (1999) through the study of T/P global mean sea level change and continental water storage change. From eq. (2), one finds that LOD excitation ψ_3 is proportional to $C_{00}-C_{20}$, the difference between degree 0 and 2 zonal spherical harmonics (Chao & O'Connor 1988b). For a global system, C_{00} is normally assumed to be zero because of the general assumption of mass conservation. However, for a single component, C_{00} represents the integral of total mass and is not necessarily a constant, for example, the total mass in continental water storage and the oceans in this study.

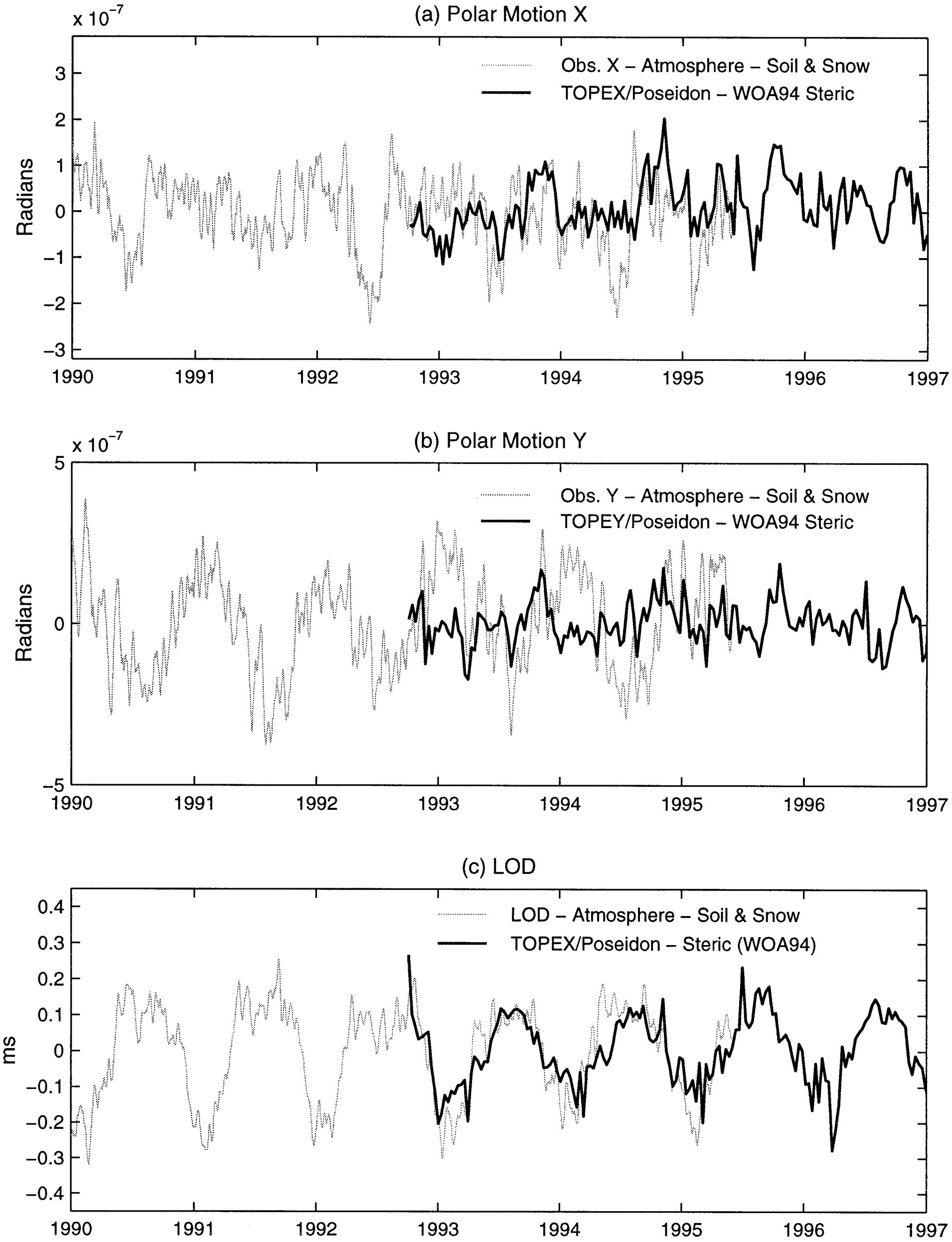

Figure 3. The remaining variations of polar motion (X, Y) and LOD (thin grey curves) after both AAM and HAM contributions have been removed compared with oceanic excitations (thick black curves) estimated from non-steric sea level change (TOPEX/Poseidon, WOA94 steric). Results for X, Y and LOD are shown in (a), (b) and (c) respectively.

The generally good agreement between T/P OAM excitation and X, Y and LOD residual signals, especially at intra-seasonal timescales, is a strong indication that some of the T/P-determined sea level anomalies result from mass transport. Satellite altimetry has the potential to detect large-scale oceanic mass variations when combined with other techniques (e.g XBT). The good agreements presented in this study not only indicate that the ocean may play an important role in exciting variations in Earth rotation, but also reveal some insights into the frequency response of the pressure loading effect over the oceans, which may enhance our understanding about the IB assumptions in reality. Further discussion of this is beyond the scope of this study. The agreement between T/P LOD and residuals is subject to change if we choose a different atmospheric model (e.g. the NCEP AAM). This is due to the dominant atmospheric contribution to LOD variation. Any slight differences between the models will cause significant discrepancies in the residuals.

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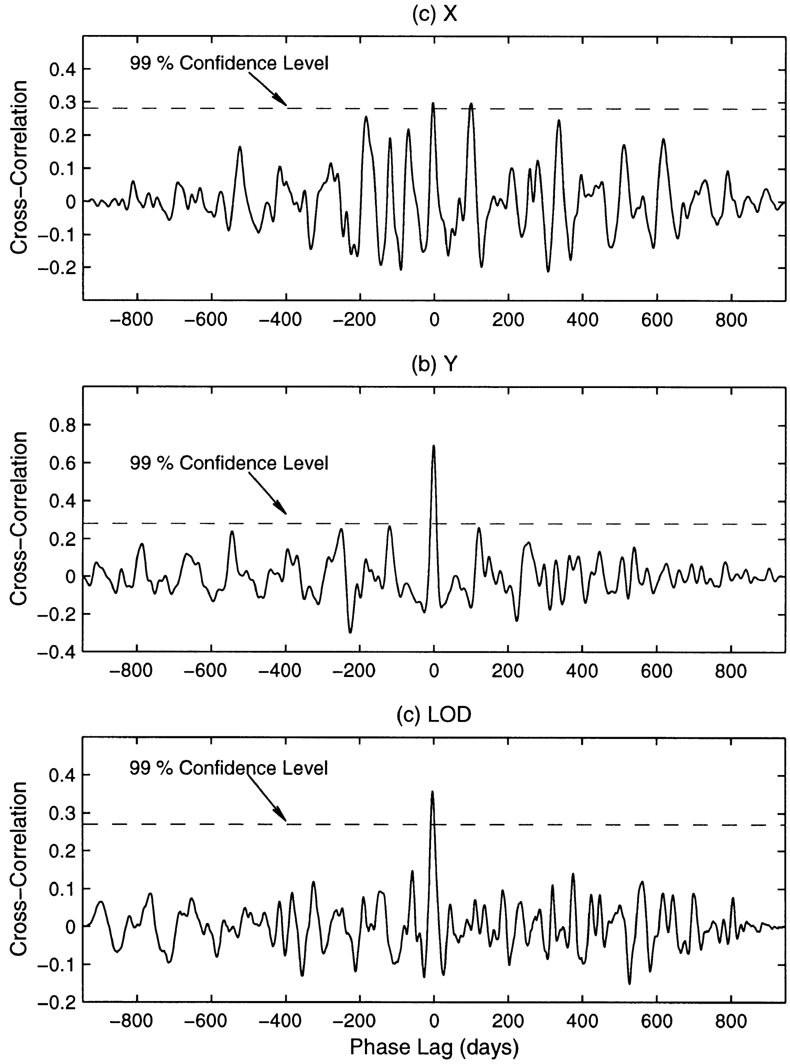

Figure 4. Cross-correlation analysis for X, Y and LOD between oceanic excitations (TOPEX/Poseidon, WOA94 steric) and the remaining signals not accounted by the atmosphere and hydrosphere. Seasonal (annual and semi-annual) variations are removed from all time-series.

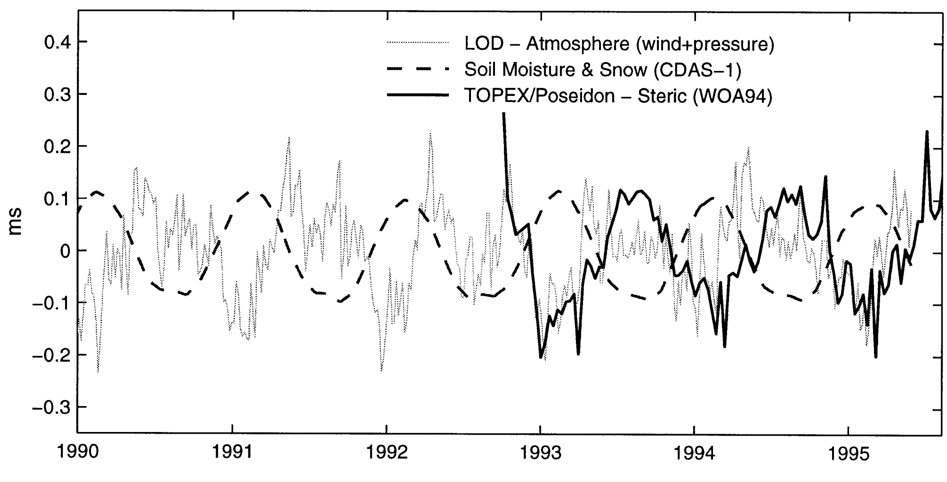

Figure 5. Hydrological (thick dashed curve) and oceanic (thick solid curve) excitations to LOD superimposed by the remaining LOD variations (thin grey curve) not accounted for by the atmosphere.

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