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Geophysical contributions to satellite nodal residual variation

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Abstract. Even-degree zonal gravitational variations due to mass redistribution within the Earth's system, especially in the atmosphere, hydrosphere, and oceans will lead to variations in the nodal precession rate of satellite orbit. The accurately measured nodal variation for LAGEOS 1 provides a means to study planetary-scale mass redistributions and gravitational variations from the space. In this paper, we investigate atmospheric and hydrologic contributions to the LAGEOS 1 nodal changes using barometric pressure, soil moisture, and snow accumulation values from data-assimilating numerical models. Oceanic effects are estimated from nonsteric sea level change determined by TOPEX/Poseidon satellite radar altimeter observation and a simple model for steric sea level changes. The results are compared with the LAGEOS 1 nodal change time series observed by satellite laser ranging. At annual and semiannual time scales, the atmosphere and hydrosphere provide significant contributions. The atmosphere provides broadband excitation of nodal changes at intraseasonal timescales. Seasonal and intraseasonal nontidal oceanic effects are also significant. General agreement between predicted and observed nodal precession rate residuals is improved relative to earlier studies, in part because of the better estimation of hydrological effects and new assessment of nontidal oceanic effects.

1. Introduction

Mass redistribution within the Earth's system will change the external gravitational field and produce perturbations to satellite orbits. Analysis of satellite orbit variations, particularly for the LAGEOS satellite, has been demonstrated to be an effective means for determining the temporal variations of the Earth's external gravitational field [*Yoder et al.*, 1983; *Gutierrez and Wilson*, 1987; *Cheng et al.*, 1989; *Nerem et al.*, 1993; *Chao and Eanes*, 1995]. Continuing improvements in satellite laser ranging (SLR) technique and gravitational modeling [*Tapley et al.*, 1996] enable detection of minute temporal variations in the low spherical harmonic degree gravitational field [*Cheng et al.*, 1989; *Nerem et al.*, 1993; *Gegout and Cazenave*, 1993; *Dong et al.*, 1996; *Watkins and Eanes*, 1997; *Kar*, 1997; *Eanes et al.*, 1997a, b].

The rate of change with time of the intersection point of the satellite orbit plane with the equatorial plane is termed the nodal precession rate (NPR). Changes in NPR are caused by time variations in a linear combination of even-degree zonal harmonics (degree 2, 4, ...) and can be accurately determined from analysis of laser ranging data from satellites such as LAGEOS (with nearly circular orbits). *Chao and Eanes* [1995] investigated the atmospheric contribution to LAGEOS 1 nodal residual variation using the European Center for Medium-Range Weather Forecast (ECMWF) surface pressure data and discussed the potential hydrological contribution based on the results from *Chao and O'Connor* [1988]. They concluded that the atmosphere is a major contributor to the observed LAGEOS NPR residual at seasonal and intraseasonal timescales, and that continental water storage provides an important annual excitation as well. However, agreement at the semiannual period was poor, and the atmosphere and hydrosphere were unlikely to explain the semiannual discrepancy. This suggested that other geophysical sources might be important (e.g., the oceans) or that estimates of atmospheric and hydrologic mass variations, especially water mass redistribution might be poor. *Dong et al.* [1996] used different models to further estimate atmospheric and ocean tidal effects on LAGEOS nodal rate variations and came to a similar conclusion. The major uncertainties are likely from continental water and nontidal oceanic effects [*Chao and Eanes*, 1995; *Dong et al.*, 1996].

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The rapid development of climate data assimilation systems and remote sensing techniques provides new opportunities to study atmospheric, hydrologic, and nontidal oceanic mass redistribution and corresponding contributions to satellite NPR residuals. The atmospheric contribution will be estimated from the surface pressure field of the National Center for Environmental Prediction, National Center for Atmospheric Research (NCEP-NCAR) Climate Data Assimilation System I (CDAS 1) [*Kalnay et al.*, 1996], and hydrologic effects will be based on the soil moisture and snow fields of CDAS 1. In addition, the nontidal oceanic contributions are estimated from TOPEX/Poseidon data combined with a simplified steric sea level change model [*Chen et al.*, 1998; *Chen and Wilson*, 1999]. Geophysical model contributions will be compared with LAGEOS 1 SLR determination and the results of *Chao and Eanes* [1995] at different timescales.

2. Theory

The geopotential field is conveniently expressed in a spherical harmonic expansion as [*Lambeck*, 1980]

$$U(r,\phi,\lambda) = \frac{GM_e}{r}\left[1+\sum_{n=2}^{\infty}\sum_{m=0}^{n}\left(\frac{R_e}{r}\right)^n P_{n,m}(\sin\phi) \cdot (C_{n,m}\cos m\lambda + S_{n,m}\sin m\lambda)\right], \quad (1)$$

where ϕ and λ are the latitude and east longitude, r is the geocentric distance, M_e and R_e are the mass and equatorial radius of the planet Earth, G is gravitational constant, $P_{n,m}(\sin\phi)$ are the Legendre polynomials of degree n and order m, and $C_{n,m}$ and $S_{n,m}$ are Stokes coefficients of degree n and order m (unnormalized).

Gravitational variations due to mass redistribution within the Earth's system are represented by dimensionless variations of $C_{n,m}$ and $S_{n,m}$. In this study we are particular interested in the even-degree zonal ($m = 0$) terms C_n (or $C_n = -J_n$ as normally denoted), which contribute to satellite NPR perturbations. Variations of C_n due to surface mass load change ($\Delta L(\phi,\lambda,t)$, in units of mass per unit area element) associated with atmospheric surface pressure, continental water storage, and nonsteric sea level change are expressed as [*Lambeck*, 1980; *Chao and Eanes*, 1995]

$$C_n(t) = \frac{(1+k'_n)R_e^2}{M_e}\int \Delta L(\phi,\lambda,t)P_n(\sin\phi)\cos\phi\, d\phi\, d\lambda, \quad (2)$$

where k'_n (n = 2, 4, 6, ...) are the Earth's load Love numbers accounting for the elastic yielding effect of the solid Earth under surface loading [*Farrell*, 1972]. From the computation by *Farrell* [1972], k'_2 = -0.31, k'_4 = -0.13, k'_6 = -0.09, etc. $\Delta L(\phi,\lambda,t)$ will be computed from variations of atmospheric surface pressure, continental water storage, and nonsteric sea level change accordingly (see section 3).

Satellite NPR changes reflect the effects of a linear combination of changes of even-degree zonal Stokes coefficients [*Eanes and Bettadpur*, 1995]. The coefficients of this linear combination are satellite-dependent, and for LAGEOS 1 , the result is [*Chao and Eanes*, 1995; *Eanes and Bettadpur* , 1996]

$$\sigma = (-41.6C_2 - 15.4C_4 - 3.3C_6 - 0.2C_8 - 0.1C_{10}) \times 10^{11}, \quad (3)$$

where C_n (n = 2, 4, ..., 10) are unnormalized even-degree zonal Stokes coefficients (equation (2)) and σ is in units of milliarcsecond (mas) per year.

3. Data

3.1. Atmosphere

CDAS 1 is a near real-time climate model running from January 1958 to the present. Atmospheric surface pressure data are taken from CDAS 1 for the period from January 1973 to April 1998. The spatial resolution is 2.5° latitude by 2.5° longitude, and temporal resolution is 6 hours. Mass load variations due to atmospheric pressure change ($\Delta P(\phi,\lambda,t)$) are computed by

$$\Delta L_{atm}(\phi,\lambda) = \frac{\Delta P(\phi,\lambda)}{g}, \quad (4)$$

where, g = 978.03 cm/s^2 is the acceleration of gravity. An inverted barometer (IB) correction is applied by including pressure variations only over land and assuming a constant pressure over the oceans. To use a constant pressure over the oceans instead of instantaneous mean pressure for atmospheric IB correction is simply because that the TOPEX/Poseidon Geophysical Data Record (GDR) data used a constant reference pressure [*Callahan*, 1993] (as long as one uses the same IB formulation for both the atmosphere and the oceans, the combined effects will be roughly the same). We also estimate the atmospheric contribution without the IB correction (denoted as NB in the table and figures) in order to compare our results with those of *Chao and Eanes* [1995] for both IB and NB cases.

3.2. Hydrology

We estimate continental water storage changes from soil moisture and snow variation, using the CDAS 1 monthly diagnostic soil moisture and snow accumulation fields [*Kalnay et al.*, 1996]. The data are given on a Gaussian grid of 1.875° longitude (even) and about 1.905° latitude (uneven) and cover the period January 1958 to the present. The first layer of the soil moisture field includes the top 10 cm of soil, and the second and final layer extends from 10 cm to 200 cm depth (190 cm in thickness). Soil water content is represented by volumetric fraction, and snow load variations are given by water equivalent snow accumulation. Continental water storage changes are then computed by adding soil water (layers 1 and 2) and snow water variations [*Chen et al.*, 1998, 1999].

3.3. Oceanic Mass Redistribution

Ocean load variations are estimated from sea level anomalies using the TOPEX/Poseidon (T/P) Geophysical Data Record (GDR), provided by the NASA Jet Propulsion Laboratory (JPL). All media, instrument, and geophysical corrections were applied [*Callahan*, 1993], including ionosphere delay, wet and dry troposphere delay, electromagnetic bias, tides, and inverted barometer (IB) response (assuming a constant mean barometric pressure). However, several changes were made to update models and correct errors. The original GDR orbits were replaced by those computed using the joint gravity model 3 (JGM-3) [*Tapley et al.*, 1999], the ocean tide model was replaced with the UT/CSR 3.0 model [*Eanes and Bettadpur*, 1995], and an error in the pole tide correction was removed. Sea level anomalies, deviations from a 4-year mean surface, were computed by interpolating the data to a fixed grid and then removing the mean sea surface height. The sea surface anomalies were averaged into a uniform $1° \times 1°$ grid for cycles 10-211 (December 1992 to June 1998).

Observed sea level anomalies can be divided into steric and nonsteric sea level change. The steric change is the portion due to density variation, introduced by temperature and salinity variations but dominated by temperature. The steric component involves no mass changes, so it is estimated and subtracted, leaving the nonsteric component arising from mass redistribution within the oceans and water exchange between the oceans and other components in the Earth system, mainly the atmosphere and hydrosphere. A simplified steric sea level change model [*Chen et al.*, 1998, 1999], derived from the top 14 layers (0-500 m depth) of the climatological mean three-dimensional ocean temperature field of the World Ocean Atlas 1994 (WOA94) [*Levitus and Boyer*, 1994] is adopted and subtracted from the T/P data to obtain an estimate of the nonsteric component.

3.4. LAGEOS 1 Nodal Residual

LAGEOS 1 was launched in 1976 into a near circular orbit. The nominal constant nodal precession rate is about 4.51×10^8 mas/yr [*Chao and Eanes*, 1995]. A 22-year's long-arc solution (1976-1998) of the nodal residual is solved at a 3-day interval. The time series is smoothed with an effective cutoff period of 30 days. The tidal effects are removed using UT/CSR 3.0 [*Eanes and Bettadpur*, 1995]. Owing to the relatively poorer quality of the SLR data and smaller number of stations available in the first several years, the LAGEOS 1 solution shows some abnormal variability during that period. Therefore we only include the LAGEOS 1 nodal residual solution of the period 1985 to 1998 in this analysis.

4. Results and Comparisons

4.1. Atmospheric Contribution

Figures 1a and 1b show the comparisons between observed LAGEOS 1 NPR residuals and atmospheric contributions for IB and non-IB (NB), respectively. A Butterworth low-pass filter with a 30-day cutoff period is applied to the estimated IB and NB atmospheric time series. Atmospheric surface pressure variations are responsible for a significant portion of the observed variability, especially at annual and intraseasonal period. The IB atmospheric excitation is generally smaller than observed, while the NB atmospheric excitation is larger. This is clearly demonstrated in the power spectra shown in Figure 2. LAGEOS 1 power falls mostly between the IB and NB spectra. Furthermore the LAGEOS 1 semiannual spectral peak (Figure 2 and Table 1), is larger than both IB and NB spectra, consistent with the earlier finding of *Chao and Eanes* [1995].

After seasonal (annual and semiannual) variations are removed, cross correlations between the LAGEOS 1 series and both IB and NB atmospheric series indicate that there is strong correlation supporting what can be seen in the time series plots of Figure 1. The IB series show somewhat stronger correlation [correlation coefficient: 0.76 (IB) versus 0.65 (NB)]. This is also demonstrated in the RMS (root-mean-square) of the residuals (LAGEOS - atmosphere), which is 76.8 mas/yr for the IB case and 92.9 for the NB case. Atmospheric series are in quite good agreement with the results of *Chao and Eanes* [1995] based on the ECMWF atmospheric model. Annual and semiannual components of the three series from Figures 1a and 1b are estimated using least squares and are listed in Table 1, together with the estimates by *Chao and Eanes* [1995].

4.2. Continental Water Effects

Figures 3a and 3b show the estimated hydrologic contributions combined with the IB and NB atmospheric time series, superimposed by LAGEOS 1 NPR observation. Amplitudes and phases of annual and semiannual hydrologic excitations are listed in Table 1, and the corresponding estimates from *Chao and Eanes* [1995] are provided for comparison. The hydrologic series contains strong annual and semiannual components and accounts for much of the remaining seasonal variability. The best agreement appears to be for the IB case (Table 1). Owing to the lack of observational data as input, the CDAS 1 soil moisture and snow data do not show strong intraseasonal and interannual variability, which may obviously exist in the real world.

Our hydrologic estimates are in reasonably good agreement with results given by *Chao and Eanes* [1995] for the annual excitation, but semiannual estimates are nearly out of phase. Our semiannual estimate agrees better with the LAGEOS 1 series. The significant hydrological effects on LAGEOS 1 nodal residuals are reflected in the RMS changes. After hydrological contri-

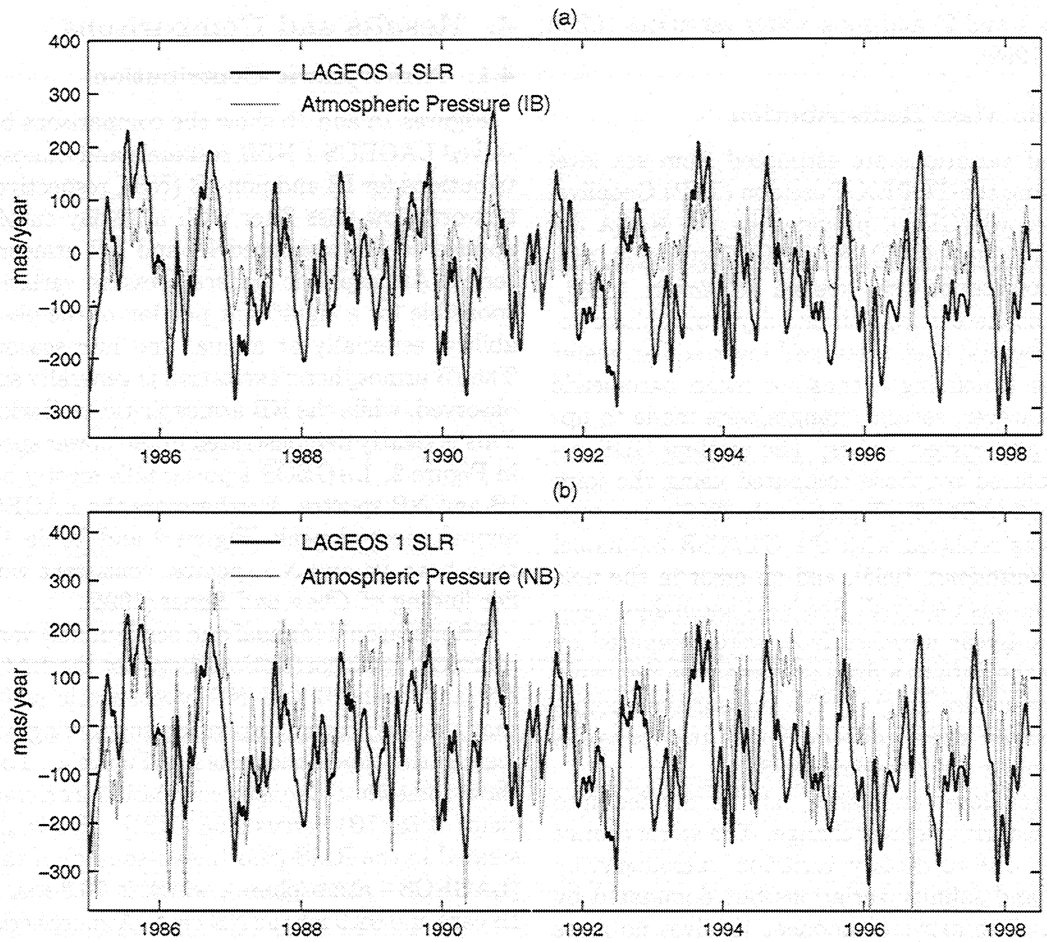

Figure 1. (a) The IB atmospheric contribution (dark solid curve) to LAGEOS 1 nodal residual variation, superimposed by LAGEOS SLR observation (light dotted curve); The RMS of the residuals between the two series is 76.8 mas/yr. (b) The non-IB (NB) atmospheric contribution (dark solid curve) to LAGEOS 1 nodal residual variation superimposed by LAGEOS SLR observation (light dotted curve). The RMS of the residuals between the two series is 92.9 mas/yr.

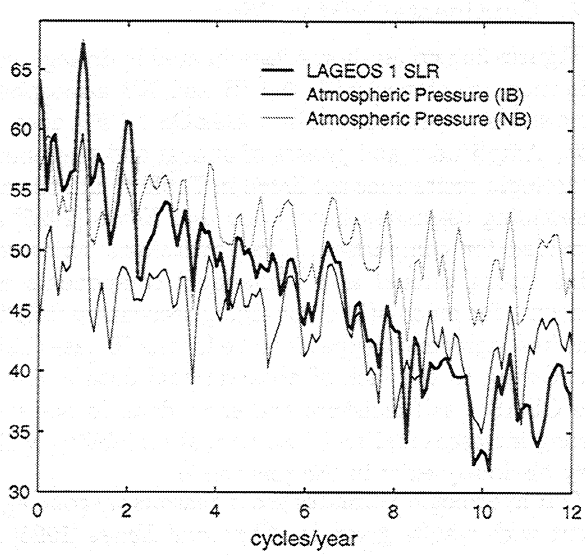

Figure 2. Power density of observed LAGEOS 1 nodal residual variability (thick solid curve) compared with the power densities of the IB (thin solid curve) and NB (thin light dotted curve) atmospheric excitations computed from CDAS 1 surface pressure data.

butions are further subtracted from the LAGEOS observation, the RMS decreases from 76.8 (for LAGEOS - IB atmosphere) to 63.5 mas/yr (for LAGEOS - IB atmosphere - hydrosphere). For the NB atmosphere, the RMS change is very small (92.9 versus 92.3 mas/yr) due to the particularly large atmospheric effects in the Non-IB case. These results support the IB assumption.

4.3. Contributions From the Oceans

Figure 4 shows the estimated oceanic contributions to the LAGEOS 1 NPR residual from TOPEX/Poseidon data, compared with the residual variations after atmospheric and hydrological effects are subtracted from LAGEOS 1 NPR time series. The oceans provide significant contributions to LAGEOS 1 nodal residual change at a broad band of frequencies as well. A good seasonal agreement is evident, especially during the period 1996 to 1998. The role of the oceans in driving intraseasonal variations of LAGEOS 1 NPR residuals is demonstrated in the cross-correlation analysis between the estimated oceanic contribution and the LAGEOS 1 NPR residuals (Figure 5). Seasonal (annual and semiannual) vari-

Table 1. Least Squares Fit of Annual and Semiannual Variations in LAGEOS 1 Nodal Residual Determination and Geophysical (Atmospheric, Hydrologic, and Oceanic) Contributions.

Sources	Annual		Semiannual	
	Amplitude mas/yr	Phase deg	Amplitude mas/yr	Phase deg
LAGEOS 1 SLR	103.1	209	58.5	293
Atmosphere (IB)	38.9	212	14.0	282
Atmosphere (NB)	94.7	183	29.0	305
Atmosphere (IB, CE)	44.9	204	10.8	274
Atmosphere (NB, CE)	101.5	180	19.4	298
Water	43.7	218	14.0	284
Water (CE)	59.5	239	24.1	86
Ocean	30.0	234	2.5	295
Sum (IB, all)	111.4	220	30.4	284
Sum (IB, air+water)	82.5	215	27.9	283
Sum (NB, air+water)	133.1	194	42.3	298
Sum (IB, CE)	98.5	223	13.5	80
Sum (NB, CE)	141.4	201	12.8	33

CE indicates results from *Chao and Eanes* [1995]. The phase (ϕ) is defined as $sin(2\pi ft+\phi)$, and the epoch (t) is referred to January 1, 0:00 UT.

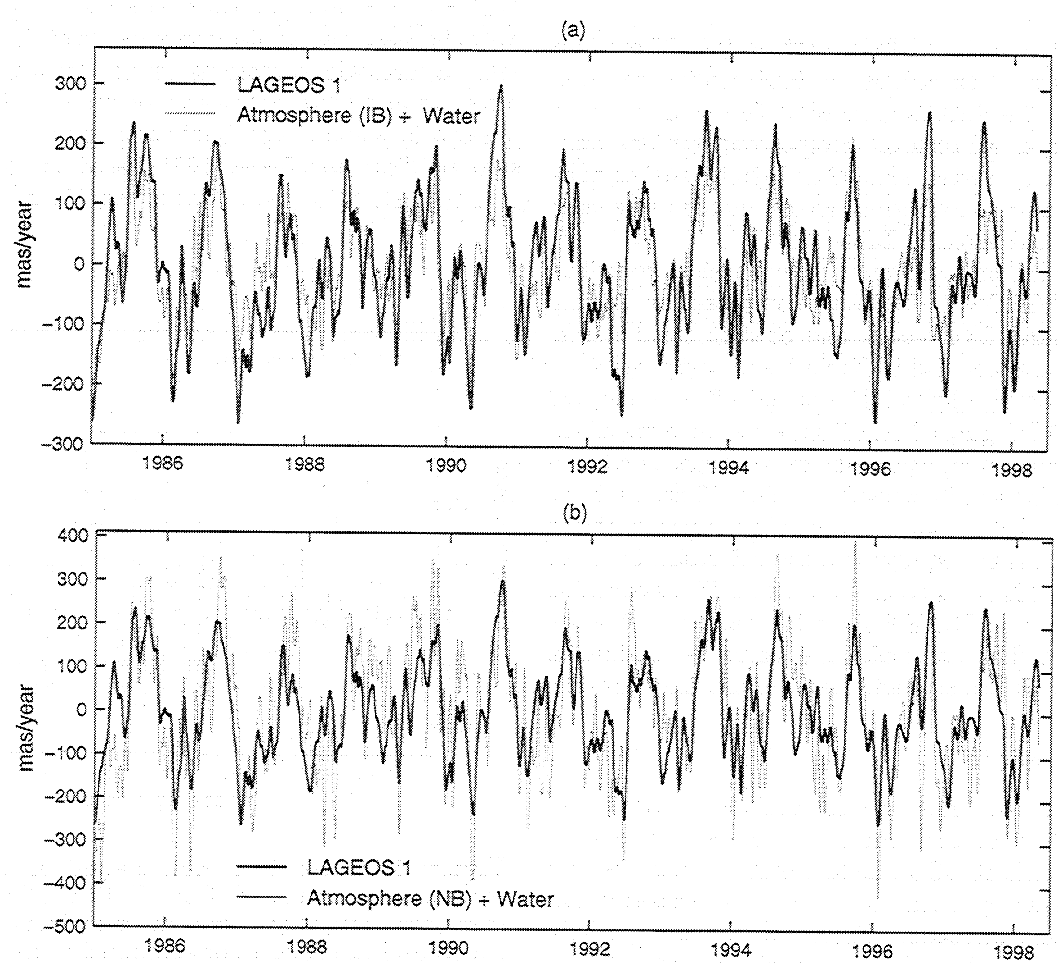

Figure 3. (a) Combined hydrologic and IB atmospheric contribution superimposed by the LAGEOS 1 SLR nodal residual (light dotted curve). The RMS of the residuals between the two series is 63.5 mas/yr. (b) Same as Figure 3a, but for the NB atmosphere. The RMS of the residuals between the two series is 92.3 mas/yr.

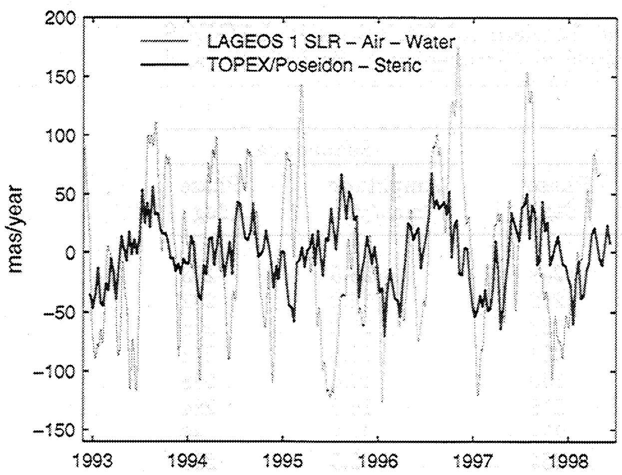

Figure 4. Oceanic contribution (dark solid curve) to LAGEOS 1 nodal residual change from nonsteric sea level anomalies, superimposed by the remaining LAGEOS 1 nodal residual change not accounted by the atmosphere and hydrosphere (light dotted curve). The RMS of the residuals between the two series is 58.8 mas/yr.

ations are first removed from both series. There is a good correlation, exceeding the 99% confidence level, at zero lag. The RMS is reduced to 58.8 mas/yr (from 63.5 mas/yr) if we remove oceanic contributions from the residual time series. Annual and semiannual components of oceanic contributions are estimated using least squares and are listed in Table 1.

Total annual and semiannual geophysical contributions to LAGEOS 1 NPR are computed by adding IB atmospheric, hydrologic, and oceanic components. The results are included in Table 1 and compared with the (atmospheric + hydrologic) budgets from *Chao and Eanes* [1995]. Figures 6 and 7 show vector plots of annual and semiannual variations for the various components assuming an IB atmosphere. The NB atmospheric result is included in this paper only to compare with the IB result (from this study) and the NB result by *Chao and Eanes* [1995]. Because the same IB assumption is applied to the TOPEX/Poseidon data, in doing the total budget (i.e., atmosphere + ocean + continental water), the IB atmospheric result is the only possible selection.

5. Discussion

This study confirms the conclusions of *Chao and Eanes* [1995] that the atmosphere plays a significant role in driving LAGEOS 1 nodal residual variations over a broad frequency band, in particular at seasonal and intraseasonal timescales. Slight differences, especially for the IB atmosphere, between our estimate and that of *Chao and Eanes* [1995] may be due to the different atmospheric models and slightly different treatment of the IB assumption (we use a constant mean pressure over the oceans instead of a variable mean pressure). Because the same IB assumption (using a constant mean pressure over the oceans) was applied in the TOPEX/Poseidon GDR data [*Callahan*, 1993], atmospheric pressure loading effects over the oceans are simply converted into equivalent sea level changes in the TOPEX/Poseidon data and should be reflected in the oceanic estimate derived from the TOPEX/Poseidon data. Slightly different land mask definitions could be another source of differences in the results.

Atmospheric water vapor is not treated separately in this study. Even though the phase changes of water vapor at the surface (via precipitation and evapotranspiration) virtually do not change the gravity field, when we take into account atmospheric, oceanic, and hydrological effects at the same time, there is no need to separate the wet atmosphere from the dry atmosphere. Some of the pressure changes due to water vapor phase change will be compensated by water mass load change (through change of soil moisture and snow) at the surface.

CDAS 1 soil moisture and snow accumulation fields provide a new opportunity to investigate continental water storage change and corresponding effects on LAGEOS 1 NPR residual. Water storage changes are probably the least well known components of the Earth system. Hydrologic excitations derived from CDAS 1 soil moisture and snow data agree better with LAGEOS 1 observations and are probably an improvement over results by *Chao and Eanes* [1995] based on precipitation, evapotranspiration, and surface runoff data. Improved

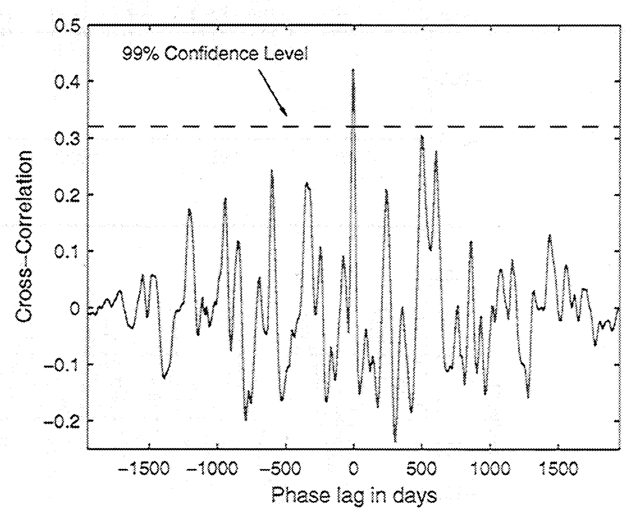

Figure 5. Cross-correlation analysis between oceanic contribution estimated from TOPEX/Poseidon nonsteric sea level change and the remaining LAGEOS 1 nodal residual changes not accounted by the atmosphere and continental water. Annual and semiannual variations are removed from both time series. The 99% confidence level is determined by Monte Carol tests using the degrees of freedom of LAGEOS 1 series (an effective 30-day interval assumed) .

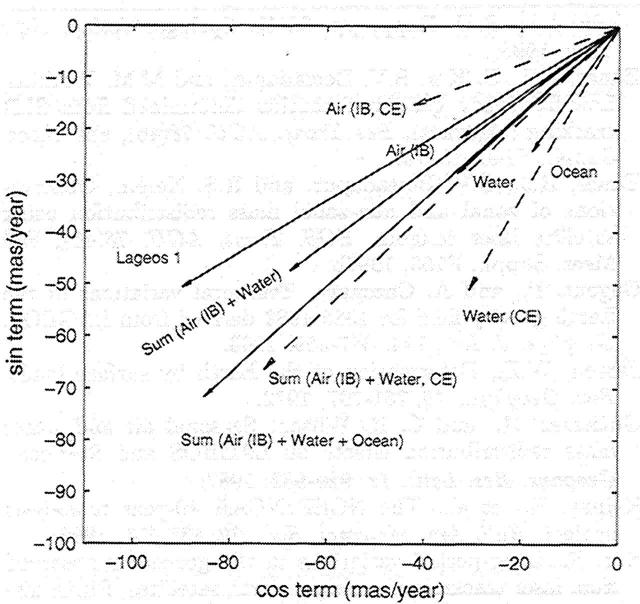

Figure 6. Vector representation of annual variations of observed LAGEOS 1 nodal residual change, geophysical contributions from the IB atmosphere, continental water, and ocean (TOPEX/Poseidon - steric). Solid arrows are results from this study. The atmospheric and hydrologic estimates from *Chao and Eanes* [1995] are shown by dashed arrows and denoted by CE for comparison.

agreement at the semiannual period is notable (Figure 7 and Table 1). At the annual period the hydrosphere is comparable to the atmosphere, in causing LAGEOS 1 NPR variations (Figure 6 and Table 1), as discussed by *Chao and Eanes* [1995]. However, some recent studies [*Chen and Wilson*, 1999; Anny Cazenave, personal communication, 1999] point out that the NCEP CDAS 1 soil moisture and snow data show substantially stronger seasonal variability than other hydrological models. Owing to the lack of observational constraints, we cannot simply come to a definite conclusion that CDAS 1 hydrological model does a better job.

There are, as well, important oceanic contributions. TOPEX/Poseidon based estimates are well correlated with the LAGEOS 1 NPR residual, although relatively smaller (Figure 4). The oceans play a notable role in driving LAGEOS 1 NPR residuals at both seasonal and intraseasonal periods (Figure 6 and Table 1). At annual scale the nontidal oceanic contribution (30.0 mas/yr) is comparable to the IB atmospheric effect (38.9 mas/yr) and continental water effect (43.7 mas/yr). However, at semiannual scale the TOPEX/Poseidon data show a very small signal (2.5 versus 14.0, and 14.0 mas/yr for the IB atmosphere and oceans, respectively).

The conclusion is that the atmosphere, continental water, and oceans all provide significant contributions to low-degree zonal variation of the gravity field. The combined geophysical excitations explain most of annual, 50% of semiannual, and a major part of intraseasonal variations in LAGEOS 1 nodal residual observation. Despite these notable improvements, there are remaining discrepancies, especially at semiannual scale, which are not surprising given that contributions of both the oceans and continental water are fairly uncertain. However, both the oceans and continental water are the objects of intense study and modeling efforts, and it is likely that the situation will improve rapidly.

The significant atmospheric, hydrological, and oceanic effects on Earth gravitational change indicate great potentials of using LAGEOS (and also other satellites) SLR measurements and the future Gravity Recovery and Climate Experiment (GRACE) observations to study water mass variation over the land and within the oceans. Combining LAGEOS 1 and LAGEOS 2 (launched in 1992) SLR data or using multi-satellites SLR data, different zonal and nonzonal terms of the gravitational change can be separated, such as C_{10}, C_{20}, C_{30}, C_{11}, S_{11}, C_{21}, S_{21}, etc. [*Eanes et al.*, 1997a, b; *Cheng and Tapley*, 1999]. These results provide a much broader base to study Earth gravitational variation and water mass redistribution within the Earth system. They also provide opportunities to develop scientific requirements for the GRACE mission when high-accuracy gravitational determinations are available in the future.

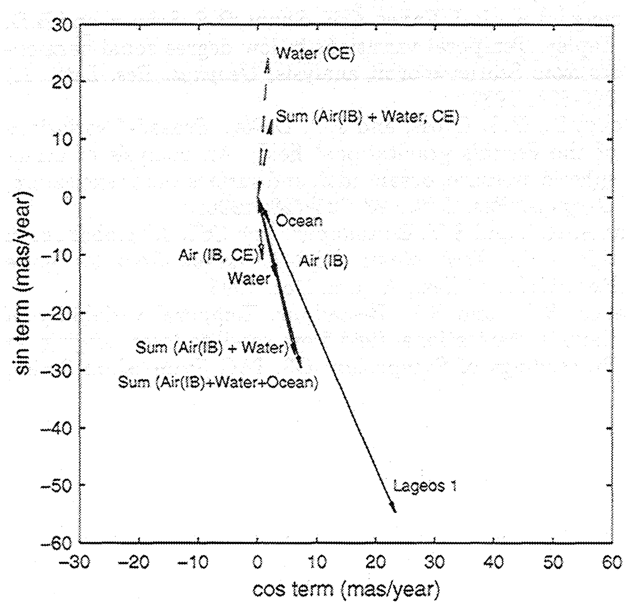

Figure 7. Vector representation of semiannual variations of observed LAGEOS 1 nodal residual change, geophysical contributions from the IB atmosphere, continental water, and ocean (TOPEX/Poseidon - steric). Solid arrows are results from this study. The atmospheric and hydrologic estimates from *Chao and Eanes* [1995] are shown by dashed arrows and denoted by CE for comparison.

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