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Geophysical interpretation of observed geocenter variations

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Abstract. Geocenter variations are caused by mass redistribution within the Earth system, especially the atmosphere, oceans, and continental water. Using surface pressure fields, and soil moisture and snow depth fields of the NCEP-NCAR Climate Data Assimilation System I (CDAS-1), we estimate contributions from variations in atmospheric surface pressure and continental water storage to the Earth's geocenter (center of mass) variation. In addition, sea surface anomalies determined by the TOPEX/POSEIDON altimeter are used to investigate geocenter variations resulting from ocean mass redistribution. These sea surface height data were corrected using a simplified steric model. A comparison with observed geocenter variations derived from Lageos 1 and 2 satellite laser ranging data indicates that the atmosphere, oceans, and continental hydrological cycle all provide significant contributions at different frequencies. Geocenter variations estimated in this paper are in reasonably good agreement with results given by *Dong et al.* [1997] for atmospheric and ocean contributions, but not for the estimates of continental hydrological contributions.

1. Introduction

The geocenter is defined as the mass center of the Earth system, including the solid earth, oceans, and atmosphere. Space geodetic techniques, such as satellite laser ranging (SLR) and the Global Positioning System (GPS), have demonstrated that the geocenter moves a few millimeters to centimeters relative to the International Terrestrial Reference Frame (ITRF) over timescales ranging from diurnal to interseasonal [*Watkins and Eanes*, 1997]. The ITRF is defined by geodetic stations fixed to the Earth's crust, and geocenter variations relative to the ITRF directly affect estimates of earth orientation, satellite orbital motion, low degree gravitational field variations, and all space geodetic measurements that use the ITRF as a reference system.

Observed geocenter variations are produced by mass redistribution within the Earth system, especially surface mass load changes associated with the atmosphere, oceans, and the continental hydrological cycle. *Dong et al.* [1997] estimated the geocenter variations caused by atmospheric pressure variations, ocean bottom pressure, and land water storage fluctuations using the European Center for Medium-range Weather Forecasts (ECMWF) atmospheric model, two ocean general circulation models, the modular ocean model (MOM) and isopycnal model (ISO), and a continental water storage data set compiled by *Lei and Gao* [1992]. They concluded that the amplitudes of geocenter variations introduced by geophysical fluids (air and water) were less than 1 cm, about the same magnitude as the observed geocenter motions [*Dong et al.*, 1997].

In this paper we use different models for the atmosphere, continental hydrological cycle, and oceans to study mass redistribution in these three major components of the Earth system and to estimate the associated geocenter variations. Estimated geocenter variations are compared with observations from Lageos 1/2 SLR data and with the results given by *Dong et al.* [1997].

The geocenter vector ($\mathbf{R}_{cm}$) is defined as the displacement of the geocenter from the ITRF origin. Mass redistribution within the Earth system will change $\mathbf{R}_{cm}$. In spherical coordinates, mass load variations on a rigid Earth result in

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$$\mathbf{R}_{cm} = \frac{1}{M_E} \int \mathbf{R} L(\phi, \lambda) \cdot ds \quad (1)$$

where ϕ is latitude, λ is east longitude, M_E is the mass of the planet Earth, $L(\phi, \lambda)$ is the mass load change at the surface position $\mathbf{R}(\phi, \lambda)$, $ds = R_E^2 \cos\phi d\phi d\lambda$ is the surface area associated with mass load variation $L(\phi, \lambda)$ in units of mass per area, and R_E is the mean radius of the earth. In Cartesian coordinates with a gridded surface mass load scheme the three components (X, Y, Z) of the geocenter vector are given by

$$\begin{aligned} X_{cm} &= \frac{R_E}{M_E} \sum_{\phi=-\frac{\pi}{2}}^{\frac{\pi}{2}} \sum_{\lambda=0}^{2\pi} \cos\phi \cos\lambda L(\phi, \lambda) \Delta s \\ Y_{cm} &= \frac{R_E}{M_E} \sum_{\phi=-\frac{\pi}{2}}^{\frac{\pi}{2}} \sum_{\lambda=0}^{2\pi} \cos\phi \sin\lambda L(\phi, \lambda) \Delta s \quad (2) \\ Z_{cm} &= \frac{R_E}{M_E} \sum_{\phi=-\frac{\pi}{2}}^{\frac{\pi}{2}} \sum_{\lambda=0}^{2\pi} \sin\phi L(\phi, \lambda) \Delta s \end{aligned}$$

In terms of degree one unnormalized Stokes coefficients $(C_{1,1}, S_{1,1}, C_{1,0})$ the above equations can be simplified as

$$\begin{aligned} X_{cm} &= R_E C_{1,1} \\ Y_{cm} &= R_E S_{1,1} \quad (3) \\ Z_{cm} &= R_E C_{1,0} \end{aligned}$$

Analysis by *Dong et al.* [1997] shows that the deformational effect on degree one spherical harmonics is very small (about 2%), and a correction for deformation is therefore not applied in this paper.

2. Data

2.1. Atmosphere Models

Mass load variations due to the atmosphere are proportional to surface pressure variations. We use surface pressure fields from the NCEP-NCAR Climate Data Assimilation System I (CDAS-1), part of the NCEP-NCAR 40-year reanalysis system [*Kalnay et al.*, 1996], running from January 1974 to the present with a monthly sampling rate. The pressure is given on a Gaussian grid of 1.875° in longitude and about 1.904° (uneven) in latitude. Mass load variations (in g/cm^2) due to the atmosphere are computed by,

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

where ΔP is surface pressure variation and the acceleration of gravity g = 978.03 cm/s^2 is assumed to be constant. A standard inverted barometer (IB) correction is applied in computing atmospheric contribution, i.e., we include pressure variation only on land and assume a constant pressure over the oceans. The reason we use a constant pressure instead of the instantaneous mean pressure over the oceans [*Dong et al.*, 1997] is that the same IB assumption is also applied in TOPEX/Poseidon data [*Callahan*, 1993].

2.2. Sea Level Anomalies

The TOPEX/Poseidon (T/P) satellite altimeter has provided accurate global measurements of sea level change every 10 days for more than 5 years. The T/P data used in this paper include cycles 2 through 168, which cover October 1992 through April 1997. Mass load variations are estimated from sea level anomalies using the T/P Geophysical Data Record (GDR), provided by the NASA Jet Propulsion Laboratory (JPL) with all media, instrument, and geophysical corrections applied [*Callahan*, 1993], including ionosphere delay, wet and dry troposphere delay, electromagnetic bias, tides, and IB response. In this study, Joint Gravity Model (JGM-3) derived orbits are applied to improve the orbit determination [*Tapley et al.*, 1996], and the ocean tide model has been replaced with the University of Texas (UT) CSR 3.0 model [*Eanes and Bettadapur*, 1995].

Observed sea level variations over large spatial scales are a consequence of water mass redistribution and steric effects, including thermal expansion and salt advection. Thermal expansion associated with heat storage change in the ocean is the dominant steric effect. This part of sea level variation has virtually no contribution to mass load variations over the oceans. A simplified thermal expansion model [*Chen et al.*, 1998] is applied to estimate seasonal steric sea level changes using the temperature fields in the NOAA World Ocean Atlas 1994 (WOA94) [*Levitus and Boyer*, 1994]. WOA94 provides 1° × 1° objectively analyzed average temperature fields for the 12 months of the year for 19 layers from the surface to 1000 m depth. Temperature variations relative to the annual mean temperature field are derived for the top 14 layers (0 to 500 m depth, which covers most of the mixing layer in the ocean) and applied to estimate steric sea surface height change for a given month. A 5° × 5° two-dimensional moving average filter has been applied to the steric sea surface height fields. The monthly fields of sea surface height changes introduced by steric effect are linearly interpolated to each T/P repeat cycle with the same spatial resolution as the one we used in T/P sea level anomaly data and are then removed from the observed sea level anomaly fields. The mass load variation over the ocean is determined by

$$L_{ocean}(\phi, \lambda) = \Delta H(\phi, \lambda) \rho \quad (5)$$

where ΔH is sea level change relative to the mean after the estimated steric effect is removed and $\rho = 1.03$ g/cm^3 is the mean density of seawater. This steric correction significantly decreases the observed seasonal sea level varibility, especially in the northern hemisphere, for example, in the northern Pacific the RMS of mean

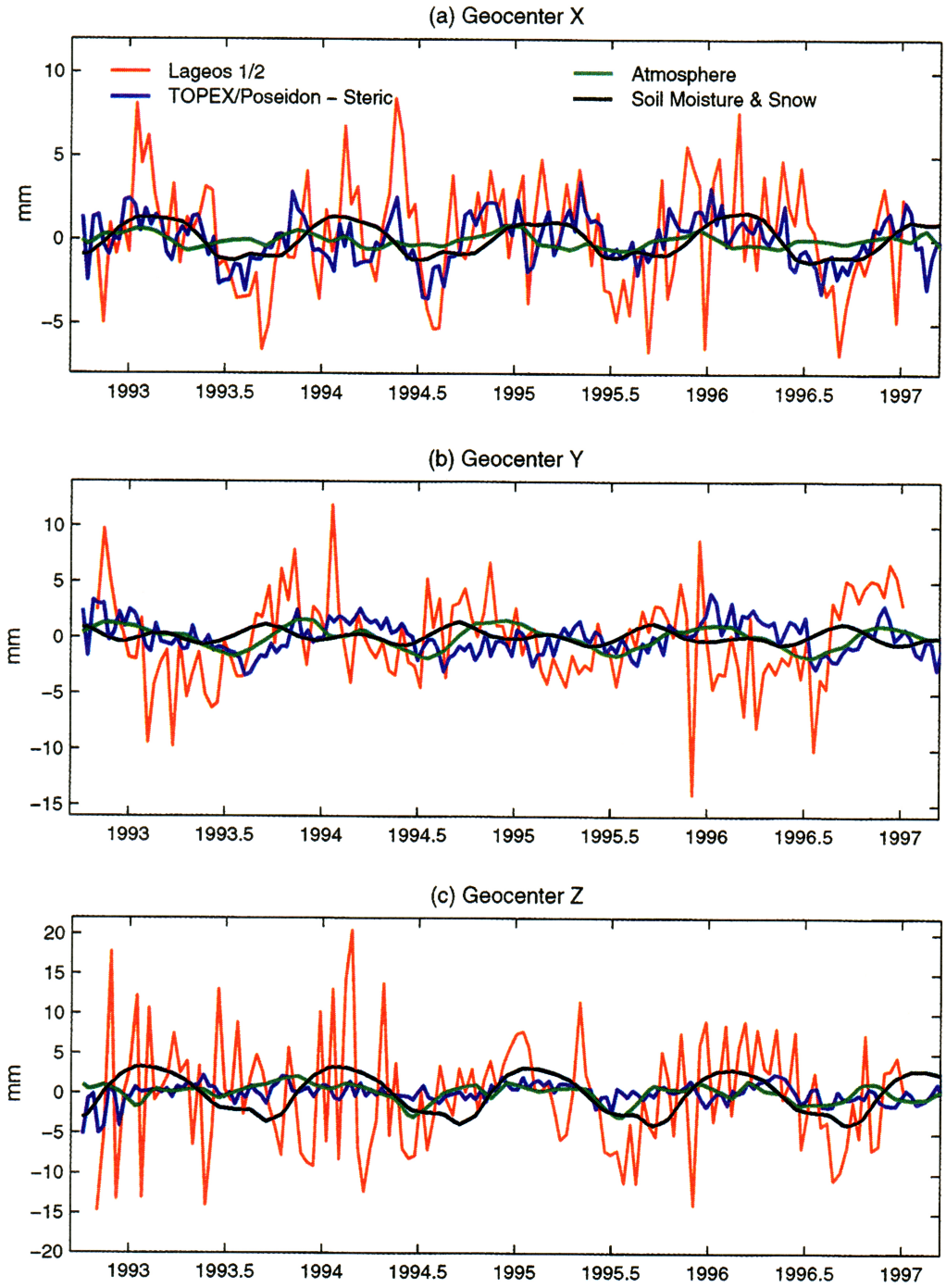

Plate 1. The three components (a)X, (b)Y, and (c)Z of observed geocenter solutions from Lageos 1 and Lageos 2, along with the atmospheric, continental hydrological, and oceanic contributions.

sea level anomaly varies from 3.1 mm to 1.4 mm before and after the steric correction is applied.

2.3. Hydrological Model

Mass redistribution on land due to the global continental hydrological cycle has been conventionally investigated using precipitation, evapotranspiration, and surface runoff data [*Kuehne and Wilson*, 1991; *Lei and Gao*, 1992; *Hinnov and Wilson*, 1987], either from quite sparse meteorological observations or from simplified hydrological models. In this paper we employ a new approach to estimate continental water storage changes, using the assimilated soil moisture fields and water equivalent snow depth fields in the NCEP-NCAR CDAS-1 climate system. The monthly surface diagnostic soil moisture fields contain two layers, which cover the top 2 m of soil (0-10 cm and 10-200 cm). The spatial resolution is described by the same Gaussian grid

Table 1. Observed and Estimated Annual and Semiannual Geocenter Variations

Source		Annual		Semiannual	
		Amplitude, mm	Phase, deg	Amplitude, mm	Phase, deg
Lageos 1/2	x	2.18	31	1.08	164
[*Eanes et al.*, 1997]	y	3.20	151	0.77	213
	z	2.79	45	0.38	13
Pressure (ECMWF)	x	0.55	104	0.23	90
[*Dong et al.*, 1997]	y	1.31	91	0.38	217
	z	0.87	133	0.73	271
Pressure (CDAS-1)	x	0.37	116	0.16	100
[this study]	y	1.26	94	0.41	217
	z	0.80	100	0.75	252
Land water (P-E-R)	x	3.28	25	0.84	319
[*Dong et al.*, 1997]	y	2.94	185	0.94	48
	z	3.57	40	0.66	344
Soil Moisture + Snow	x	1.28	44	0.15	331
[this study]	y	0.52	182	0.56	312
	z	3.30	43	0.50	75
Oceans (ISO model)	x	1.05	79	0.39	248
[*Dong et al.*, 1997]	y	0.09	121	0.29	282
	z	0.18	218	0.16	41
Oceans (TOPEX/Poseidon)	x	0.96	73	0.86	187
[this study]	y	0.97	52	0.73	173
	z	0.49	3	0.25	232
Total	x	4.22	44	0.83	30
[*Dong et al.*, 1997]	y	3.19	159	0.43	26
	z	3.46	55	1.10	313
Total	x	2.38	64	0.75	181
[this study]	y	2.00	90	0.89	221
	z	4.10	48	0.50	238

Variations were observed from Lageos 1 and Lageos 2, and estimated from atmosphere, continental hydrological cycle, and sea level variation and compared with the estimates of *Dong et al.* [1997]. The sign and phase errors in Dong's land water components have been corrected (D. Dong, personal communication, 1997). See text for definition of source terms. The phase is defined as follows: 0 refers to 0000 hours, January 1. Steric correction is applied to TOPEX/Poseidon data.

for surface pressure fields. Water content is represented by volumetric fraction, and total water storage changes (in g/cm^2) for a given grid point are estimated by integrating water content in the two soil moisture layers, and the equivalent water content in snow depth fields, as

$$L_{soil}(\phi,\lambda) = \sum_{i=1,2} \eta_i(\phi,\lambda) h_i \rho_o \tag{6}$$

$$L_{snow}(\phi,\lambda) = \Delta N(\phi,\lambda) \tag{7}$$

where η_i is the volumetric soil moisture for layer i, $i = 1, 2$, $h_1 = 10$ cm, $h_2 = 190$ cm, and $\rho_o = 1$ g/cm^3 is the water density. Variation of water equivalent snow depth (ΔN) gives directly the mass load variation (in g/cm^2).

In the CDAS-1 model assimilation, snow water is maintained constant over Antarctica (H. L. Pan, personal communication, 1998), which is also shown in the data. Even though we do see a huge snow variation along the edge of the Antarctic, especially on the west edge, these changes are just outside the landmask. In computing the hydrological contribution to geocenter motion, we actually exclude the entire Antarctic. This could be a major error source in our hydrological computation.

2.4. Observed Geocenter Motions

Geocenter variations are determined from a combination of Lageos SLR data. Translational motion of the ITRF with respect to the geocenter can be determined from SLR orbital residual analysis. Major error

sources include the mismodeling of nongravitational accelerations and orbital effects of time variable spherical harmonics of degrees greater than one [*Eanes et al.*, 1997]. A 4-year time series of geocenter solutions using 12-day intervals was determined from a combination of Lageos 1 and Lageos 2 SLR data. Plate 1 shows the three components of observed geocenter variations from Lageos 1/2. The amplitude and phase of annual and semiannual variations are listed in Table 1. Uncertainty is estimated to be ±3.5 mm in X, ±3.8 mm in Y, and ±8.6 mm in Z. The poorer determination of the Z component is a result of the geometry of the Lageos orbit and the distribution of the SLR stations. Observed geocenter motion shows both clear seasonal signals and a broad band of high-frequency variations. An interesting question is whether these high-frequency variabilities are real signal or noise.

3. Results and Comparisons

3.1. Atmospheric Contributions

The three components of predicted geocenter variations due to atmospheric pressure are shown in Plate 1, overlapped with Lageos solutions. The atmosphere appears to be responsible for much of the variability in the Y component due to the distribution of ocean/land, while its contributions to the X and Z components appear less important. Table 1 provides quantitative comparisons for annual and semiannual components and shows that there is reasonably good agreement with annual terms given by *Dong et al.* [1997] in both amplitude and phase (see Table 1).

3.2. Continental Hydrological Effects

Geocenter motions predicted from continental water storage change are also shown in Plate 1, with seasonal components in Table 1. The results indicate that the continental hydrological cycle provides significant contributions to the X and Z components, especially Z. The continental hydrological cycle accounts for over half the observed annual variation in the X component and has nearly the same phase (see Table 1) and appears to be the dominant contributor to the Z component. The hydrological model predictions from this study are quite different from the results of *Dong et al.* [1997] in the X and Y component (see Table 1), while the agreement in Z is very good in both amplitude (3.30 mm vs. 3.56 mm) and phase (43° versus 40°; see Table 1 for phase definition).

3.3. Contributions From the Oceans

The potential oceanic contributions computed from T/P sea surface anomalies are shown in Plate 1, along with atmospheric and hydrological predictions. Mass variations within the oceans account for a major part of the observed geocenter variations in the X and Y components, especially the X component, mainly because the geographical orientation of the oceans is close to the X direction (Greenwich meridian). Figure 1 shows the estimated cross correlations between observed geocenter motion and T/P prediction after seasonal variations (annual and semiannual) are removed from both series. There is a good correlation in X over a wide range of frequencies, and the agreements in Y and Z are relatively poorer. The annual variation in the X component (1.0 mm and 73°) is in very good agreement with *Dong et al.*'s [1997] estimation (1.1 mm and 79°) from ocean bottom pressure using the ISO ocean circulation model (see Table 1).

3.4. Overall Budget of Geocenter Variations

The X, Y, and Z components of combined geocenter variations caused by mass variations in geophysical fluids, including atmospheric pressure, the continental

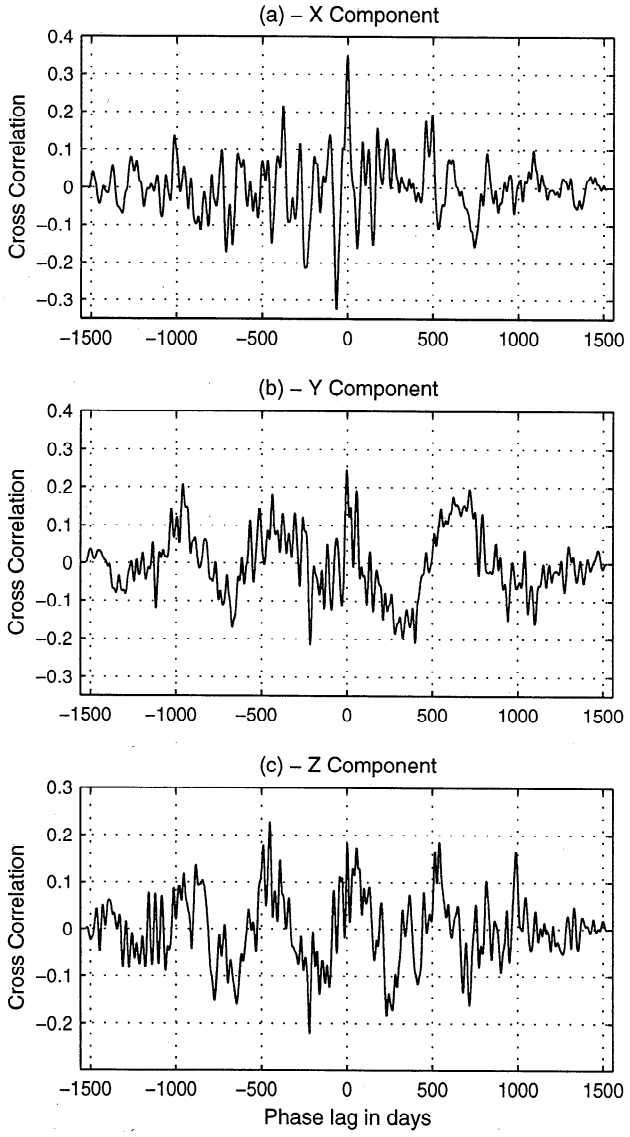

Figure 1. Cross correlations between nonseasonal residuals of observed geocenter motions and T/P predictions for the (a)X, (b)Y, and (c)Z components.

hydrological cycle, and sea level anomalies, are shown in Figure 2, in comparison with the Lageos observations. The annual and semiannual variations of each component are listed in Table 1. We have also calculated the total annual variations for the three major contributors given by *Dong et al.* [1997]; however, we omit the ocean tidal effect, which is about 2 orders of magnitude smaller. Figure 3 shows vector representations of seasonal geocenter variations from Lageos solution, atmospheric pressure, the continental hydrological cycle, and ocean mass redistribution for the three components. The overall seasonal variations estimated from *Dong et al.* [1997] are also included.

4. Discussion

Comparisons of the observed geocenter motions with the predicted effects of geophysical fluids indicate that the atmosphere, the continental hydrological cycle, and the oceans are all important contributors. The atmosphere is predicted to have large contributions in the Y component, while the oceans tend to dominate in the X

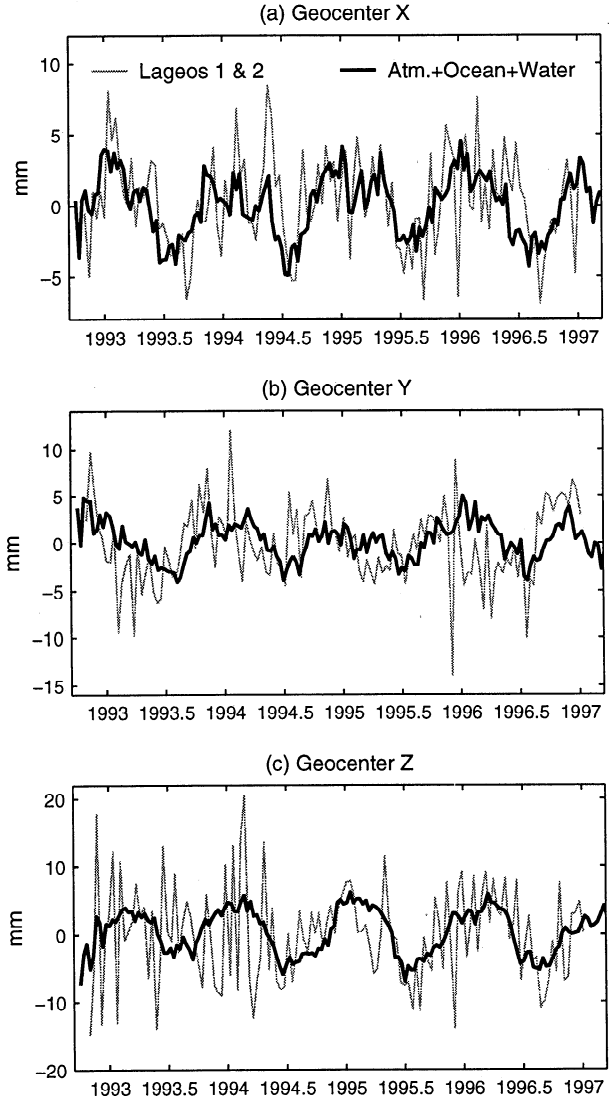

Figure 2. The total budget of geocenter variations from atmospheric pressure variations, continental water storage changes, and sea level variations, in comparison with the observed geocenter variations from Lageos 1/2, for the (a)X, (b)Y, and (c)Z components.

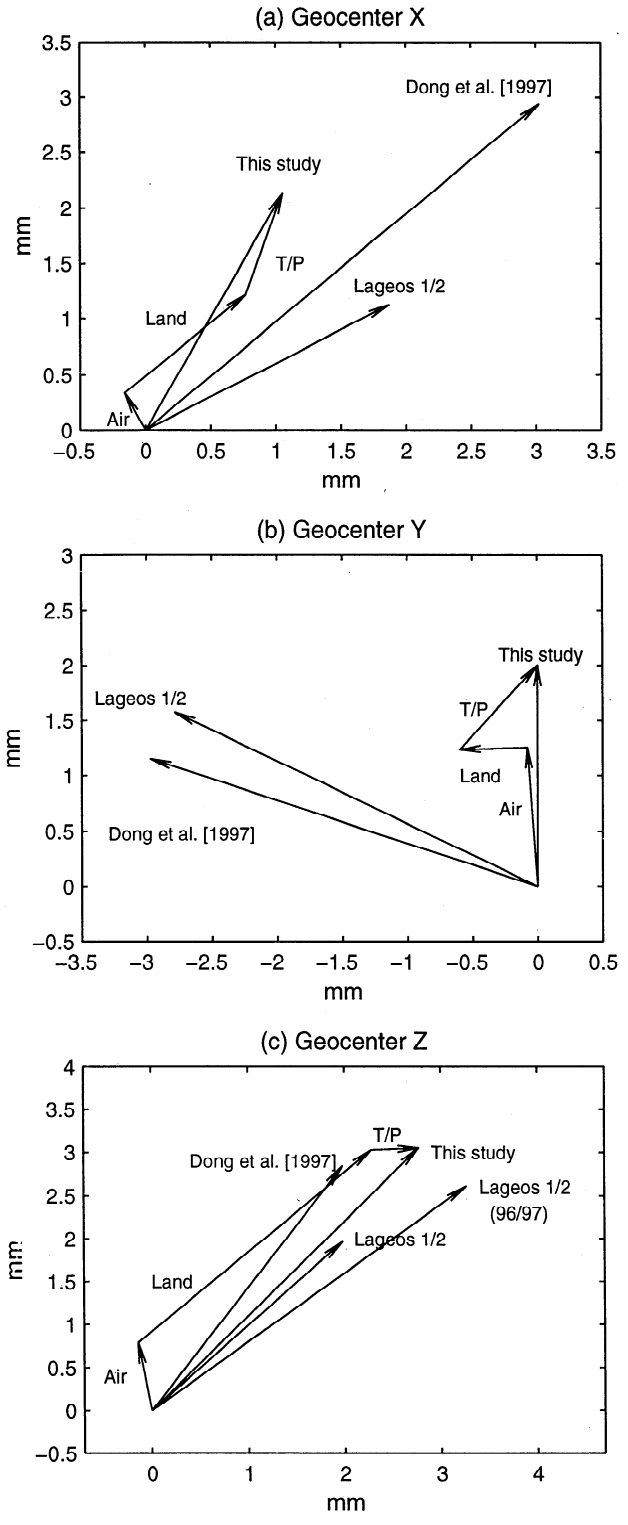

Figure 3. Vector representation of annual geocenter variations of the three components (a)X, (b)Y, and (c)Z . The results from this study are shown together with the Lageos 1/2 solution and the estimates given by *Dong et al.* [1997] (the sign and phase errors of *Dong et al.* [1997] are fixed).

component over a wide range of frequencies, mainly as a result of the geography of continents along Y and the oceans along the X direction. The continental hydrological cycle provides significant contributions to X and Z, especially the Z component. Large seasonal variability (about 3.3 mm) in the Z component is due to the opposite phase in the two hemispheres.

The good correlation of nonseasonal variations in the X component between observed geocenter motions and T/P ocean mass predictions (see Plate 1 and Figure 1) is a strong indication that some of the sea level anomalies determined from TOPEX/Poseidon altimeter data are indeed from ocean mass redistribution. This conclusion is supported by other investigations using gravity field variations, earth rotation, and the global water mass balance [*Chen et al.*, 1997, 1998].

Our atmospheric estimates are in reasonably good agreement with the results of *Dong et al.* [1997]. The slight discrepancy is possibly due to the use of different atmospheric models and differences in integration algorithms, land mask definitions, and treatment of the inverted barometer over the oceans. There is good agreement between these two studies in the predicted ocean contribution in the X component. The annual variation estimated from T/P altimeter data is nearly identical to the ISO ocean bottom pressure approach described by *Dong et al.* [1997]. However, the corresponding predicted ocean contributions to the Y and Z components do not agree well. These discrepancies could be caused by the mismodeling of the mass distribution in the ocean general circulation model or the geophysical corrections to T/P altimeter data.

Predicted geocenter variations due to continental water storage change using CDAS-1 assimilated soil moisture and snow fields are generally quite different from estimates by *Dong et al.* [1997] using a traditional precipitation, evaporation, and runoff budget, except for the Z component. The agreement in phase is relatively good (see Table 1). The agreement appears reasonable considering our generally poor knowledge of the global hydrological cycle. Many error sources may contribute to the discrepancies, including the mismodeled evapotranspiration and runoff in the traditional approach and assimilated soil and snow fields due to lack of observational input. The soil water change under 2 m depth and water exchange between soil water and groundwater could also be a major error source.

Accurately determined geocenter variations and a full understanding of the observed geocenter motions provide important information about mass redistribution in the Earth system and should provide observational constraints on mass budgets in global atmospheric and hydrological models, especially those of the snow/ice fields in the Antarctic, the Arctic, and Greenland, which are of great interest in global climate studies. Geocenter variations are also important in establishing a more accurate ITRF system, which influences virtually all geodetic observations.

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