Seasonal Variations of the Earth's Gravitational Field: An Analysis of Atmospheric and Ocean Tidal Excitation

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Abstract. Laser ranging measurements to a single satellite are sensitive to the Earth's gravitational field and its temporal variations. Using 13 years (1 980-1992) of LAGEOS I laser ranging data, we have recovered monthly mean linear combinations of even and odd degree zonal spherical harmonic coefficients of the Earth's gravitational field, Because unmodeled once-per-revolution ac.colorations of L AGEOS] of currently unknown origin contaminate the recovered odd degree zonal gravitational field coefficients, we focus our attention in this report on the even combination which exhibits a significant secular trend as well as dominant seasonal variations (at annual and semi-annual periods). Comparing this observed result With the Same linear combination Of even zonal spherical harmonic coefficients derived from gridded global surface pressure data of the National Meteorological Center (NMC) from] 984 to 1992 indicates that atmospheric pressure fluctuations are the dominant cause of the observed even zonal gravitational field variations at the annual period, explaining the observed amplitude to within 1σ and the phase to within 20. At the semi-annual period, the modeled effect of the self-consistent equilibrium ocean tide is found to be greater than that of atmospheric pressure fluctuations, with agreement with the observat ions seen at the 1 σ level when both effects are considered. The influence of seasonal variations in groundwater is also discussed.

1. INTRODUCTION

The Earth is a dynamic system– it has a fluid, mobile atmosphere and oceans, a continually changing global distribution of ice, snow, and ground water, a fluid core that is undergoing some type of hydromagnetic motion, a mantle both thermally convecting and rebounding from the glacial loading of the last ice. age, ant] mobile tectonic plates. These processes affect a number of global geodynamic properties of the Earth including its gravitational field, rotation, and location of the Earth's center-of-mass relative to the crust. Since the gravitational field of the Earth changes only in response to net mass redistributions, observations of the Earth's time varying global gravitational field allow the isolation and subsequent investigation into the changing mass distribution of the Earth (see

for example, *Yoder et al., 1983; Rubincam, 1984; Cheng et al,* 19S9; *Nerem et al, 1993; Gegout and Cazenave, 1993).* Here, we investigate seasonal variations in the Earth's gravitational field through the analysis of LAGEOS 1 satellite laser ranging (SLR) measurements spanning 1980 to 1992. Global surface pressure data from the National Meteorological Center (NMC) spanning 1984 to 1992 arc analyzed to study the contribution of atmospheric mass redistributions to the observed variations of the Earth's gravitational field, in addition, a self-consistent equilibrium ocean tide model [*Ray and Cartwright, 1994] is* used to predict the contribution of the annual and semi-annual ocean tides to the observed seasonal gravitational field variations, and the contribution of seasonal groundwater variations is also considered. Since laser ranging measurements to a single satellite arc only sensitive to certain satellite-dc~>cl~clc~~t linear combinations of the even and, separately, odd degree zonal gravitational field coefficients, wc form those same linear combinations of coefficients when modeling the effect on the gravitational field of seasonal atmospheric pressure, ocean tidal, and groundwater variations.

2. DATA ANALYSIS

Wc analyze LAGEOS I laser ranging measurements acquired during 1980-1992 utilizing the GEODYN software package to perform numerical integration of sate]] itc orbits and to construct normal matrices for c.very monthly orbit segment. The a priori models adopted in determining the LAGEOS 1 orbit arc: Wahr's solid Earth tide model, an equilibrium mode] for the 18.6 year tide [*Trupin and Wahr, 1990],* the JGM-2 gravitational field model [*Nerem et al.*, 1994b] and its corJ"e.spending ocean tide model. Since both the annual (Sa) and semi-annual (Ssa) tides of the JGM-2 ocean tide model arc contaminated by the effects of annual and semi-annual fluctuations in atmospheric mass distribution, wc set to zero the zonal Sa and Ssa ocean tide amplitudes through spherical harmonic degree 8 in order to fully remove from the a priori model the contributions of seasonal atmospheric pressure and ocean tide variations. The effects of solar radiation pressure, albedo, atmospheric drag, and Yarkovsky thermal drag [*Rubincam, 1988]* arc included. Gene.ral relativistic corrections [*Huang et al.*, 1990] arc taken into account and the DE200 planetary ephemeris is adopted, 'l'he JGM-2 model relate.d site coordinates and velocities arc held fixed, and the geometrical corrections of site positions duc to solid Earth tide and ocean tide loading [*Scherneck,* 1991] are employed. The SPACE92 Earth orientation series *[Gross,* 1993] was adopted to provide Universal Time (UT1-l'AI) and polar motion.

The considered parameters in our analysis include satellite state vectors every 30 days with along-track acceleration parameters solved for every 15 days, MoJ~thly-averaged

normalized geopotential spherical harmonic coefficients through degree and order 8 arc determined at monthl y intervals. In total, 85 parameters are considered for each month-long interval. Note that since ranges to a single satellite are only capable of determining certain linear combinations of the gravitational field coefficients, wc impose a general mapping function [*Dong and Bock*, 1989] to each normal matrix to project the 77 considered geopotential coefficients onto 4 independent parameters. In this study, the chosen independent parameters are 1 inear combinations of the even and, separately, the odd degree zonal gravitational field coefficients, as well as two additional linear combinations of the non-zonal coefficients.

The effect of surface mass variations on the Earth's global gravitational field as parameterized by the full y normalized gravitational field coefficients (C_{lm}, S_{lm}; also known as the Stokes coefficients) can be shown to be [*e.g., Chao*, 1 994]:

$$\begin{matrix} C_{lm} \\ S_{lm} \end{matrix} = \frac{1+k_l'}{2l+1} \frac{R_e^2}{M} \int_s q(\varphi,\lambda) \begin{matrix} \cos(m\lambda) \\ \sin(m\lambda) \end{matrix} P_{lm}(\sin\varphi)\, dS \qquad (1)$$

where M is the mass of' Earth, R_e is the radius of the Earth, k_l' is the load Love number of degree 1, φ is the latitude, λ is the longitude, and $P_{lm}(\sin\varphi)$ are normalized Legendre functions with the integral of $P_{lm}^2(\sin\varphi)$ over the surface of a sphere equal to 4π. In this study, we set k_2' = -0.308, k_4' = -0.132, k_6' = -0.089 and k_8' = -0.078 [*Farrel*, 1972]. The surface load mass density is denoted by $q(\varphi,\lambda)$. For the case of surface pressure loading, $q(\varphi,\lambda) = p(\varphi,\lambda)/g$, while for ocean tide loading, $q(\varphi,\lambda) = \rho_w h(\varphi,\lambda)$. Here, g is the gravitation] acceleration, $\rho_w = 1025\ kg/m^3$ is the ocean water densit y, and $h(\varphi,\lambda)$ is the ocean tide height (set to zero over land).

The NMC gridded global surface pressure data used here spans 1984-1992 at 12-hour intervals with a spatial resolution of 2.5° x ?.. SO. The atmospheric coefficients at each 12-hour interval arc calculated for both the non-inverted barometer (NIB) and inverted barometer (IB) models for the response of the oceans to atmospheric pressure variations. The NIB model treats the ocean as a rigid body thereby fully transmitting the imposed surface loading to the underlyi ng oceanic crust. On the other hand, the IB model considers the ocean's response to surface loading as purely isostatic. The response of the real ocean is likely to be somewhere between these two extremes. Using (1), wc calculate the atmospheric pressure-induced zonal gravitational field coefficients to degree 8 and form monthly means over the same time intervals as the LAGEOS solutions. For comparison

with the I-AGP;OS-observed gravitational field coefficients, the same linear combination of the even zonal harmonics (see following sections) arc formed using the monthly means of the atmospheric geopotential coefficients for both the 1 B and NIB cases.

3. RESULTS AND COMPARISONS

By definition, the linear combinations of the even and, separately, odd gravitational field coefficients are given by:

$$C_{even} = C_{20} + a_4 C_{40} + a_6 C_{60} + a_8 C_{80} + \ldots \quad (2)$$
$$C_{odd} = C_{30} + a_5 C_{50} + a_7 C_{70} + \ldots$$

Here $a_4, a_5, \ldots . a_8$ are the linear combination coefficients. The observed monthly C_{even} and C_{odd} solutions recovered from the LAGEOS I satellite laser ranging measurements spanning 1980 - 1992 are plotted in Figure 1. To focus on the temporal variations of the gravitational field, wc have removed the mean values from the monthly C_{even} and C_{odd} solutions. For the C_{even} series, the dominant structures arc the annual and semi-anJ~Llal variations with a significant secular trend and some. indication of interannual variations. For the C_{odd} series, the dominant structures are annual Variations with the so-called "] AGEOS anomaly" [*Eanes and Watkins*, 1991] appearing in 1989, 1991 and 1992. These apparently anomalous variations in the estimated C_{odd} series arc thought to be caused by unmodeled once-per-revolut ion perturbation forces, to which the LAGEOS orbital eccentricit y is very sensitive. Recent study [*Nerem et* al., 1994a] suggests that the "LAGEOS anomal y" may be linked to perturbations caused by the atmospheric thermal tide (S_1), which is not considered in this study. Since the "missing" unmodeled perturbation forces appear to be predominant in the C_{odd} series and arc still under investigation, we will focus our discussion here on the C_{even} series.

The trend of the C_{even} estimates from 1980 to 1992 is $1.33 \pm 0.16 \times 10^{-11}$ l/year, which is consistent with previous results at the one σ level and is attributable to the effects of postglacial rebound [*Yoder at al*, 1983; *Rubincam*, 1984; *Cheng et al,, 1989; Eanes am-l Watkins, 1991; Gegout and Cazenave, 1991, Nerem at al., 1993]. To* obtain seasonal variations of the C_{even} estimates, wc first apply a high-pass filter with a period cutoff of *2* years. From 1984 to 1992 (the interval of the available NMC atmospheric pressure data), the amplitudes of the annual and semi-annual variations of C_{even} arc $1,10 \pm 0.09 \times 10^{-10}$ and $0.92 \pm 0.09 \times 10^{-10}$, respectively (see Table 1). For the 1980-1989 time period, our annual amplitudes and phases as well as the semi-annual phase are in agreement at the one

Table 1

	Annual variation		Semiannual variation	
C_{even} from LAGEOS	amp $(1\ 0^{-10})$	phase (deg)	amp (10-10)	phase (deg)
1984-1992	1.10 (0.09)	28.6 (4,8)	0.92 (0.09)	114.9 (5.6)
1980-1989	1.13 (0.09)	2'/.8 (4.9)	0,94 (0.09)	111.0 (5.8)
1980-1989 (*Nerem et al.*)	1.20	25	1.13	108

l'base is relative. to January 1, The numbers in parentheses rc.present 1 σ formal uncertainties.

σ level with the results of *Nerem* et *al. [1993]* with the amplitude of our semi-annual estimate being smaller than theirs by two σ (Table 1).

Figure *2* compares the C_{even} linear combination of even degree zonal gravitational field coefficients recovered from LAGEOS 1 laser ranging measurements with just the C_{20} coefficients estimated from the NMC global pressure data for both the NIB and IB models. In this comparison, the low frequency components with periods longer than 2 years have been removed. The amplitudes and phases of the annual and semi-annual variations arc listed in '1'able 2; both visual ant] numerical comparisons, especially of the annual amplitude, indicate a marginal preference for the NIB mode.1. For the semi-annual variations, the C_{20} atmospheric pressure-induced geopotential amplitudes of both the NIB and IB models are onl y 10% of the observed C_{even} linear combination with about 60° phase differences. Th us, the direct comparison of the observed C_{even} linear combination with the atmospheric pressure-inc]uccd C_{20} is in conflict with the expectation that on seasonal and longer time scales the ocean's response to surface loading is close to the IB model [*Trupin and Wahr,* 1 990].

The problem here, of course, is that this comparison was clone between a linear combination of the observed even degree zonal gravitation] field coefficients with just the second degree zonal coefficient of the modeled atmospheric pressure-iJ)clLJcccl gravitational field, The contributions from higher degree ($l = 4, 6, \ldots$) even zonal coefficients of the atmospheric pressure-i nduced gravitations] field must be taken into account by forming that same linear combination of them to which laser ranging measurements to the LAGEOS I

I'able *2:* Variations of even zonal gravitational field from atmosphere, groundwater and ocean in comparison with the recovered geopotential coefficients from LAGEOS I

l'base is relative to January 1, 1984 in sine. convention. C_{even} of groundwater variations is constructed using the second and fourth degree gravitational coefficients of *Chao and O'Connor* [1988]. Both Sa and Ssa oceanic tidal contributions are combinations of the second to eighth even degree spherical harmonics. The numbers in parentheses represent 1 σ uncertainties. For LAGEOS I solutions, the numbers come from the. formal uncertainties. For NMC solutions, the numbers are estimated from scatter analysis.

(a) Annual variation

1984-1992	amp (10^{-10})		phase (deg)	
LAGEOS	1.10 (0.09)		28.6 (4.8)	
ocean tide C_{even}	0.09		267.7	
NMC C_{20} only	O.98(O.1O)(IWR)	0.66(().07) (IB)	5.2 (S.8) (NIB)	26.2(6.4) (IB)
NMC C_{even}	1.32(0 .15)(N1D)]	.01 (().] 1) (IB)	6.0 (6,5) (NIB)	16.5(6.4) (IB)
atmos+tide	1.31 (NIB)	0.98 (IB)	2. 1(NIB)	11,5 (IB)
ground water C_{even}	0,63		59.3	
atnlos+-tide+-water	1.73 (Nil])	1.48 (IB)	19.9 (NIB)	29.9 (IB)

(b) Semiannual variatic ı

1984-1992	amp (10^{-10})		phase (deg)	
LAGEOS	0.92 (0.09)		114.9 (5.6)	
ocean tide C_{even}	0,55		I 10.7	
NMC C_{20} only	0,09(0. 10)(NIB)	0.09(0.07) (IB)	77.6(63 .0)(NIB)	170.1 (46.9)(IB)
NMC C_{even}	2.42(0. 15)(NIB)	0.28(0. 11) (IB)	06.6(20 .6)(NIB)	118,5(23.4)(]]])
atmos+tide	0.97 (NIB)	0.83 (IB)	108.9 (NIB)	113.3 (IB)
ground watt.r C_{even}	0,26		*266.3*	
at mos+t ide+water	0.74 (NIB)	*0.61* (NIB)	*116.7* (NIB)	*124.S* (IB)

satellite are sensitive [*Yoder et o].,* 1983; *Gutierrez and Wilson, 1987; Cheng et al., 1989; Chao and Au, 1991].* The appropriate values to be used for the linear combination

coefficients can be determined by first noting that perturbations to the even degree renal gravitational field coefficients of the Earth primarily affect the rate of change of the longitude of the ascending node ($d\delta\Omega/dt$) of the satellite's orbit [*Yoder et al.*,1983]. From first order orbital perturbation theory wc have [*Kaula*, 1966; *Yoder et al.*, 1983; *Gutierrez and Wilson*, 1987; *Cheng et al., 1989]:*

$$\frac{\partial \delta\Omega}{\partial t} = A\ (\delta C_{20} + f_4 \delta C_{40} + f_6 \delta C_{60} + \ldots) \qquad (3)$$

where $$A = \frac{3\sqrt{5}}{2}\, n \left(\frac{R_e}{a}\right)^2 \frac{\cos i}{(1 - e^2)^2}$$

$$f_4 = \frac{3\sqrt{5}}{64} \left(\frac{R_e}{a}\right)^2 (7\sin^2 i - 4) \frac{1 + \frac{3}{2} e^2}{(1 - e^2)^2}$$

$$f_6 = \frac{7\sqrt{65}}{64} \left(\frac{R_e}{a}\right)^4 (8 - 36\sin^2 i + 33\sin^4 i) \frac{1 + 5 e^2 + \frac{15}{8} e^4}{(1 - e^2)^4}$$

a, i, and c arc the semi-major axis, inclination, and eccentricity of the satellite's orbit, and n is the satellite's mean angular velocity. For LAGEOS 1, $f_4 = 0.496$, $f_6 = 0.129$, anti $f_8 = 0.009$ [*Cheng et al.,) 989].* Thus, the desired linear combination coefficients arc $a_4 \approx f_4$, $a_6 \approx f_6$ and $a_8 \approx f_8$.

Using the above values for the linear combination coefficients a_4, a_6 anti a_8, we linearl y combine the even degree zonal atmospheric pressure-induccel gravit ational field coefficients from the NMC global pressure data for both the NIB and IB models. As before, the low frequency components having periods longer than 2 years arc removed (see Figure 3 and Table 2 for the period 1984 to 1992). The formation of the linear combination of even degree zonal atmospheric pressure-induced gravitation] field coefficients does improve the overall fit to the observations for both the NIB and IB models. The correlation coefficients between the modeled NMC pressure and observed LAGEOS 1 results increases from 0.64 to 0.75 and 0.68 to 0,73 for the NIB and IB models, respectively (also compare Figures 1 and 3). At the annual period, the IB model is in closer agreement with the observations than the NIB model, agreeing in amplitude to within one σ and in phase to within two σ. But at the semi-annual period, neither the IB or NIB models agree with the observations.

Table 3: Correlation analysis (1 984-1 992)

C_{20} only		C_{even}	
NIB 0.64 (0.424)	1130.68 (0.424)	NIB 0.75 (0.424)	1110.73 (0.424)

The number (0.424) in parenthesis represents the 99% significance level for zero correlation series with 36 samples. This value (0.424) is calculated from *t*-test for product moment correlation with N=36. Due to the filtering, the monthly estimates are correlated within the interval of 3 months. Thus the number of independent estimates is reduced from 108 to 36, which is taken into account.

Contributions from all geophysical mechanisms that can be expected to produce detectable signals should be considered when searching for the cause of the deficit at the semi-annual period. The principal non-atmospheric candidates for this deficit are likely to be ocean tidal and non-tidal mass redistributions, groundwater storage, and ice sheet volume changes. The deformation of the solid Earth due to seasonal variations in spin rate creates changes in the even degree zonal gravitational field coefficients at the 10^{-12} level, which is too small to account for the above deficit. 'J'able 2 give.s the modeled contributions of seasonal ocean tidal and groundwater storage variations to the Earth's gravitational field (in both cases the same linear combination of the even degree zonal coefficients are formed as was done above for the at mospheric pressure variations). Note that the listed sources are incomplete; some potentially important contributors, such as wind-driven oceanic mass redistribution, are not included here due to a lack of published results.

At the semi-annual period, the ocean tides are expected to make a significant contribution. On seasonal and longer time scales, the oceanic response to tidal perturbation forces is likely to be close to equilibrium [*Proudman*, 1960; *Carton and Wahr, 1986; Dickman, 1989];* d ynamical models indicate that the discrepancies from equilibrium for the Sa and Ssa tides are very small [*Dickman*, 1989]. Schwiderski's tide model is constrained by tide gauge data, which include the effects from all perturbation sources [*Schwiderski,* 1980]. In particular, on seasonal time scales the variations of the atmospheric pressure, wind-driven currents, and probably the recycling of groundwater also enter the tide gauge data, thereby contaminating Schwiderski's Sa and Ssa results through hydrodynamic] propagation. Similarly, satellite-gcoclcsy derived ocean tide models [*Christodoulidis et al,, 1988]* also contain the effects from mass variations of the atmosphere and groundwater. Since our aim is to model the ocean tidal contribution to the I.AGEOS-observed even combination of gravitational field coefficients, we calculate the Sa and Ssa ocean tidal

contributions using the grid values of admittance. for long-period sc]f-consistent equilibrium ocean tides from *Ray and Cartwright [1994]*. The effect on t he annual component is found to be quite small (1-3% of the observe.d amplitude); while the impact is much greater on the semi-annual component (nearly 6070 of the observed amplitude). With atmospheric pressure alone, only 30-45% of the observed semi-annual amplitude is accounted for; while when the ocean tidal effect is included, the amplitude and phase for ocean tide plus atmospheric pressure (for both the IB and NIB cases) arc in agreement with the observations to within one σ.

The residual formed by subtracting from the observations the modeled effects of ocean tides and atmospheric pressure fluctuations is much smaller than the modeled effect of variations in groundwater storage. This suggests that either the effects of groundwater storage arc being overestimated, or that some other geophysical mechanism is making a compensating contribution to the observed seasonal variations in the even linear combination of zonal gravitational field coefficients. A main goal of the Global Energy and Water Cycle Experiment (GEWEX; *Chahine*, 1992) program is to gain an improved understanding of the Earth's hydrological cycle. Thus, improved estimates of groundwater storage can be expected in the future. Other sources of geophysical excitation, such as the wind-driven oceanic mass redistribution, also remain to be studied. in addition, one cannot eliminate the possibil it y of incompleteness in the satel 1 itc pert urbat ion force model, errors in the atmospheric pressure data, and deviations from equilibrium of the ocean tides, that would also contribute to these apparent residuals.

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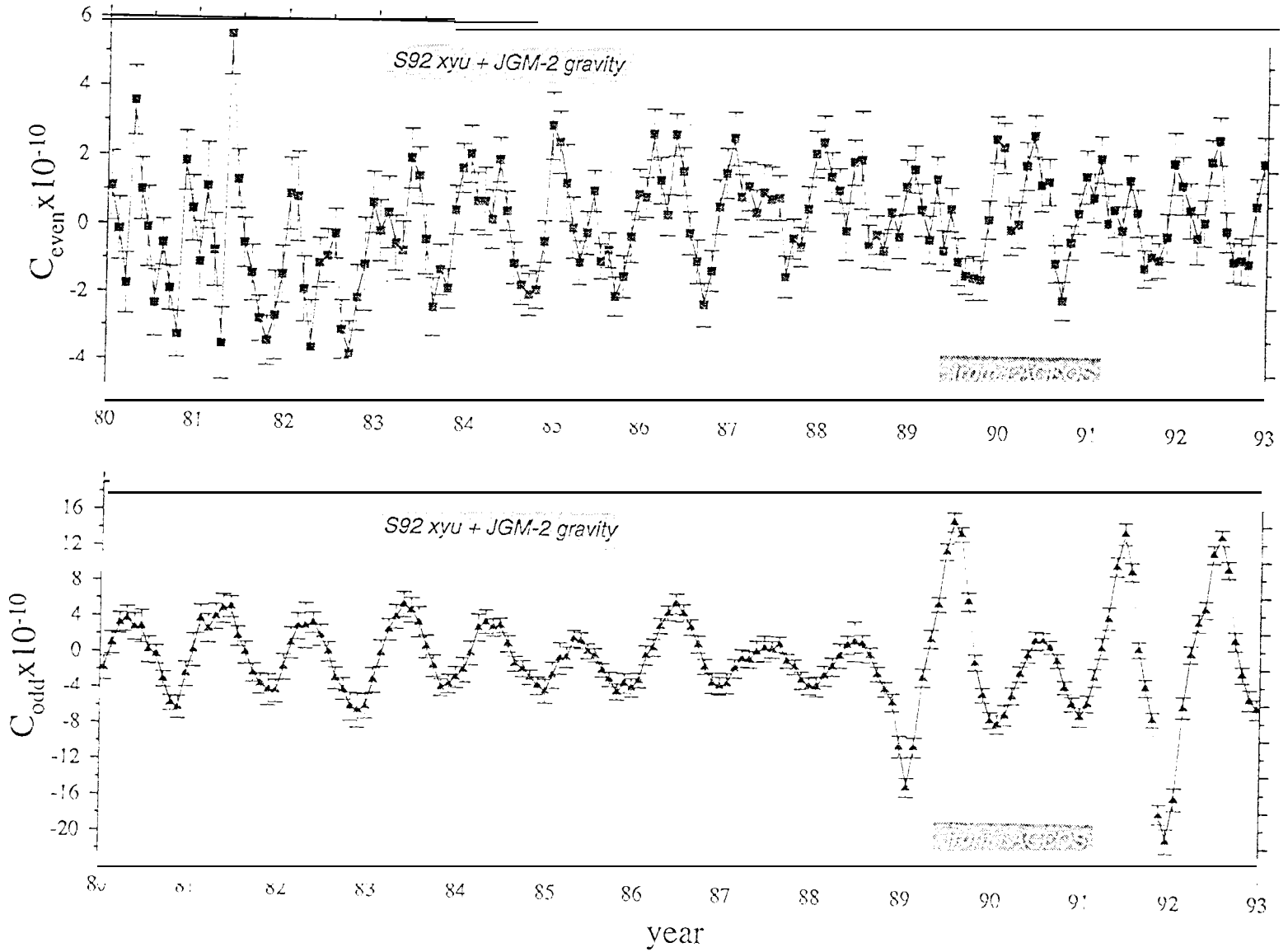

Figure 1: Monthly C_{even}, C_{odd} linear combination of gravitational coefficients from Jan. 1980 to Dec. 1992 recovered from LAGEOS I SLR data. The error bar represents a 1 σ formal uncertainty. The mean values of the C_{even}, C_{odd} have been removed in the plot.

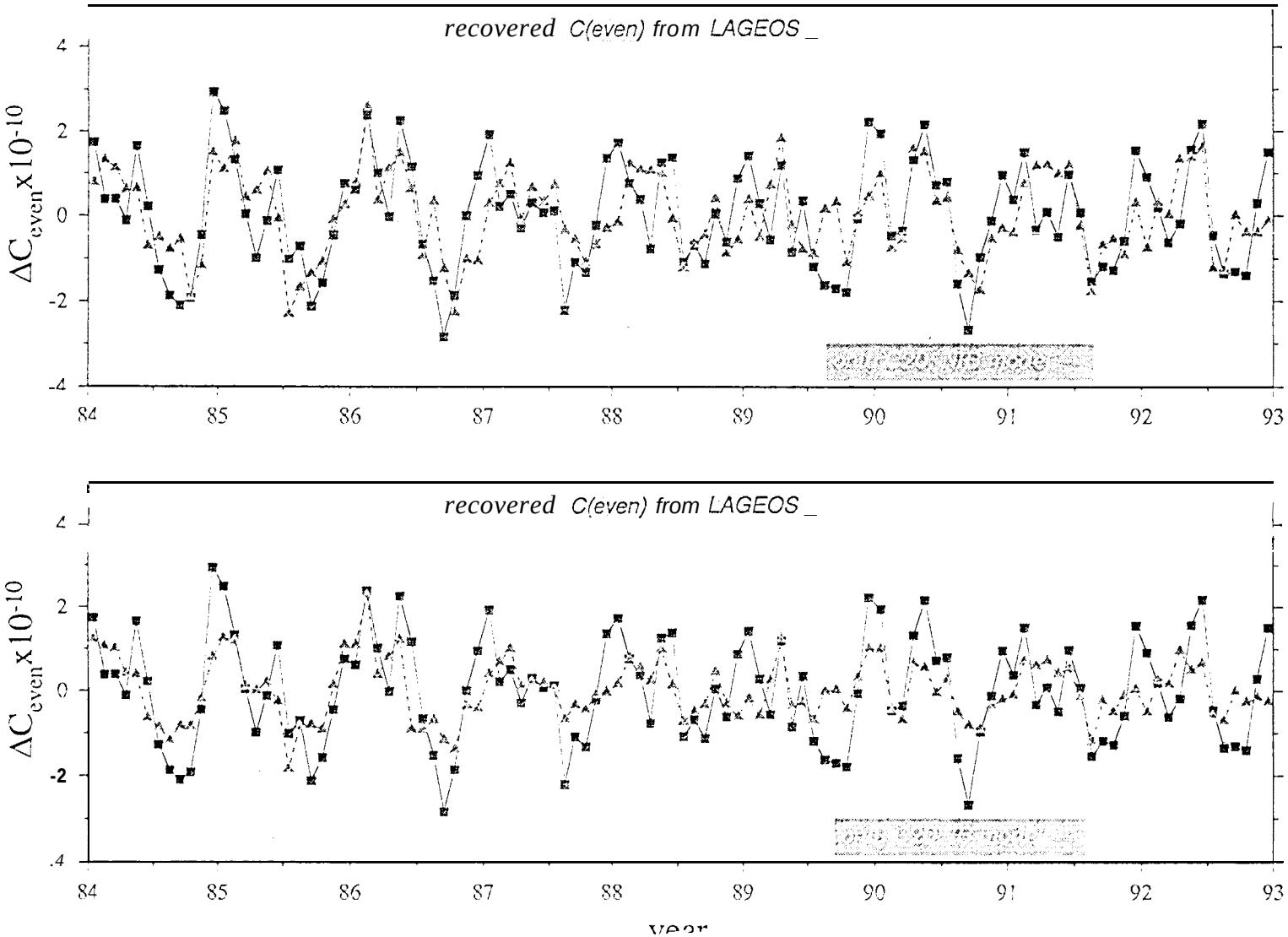

Figure 2: (a) Variations of monthly C_{even} recovered from LAGEOS I SLR data (solid line) and the variations of monthly C_{20} calculated from NMC atmospheric surface pressure data with non-inverted-barometer (SIB) model (dashed line). The variations with periods longer than two years have been removed from both series. (b) Same as (a) except the dashed line represents the variations of monthly C_{20} calculated from NMC atmospheric surface pressure data with inverted-barometer (IB) model.

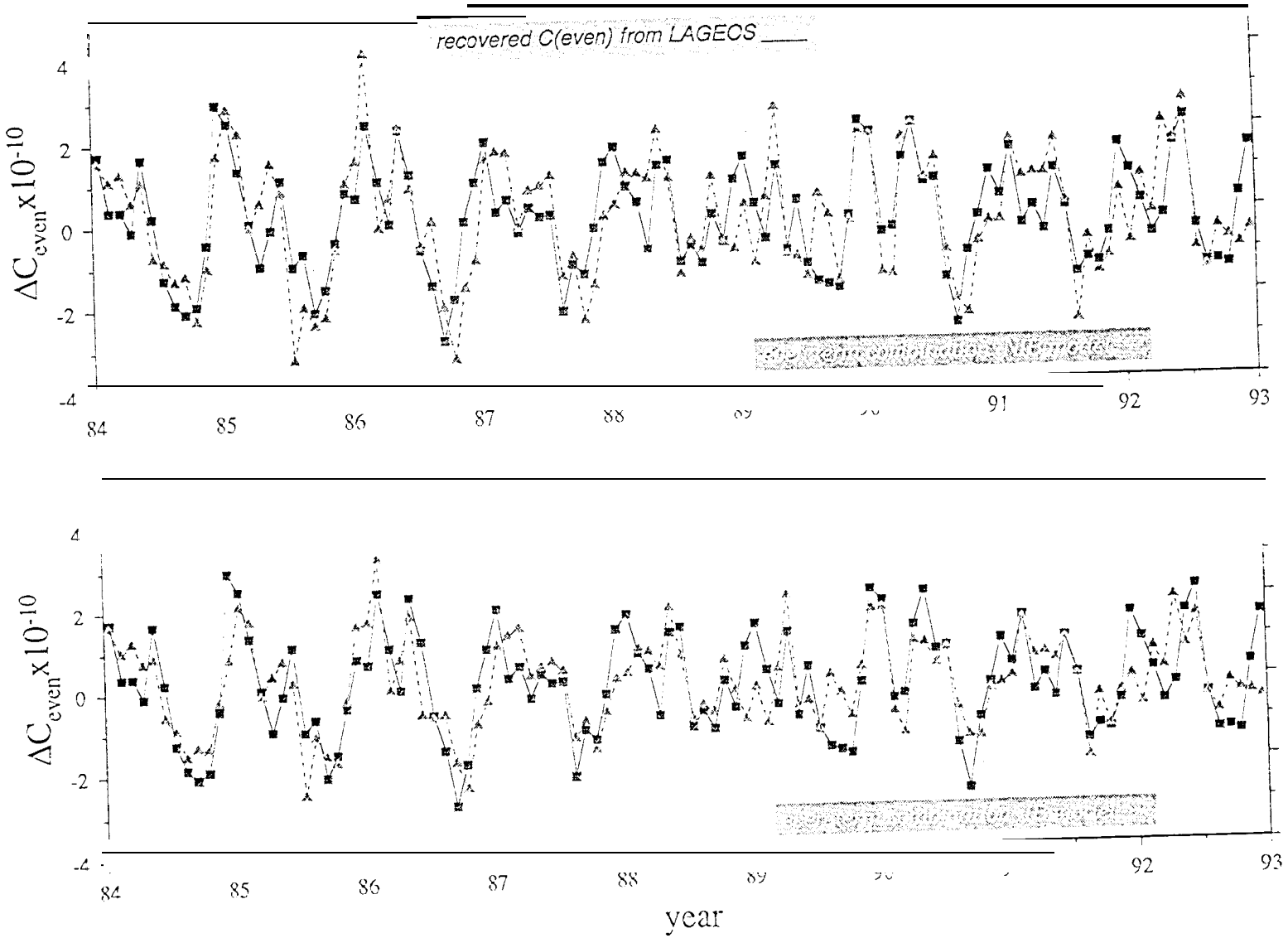

Figure 3: (a) Variations of monthly C_{even} recovered from LAGEOS I SLR data (solid line) and the variations of monthly C_{even} calculated from NMC atmospheric surface pressure data with non-inverted-barometer (NIB) model (dashed line). The variations with periods longer than two years have been removed from both series. (b) Same as (a) except the dashed line represents the variations of monthly C_{even} calculated from NMC atmospheric surface pressure data with inverted-barometer (IB) model.