Modulation of the Seasonal Cycle in Length-of-Day and Atmospheric Angular Momentum

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Abstract. Global warming, by definition, changes the atmospheric temperature field. This temperature change is not expected to be uniform, either geographically, or with height in the atmosphere. By the thermal wind equation, changes in the pole-to-equator temperature gradient will cause changes in the atmospheric zonal winds. Numerous previous studies have shown that observed length-of-day (LOD) variations on time scales of a few days to a few years are largely caused by atmospheric zonal wind fluctuations. In particular, seasonal variations in LOD have been previously shown to be dominantly caused by seasonal variations in the atmospheric zonal winds. Here, observed changes in the strength of seasonal LOD and wind-driven atmospheric angular momentum signals during 1962 to 2000 are analyzed and shown to be significantly correlated with each other and with the Southern Oscillation Index. This demonstrates that the observed seasonal LOD signal can be used as a proxy measurement for changes in the angular momentum of the seasonal zonal winds, thereby allowing changes in the seasonal zonal winds to be studied even when wind measurements are not available. In addition, the approach of studying decadal-scale changes in the strength of the seasonal cycle allows LOD measurements to be used in climate change studies, studies that cannot be undertaken directly due to uncertainties in modeling the dominant decadal-scale changes in LOD caused by core-mantle boundary processes.

Keywords. Earth rotation, atmospheric angular momentum, El Niño, Southern Oscillation

1 Introduction

Since the late 19th century, the global mean surface temperature has increased by about 0.3–0.6°C (IPCC 1995), and assuming the "best estimate" value of climate sensitivity including the effects of aerosols, coupled climate models predict that the global mean surface temperature will increase by about 2°C over the next century (IPCC 1995). The past temperature change did not occur uniformly over the globe (e.g., Folland et al. 1990), and the future temperature change is also not expected to occur uniformly. General Circulation Models (GCMs) of the atmosphere indicate that the surface temperature increase will be greater than average in the high northern latitudes in winter, and less than average in areas covered by sea-ice during the summer. The surface air is expected to warm faster over land than over the oceans, and the Northern Hemisphere is expected to warm faster than the Southern Hemisphere. In addition, the mid-troposphere is expected to warm faster than the surface, and the stratosphere is expected to cool as the troposphere warms (IPCC 1990, 1992, 1995).

Because of the nonuniform nature of the past and expected future atmospheric temperature changes, the pole-to-equator temperature gradient can be expected to change as the climate changes. By the thermal wind equation (e.g., Peixoto and Oort 1992), changes in the pole-to-equator temperature gradient will induce changes in the atmospheric zonal winds and hence in the angular momentum carried by the zonal winds.

In the absence of external torques, the atmosphere-solid Earth system can be considered to be a closed dynamical system, the total angular momentum of which is constant. As the angular momentum of the atmosphere changes (due, e.g., to climate change-induced variations in the strength of the zonal winds), the angular momentum of the solid Earth will change by an equal but opposite amount in order for the total angular momentum of the atmosphere-solid Earth system to remain constant. In fact, numerous previous studies have shown that on time scales of a few days to a few years, the observed variations in the length-of-day (LOD) are dominantly caused by fluctuations in the atmospheric zonal winds (for reviews see Hide and Dickey 1991, Eubanks 1993, Rosen 1993).

On decadal and longer time scales, however, the observed LOD variations are primarily caused by processes occurring at the core-mantle boundary

(e.g., Jackson et al. 1993). Unfortunately, these processes cannot yet be accurately modeled and removed from the LOD observations. Until this is possible, the smaller wind-induced changes in LOD on decadal and longer time scales cannot be directly investigated, and hence LOD measurements cannot be directly used in climate change studies.

However, Gross et al. (1996) have suggested an indirect approach based upon examining changes in the strength of the seasonal cycle. Numerous studies have shown that seasonal variations in the length-of-day are dominantly caused by seasonal variations in the atmospheric zonal winds (Rosen and Salstein 1985, 1991, Naito and Kikuchi 1990, 1991, Dickey et al. 1993, Rosen 1993, Höpfner 1998, Aoyama and Naito 2000). Since seasonal LOD variations are primarily caused by seasonal wind variations, any change in the strength of the seasonal zonal winds should be reflected and appear as a change in the strength of the seasonal LOD variations. Gross et al. (1996) have shown that during 1962 to 1992 the amplitudes of the seasonal LOD variations (at both annual and semiannual periods) have not been constant but have fluctuated by as much as 50%. Furthermore, they have shown that the changes in the amplitudes of the seasonal LOD variations were significantly correlated with the Southern Oscillation Index (SOI).

Here, the suggestion of Gross et al. (1996) is further developed by extending their LOD results to the present and by applying their method to wind-driven atmospheric angular momentum (AAM) data. It will be shown that during 1962 to 2000 changes in the amplitudes of the annual and semiannual components of LOD and wind-driven AAM are significantly correlated both with each other and with the SOI. This demonstrates that the observed changes in the amplitudes of the seasonal LOD variations can be used as proxy measurements of climate change-induced variations in the strength of the seasonal zonal winds, even on decadal and longer time scales.

2 Modulation of Seasonal LOD

The length-of-day data set used here is COMB2000, a combination of Earth rotation measurements taken by the techniques of optical astrometry, lunar laser ranging, and very long baseline interferometry (Gross 2001a). Prior to their combination, a number of corrections are made to the measurements in order to make them consistent with each other. In particular, a constant correction is applied to the annual term of the optical astrometric series to make it agree, on average, with the annual term of the space-geodetic measurements. In addition, solid Earth and ocean tidal effects have been removed from the measurements using the models of Yoder et al. (1981) and Kantha et al. (1998), respectively. The LOD values of COMB2000, which span January 20.0, 1962 through January 5.0, 2001 at 1-day intervals, are shown in Figure 1. The decadal-scale signal caused largely by core-mantle boundary processes is clearly evident in this figure. Since the core-mantle boundary effects cannot be accurately modeled and reliably removed from the LOD measurements, they cannot be used to study the much smaller decadal-scale signal that is expected to be caused by decadal-scale changes in the zonal winds. Instead, the seasonal LOD cycle is examined here. It is well known that the seasonal LOD cycle is dominantly caused by seasonal changes in the atmospheric zonal winds. Hence, decadal-scale changes in the strength of the seasonal LOD cycle can be unambiguously attributed to decadal-scale changes in the strength of the seasonal zonal winds.

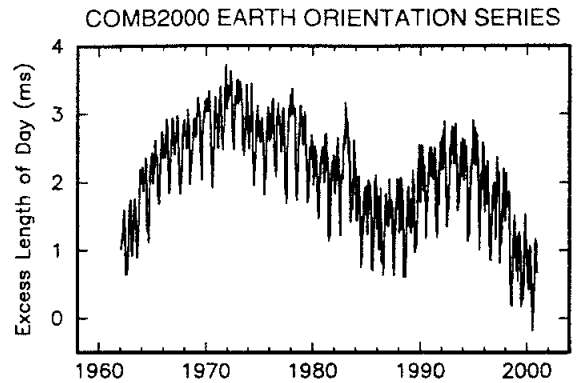

Fig. 1. The COMB2000 series of excess length-of-day values derived from a combination of independent optical astrometry, very long baseline interferometry, and lunar laser ranging measurements (Gross 2001a).

The seasonal terms of annual and semiannual period have been isolated from the COMB2000 LOD series by bandpass filtering. The pass band of the filter had a width of 0.974 cycles per year (cpy) and was centered first at 1 cpy, and then at 2 cpy, in order to isolate the annual and semiannual signals, respectively. Figure 2a shows the annual term thus recovered, and Figure 2b shows the semiannual term. As can be seen, the amplitudes of these terms have not been constant during 1962 to 2000 but have fluctuated by as much as 50% on a year-to-year basis. The amplitudes of the annual and

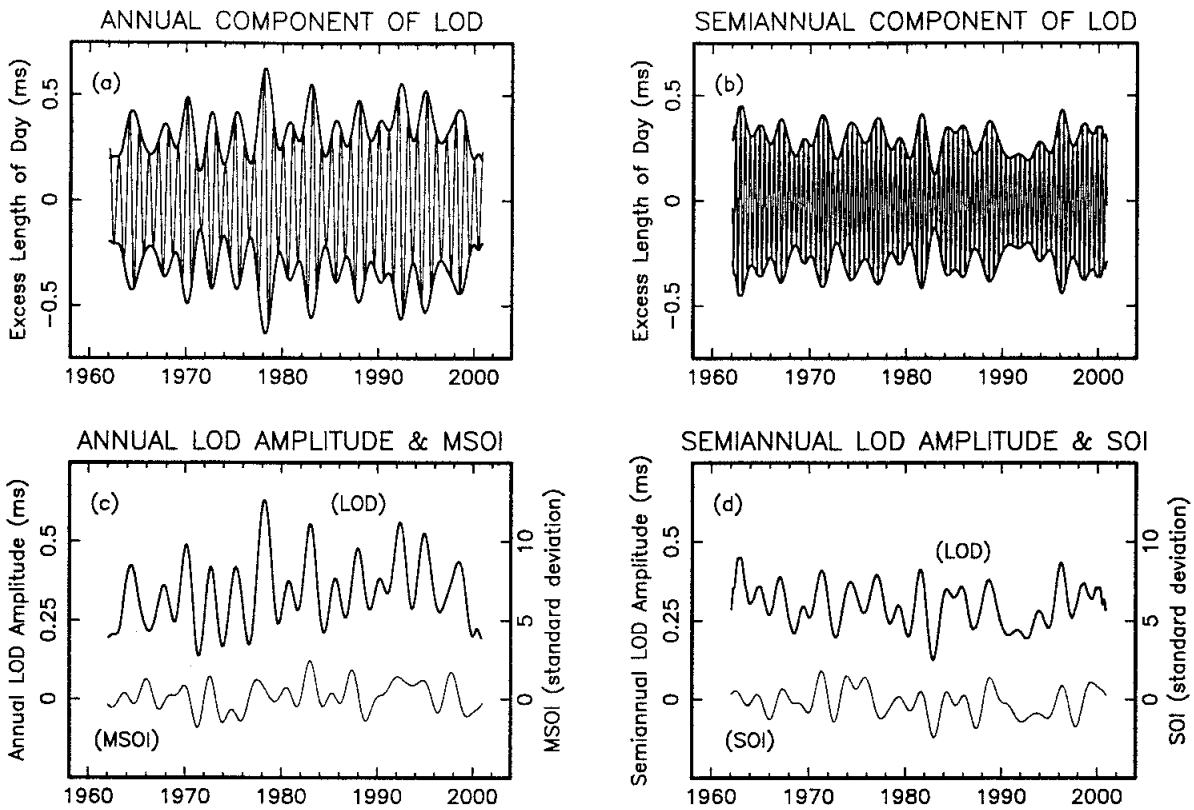

Fig. 2. Annual (a) and semiannual (b) components of the COMB2000 LOD series which have been isolated by bandpass filtering. The thick lines in (a) and (b), which have been reproduced in (c) and (d), are the amplitudes of the annual and semiannual LOD components, respectively, that have been obtained by complex demodulation. The Southern Oscillation Index is shown as the lower thin line in (d) and its negative, called here the modified Southern Oscillation Index (MSOI), is shown as the lower thin line in (c).

semiannual terms, which have been obtained by complex demodulation (e.g., Priestley 1981), are shown in Figures 2a and 2b by the thick lines. In Figures 2c and 2d the amplitudes of the annual and semiannual LOD terms (upper thick lines), which have been reproduced from Figures 2a and 2b, respectively, are compared to the Southern Oscillation Index (lower thin lines).

The Southern Oscillation Index (SOI), here obtained from NOAA's Climate Prediction Center, is the normalized difference between the Tahiti and Darwin standardized surface pressure values. In order to match the spectral content of the recovered amplitudes of the annual and semiannual LOD terms, the monthly SOI values have been smoothed by applying to them a lowpass filter having a cutoff frequency of 0.974 / 2, or 0.487 cpy. The resulting smoothed SOI values are shown as the lower thin curve in Figure 2d, and its negative, called here the modified Southern Oscillation Index (MSOI), is shown as the lower thin curve in Figure 2c.

The correlation at zero lag between the changing amplitude of the annual LOD term and the modified SOI is found to be 0.53, and that between the semiannual LOD term and the SOI is 0.67. The 99% significance level for these correlations is estimated to be 0.33 after accounting for the reduction in the number of degrees of freedom as indicated by the effective decorrelation time given by the width of the central peak of the respective autocorrelation functions. These results are comparable to those of Gross et al. (1996) who obtained values of 0.46 and 0.60, respectively, for the correlations at zero lag between the SOI and changes in the amplitudes of the annual and semiannual LOD terms. Thus, during 1962 to 2000, changes in the amplitude of the annual and semiannual LOD signals are significantly correlated with the SOI as they were during 1962 to 1992.

If observed changes in the strengths of the annual and semiannual components of LOD are to be used as proxy measures of changes in the strengths of

these components of the atmospheric zonal winds, then it must be shown that the results obtained using LOD are comparable to those obtained using the winds themselves. This can be done by examining the available estimates of the wind-driven AAM during 1962 to 2000. Once it is shown that the LOD gives the same results as the wind-driven AAM for the same time period, then the LOD can confidently be used to study changes in the zonal winds during time periods when the wind measurements themselves are not available, such as prior to the start of the AAM series in 1948.

3 Modulation of Seasonal AAM

The atmospheric angular momentum series used here is that computed from the National Centers for Environmental Prediction (NCEP) / National Center for Atmospheric Research (NCAR) reanalysis project and was obtained from the International Earth Rotation Service (IERS) Special Bureau for the Atmosphere (Salstein et al. 1993). Only the wind term was used here since the ability of seasonal LOD measurements to be used as a proxy of seasonal zonal wind changes is being studied. In this same regard, only those daily averaged axial wind AAM values spanning the same time interval as the COMB2000 LOD measurements, namely January 20.0, 1962 through January 5.0, 2001, were used. Daily averages of the 6-hour AAM estimates were formed by averaging 5 consecutive AAM values using weights 1/8, 1/4, 1/4, 1/4, 1/8. The resulting daily averaged wind-driven AAM series with its strong seasonal cycle is shown in Figure 3.

The seasonal cycle was isolated from the AAM series in exactly the same manner as it was isolated from the LOD series. The annual and semiannual components were extracted using a bandpass filter having a bandwidth of 0.974 cpy, and the changing amplitudes of the annual and semiannual terms were obtained by complex demodulation. As in Figure 2 for LOD, Figures 4a and 4b show the resulting annual and semiannual AAM components, respectively, as thin lines with the thick lines showing their amplitudes. The annual and semiannual AAM amplitudes have been reproduced in Figures 4c and 4d as the upper thick lines with the lower thin lines in Figures 4c and 4d showing the same smoothed SOI series as shown in Figures 2c and 2d.

The correlation at zero lag between the changing amplitude of the annual AAM term and the modified SOI is found to be 0.43, and that between

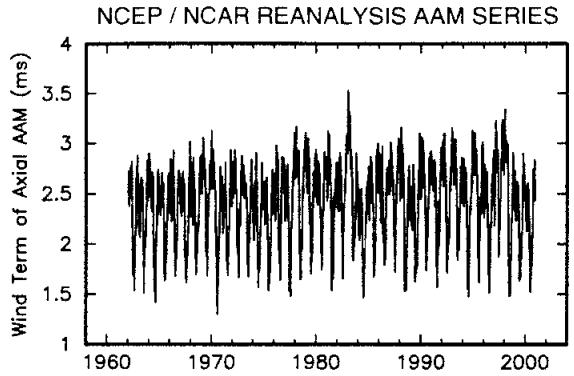

Fig. 3. Daily averages of the axial component of the NCEP/NCAR Reanalysis AAM series computed by integrating the atmospheric winds to the top of the model at 10 hPa (Salstein and Rosen 1997). No contribution to the AAM from pressure fluctuations is included here, and only those values that span the same time period as the COMB2000 LOD series are shown.

the semiannual LOD term and the SOI is 0.61. As for LOD, the 99% significance level of these correlations is estimated to be 0.33. These zero lag correlation coefficients, although somewhat lower than those obtained for LOD, show that during 1962 to 2000, changes in the amplitude of the annual and semiannual AAM signals are also significantly correlated with the SOI.

The zero lag correlation between the changing amplitude of the annual components of LOD and AAM is found to be 0.87 and that between the changing amplitude of the semiannual components is 0.91. As before, the 99% significance level of these correlation coefficients is estimated to be 0.33. This high level of correlation between the seasonal cycle of LOD and wind-driven AAM demonstrates that seasonal LOD measurements are an appropriate proxy of wind-driven seasonal AAM, and hence can be used to study changes in the seasonal zonal winds when LOD, but not wind, measurements are available.

4 Discussion and Summary

It has been shown that during 1962 to 2000 changes in the amplitudes of the seasonal LOD and AAM cycles are highly correlated with each other. This demonstrates that seasonal LOD measurements can be used as proxy measurements of wind-driven changes in the seasonal AAM cycle, thereby potentially extending studies of changes in the amplitude of the seasonal zonal winds to before the

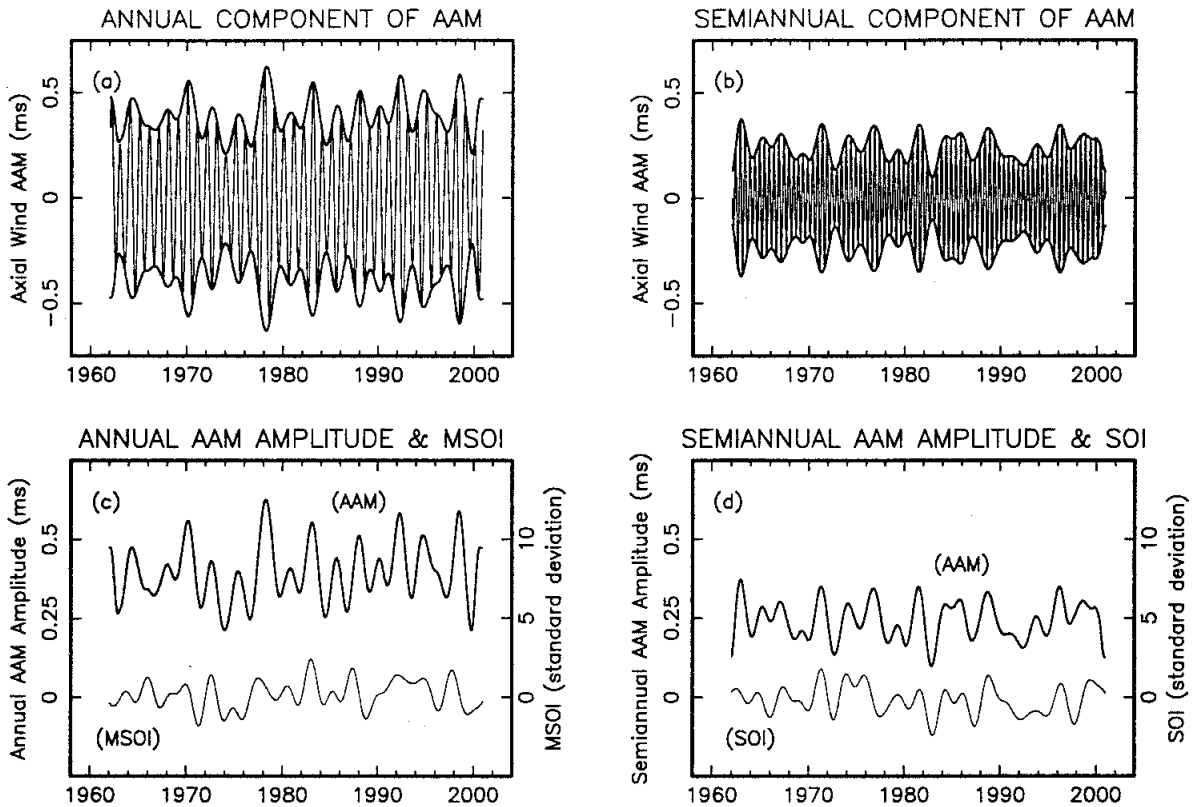

Fig. 4. Annual (a) and semiannual (b) components of the wind AAM series which have been isolated by bandpass filtering. The thick lines in (a) and (b), which have been reproduced in (c) and (d), are the amplitudes of the annual and semiannual AAM components, respectively, that have been obtained by complex demodulation. The Southern Oscillation Index is shown as the lower thin line in (d) and its negative, called here the modified Southern Oscillation Index (MSOI), is shown as the lower thin line in (c).

start of the AAM series in 1948. Although LOD series are currently available that start as early as 1656 (McCarthy and Babcock 1986), such series have been so heavily smoothed that the annual and semiannual signals have been removed from them (also see Jordi et al. 1994, Gross 2001b). In order to apply the technique of examining changes in the strength of the seasonal cycle to these longer LOD series, they will need to be rederived so that the annual, and perhaps even the semiannual, signal is retained.

It has also been shown that during 1962 to 2000 changes in the amplitude of the seasonal LOD and AAM cycles are significantly correlated with the SOI. As discussed by Gross et al. (1996), since the SOI is also correlated with LOD and AAM variations occurring on interannual time scales, the significant correlation observed here between changes in the amplitude of the seasonal cycle and the SOI is evidence for a linkage between the seasonal cycle and interannual LOD and AAM variations, a linkage that can only occur through nonlinear interactions.

Future monitoring of changes in the seasonal cycles of both LOD and AAM can provide useful metrics of ongoing changes in the climate system of both natural and anthropogenic origin. LOD may be particularly useful in this regard because it is measured directly, whereas wind-driven AAM must be determined by integrating wind measurements over the full horizontal and vertical extent of the atmosphere. LOD, and its seasonal variations in particular, may therefore have a higher signal-to-noise ratio than AAM (Dickey et al. 1992), and so may be more suitable than AAM for studying ongoing changes in climate. Furthermore, since LOD also changes in response to hydrological effects and mass displacements, its comparison with wind-driven AAM may also afford unique insights into changes in hydrology and atmospheric circulation that may accompany ongoing modifications to the climate system.

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