P2.21 ATMOSPHERIC MASS AND MOMENTUM SIGNALS IN CLIMATE AND EARTH STUDIES

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1. INTRODUCTION

The mass and the angular momentum of the atmosphere are properties whose variability relates to both climatic and geodetic signals. The total atmospheric dry mass is very nearly conserved, but water substance is exchanged with the oceans and Earth below. The horizontal distribution of atmospheric mass changes on a number of time scales, and varies both meridionally and zonally, often related to climate modes. Such variability is important to the overall terrestrial mass signal measured by the recently launched Gravity Recovery and Climate Experiment (GRACE) satellite system. Atmospheric pressure, moreover, loads the crust, leading to small vertical deformations and thus impacts the geodetic reference frame.

The angular momentum of the atmosphere is a signal that changes on many climate time scales due to the motion of winds and to atmospheric mass redistribution; angular momentum is exchanged, moreover, across the atmosphere's lower boundary. The atmospheric angular momentum signal responds to certain signals like the El Niño, which is observed in some geodetic properties such as Earth's rotation rate, reckoned by the small changes in the length of day, and also in the motions of the pole.

Global reanalysis, like that produced by the NCEP-NCAR system, capture both mass and angular momentum signals with considerable success; additionally general circulation models have been used to simulate past variability and forecast future changes in these quantities. Relevant diagnostics are calculated, collected, analyzed, and archived by the "Special Bureau for the Atmosphere (SBA)" of the International Earth Rotation Service (IERS), and include: atmospheric angular momentum in the axial and equatorial directions, torque interactions that exchange angular momentum across the lower interface, and harmonics of surface pressure, including the global mean surface pressure.

2. ATMOSPHERIC MASS

The mass of the atmosphere is very closely related to its surface pressure, given a hydrostatic relationship, and so relevant measurements of interest are noted in terms of surface pressure. We have mostly used the NCEP-NCAR reanalysis system (Kalnay et al. 1996) to determine this mass field. Geodetic studies have typically been related to the lower spatial harmonics of gravity, and hence mass; a relevant sample map of reduced spatial resolution of surface pressure to four different truncations is given in Fig. 1. We see, of course the strong influence of the continent and ocean distributions on surface pressure. With increasing resolution, the low pressure over high mountain regions, especially those with sharp topographic gradients are better defined. Earlier space-geodetic missions such as NASA's Lageos satellite could only resolve a few wave-numbers, and these were the original requirements for the use of atmospheric mass (surface pressure) measurements in geodetic studies. A sample of the low-order spherical harmonics, to degree and order 4, is shown in Fig. 2. Interestingly, the a(0,0) term is proportional to the total mass of the atmosphere; its variability is almost entirely due to loss and gain of water vapor from the atmosphere, strongest on seasonal scales. Given the March 2002 launch of the GRACE satellite system (B. Tapley, Principal Investigator), which can detect much higher resolution in Earth gravity changes, we are collecting high spectral resolution for the atmosphere; pressure from the NCEP-NCAR reanalysis surface pressure fields is reasonable to collect to its resolution, currently at triangular 62 truncation. Other sets should be collected to higher resolutions The GRACE mission will detect changes in the hydrosphere, such as ground water, from the gravitational signals. Local atmospheric pressure signals, related to mass, are also important to analyze for the purpose of the vertical loading on the ground; such information is important to detect the exact vertical reference frame of certain geodetic stations, for purposes of measuring sea level, and vertical related to changes since the last ice age.

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Measurements of the SBA are thus useful to the Special Bureau for Loading, another component of the IERS.

3. **ATMOSPHERIC ANGULAR MOMENTUM**

The angular momentum of a parcel of air in the perpendicular plane to an axis is given as its mass multiplied by the length of the radius arm to the reference axis, multiplied by the component of the velocity of the parcel in that plane, normal to the radius arm. The angular momentum of the global atmosphere about such an axis is the integration of all such parcels. When the axis is that of the Earth's rotation, then changes in the angular momentum of the atmosphere are compensated by those of other portions of the Earth, most notably the solid Earth itself; nevertheless a lesser amount does get exchanged with the oceans and between the ocean and solid Earth. Variability of angular momentum about the other two axes, namely in the equatorial plane, may be related to the wobble of the Earth, causing motions of the Earth's pole.

Angular momentum variations in the atmosphere can be conveniently separated into those due to mass fluctuations, the absolute angular momentum due to solid body rotation, and those due to the winds, the angular momentum relative to the solid Earth. An explicit formulation for the angular momentum variation that excites both variations of Earth's rotation rate (changes in length of day) and polar motion, was related to relevant Earth properties by Barnes et al. (1983). An additional element of importance here concerns the so-called inverted barometer (IB) relationship, in which the variability of the atmospheric pressure over the oceans is reduced by their isostatic response that quickly readjusts sea level in response to the overlying atmospheric load. A correction for the IB involves substituting the mean value of the atmospheric pressure overlying the oceans for atmospheric surface pressure at every over-ocean point. These excitations for the length of day and polar motion, given for mass, mass as corrected by IB, and motion, are the basic angular momentum values collected by the SBA and are reviewed in Salstein et al. (1993; see that paper's Figs. 1 and 2 for formulas, and sample angular momentum series).

The SBA collects such excitation terms from several of the world's large weather centers, currently consisting of the U.S. National Centers for Environmental Prediction, the European Centre for Medium-Range Weather Forecasts, the Japan Meteorological Agency, and the United Kingdom Meteorological Office. Besides analyses for a given time, forecasts are collected as well, out to 10 days. Such values are used operationally for navigation, especially for that of planetary spacecraft, because the knowledge of Earth's exact orientation, as well as future projections, is necessary and improved by the atmospheric angular momentum terms. Besides these operational series, values from the NCEP-NCAR reanalysis, since 1948 (Salstein and Rosen 1997), are collected so that there can be relative consistency among these excitation terms for Earth motions. These datasets are available from the Special Bureau for the Atmosphere at www.aer.com/groups/diag/sb.html. Additional information about the International Earth Rotation Service is available at www.iers.org.

We note first that the motions of the pole are related strongly to the pressure (IB) excitations. Those on subseasonal timescales, additionally including the wind term, may be seen in Fig. 3, in which moderate correlation exists between the excitations and the polar motion values. Values on longer time scales are likewise important, involving both the seasonal scale, and a natural response of the Earth at around 430 days, known as the Chandler wobble. The polar motions in particular involve the oceans in addition to the atmosphere. On seasonal scales, climate modes can force polar motions because of the anomalous pressure patterns connected with such modes. Variability in certain regions due to the pressure patterns on a range of weather and climate time scales are stronger than others; those in the middle latitudes influence the motions of the poles the most because of geometric factors (Barnes et al. 1983). Nastula and Salstein (1999) have noted that fluctuations over Eurasia and North America have impacted polar motions most strongly. On very short time scales, we have noted that fluctuations as short as 8 and 12 hours are noted in both the atmospheric excitation terms for polar motion, and in polar motion as determined methods depending on Global Positioning Systems measurements (Weber et al. 2001)

The axial angular momentum of the global atmosphere, and particularly the relative term due to the winds is an index that mirrors many climate phenomena. A lengthy plot of such values, since 1970, based on the NCEP-NCAR reanalysis (Fig. 4) demonstrates both the prominent seasonal and interannual signals present in the series. The seasonal signature, yielding maxima and minima in zonal mean belts (Rosen and Salstein 1983) during boreal winter and summer, respectively, are due to the larger annual signature of the winds and hence the zonal angular momentum in the Northern Hemisphere compared to the Southern (Fig. 5). Superimposed on the annual signal is a semi-annual one in which the boreal summer typically has a particularly steep minimum and the winter has a dip during the middle months.

The maxima in Fig. 4 occur during occurrences of El Niño when anomalous westerly zonal flow throughout much of the tropics and subtropics occurs, sometimes extending as well into higher latitudes; the events in 1983 and 1997-98 are contain record high values of the angular momentum index. The global maxima derive from momentum anomalies that often start in the lowest latitudes and propagate toward poleward (e.g., 2et al. 1997) that can be seen in Fig. 6, in the band-pass filtered belt analysis (Rosen and Salstein 1983) with NCEP-NCAR reanalysis data. In Fig. 6, the very strongest values occurred during the 1997-98 El Niño, in the subtropics of each hemisphere; interestingly a rapid transition occurred between positive and negative anomaly at the end of this event in middle of 1998. The global axial angular momentum is very strongly connected to values in the length of day; such connections occur on time scales between days and several years (Fig. 7). The common fluctuations in Fig. 7 relate to the annual and semiannual terms. Also noteworthy here, too, are subseasonal fluctuations, including the 30-60 day fluctuations associated with the Madden-Julian oscillation.

The atmosphere-solid Earth dynamic link is the subject of a large number of studies that are related to the atmospheric series produced by the Special Bureau for the Atmosphere and other groups in the International Earth Rotation Service. Lengthy series of atmospheric angular momentum provided by our data center to geodesists worldwide have helped unravel several questions involving excitations of free oscillations, the Chandler wobble, the role of diurnal and semidiurnal tides, and signals of atmospheric normal modes in the dynamics of the Earth (Brzezinski et al. 2002).

ACKNOWLEDGMENTS

This work was sponsored by NASA's Solid Earth and Natural Hazards Program, under award NAS5-01124 with additional support from the National Science Foundation under grant INT-98-07014.

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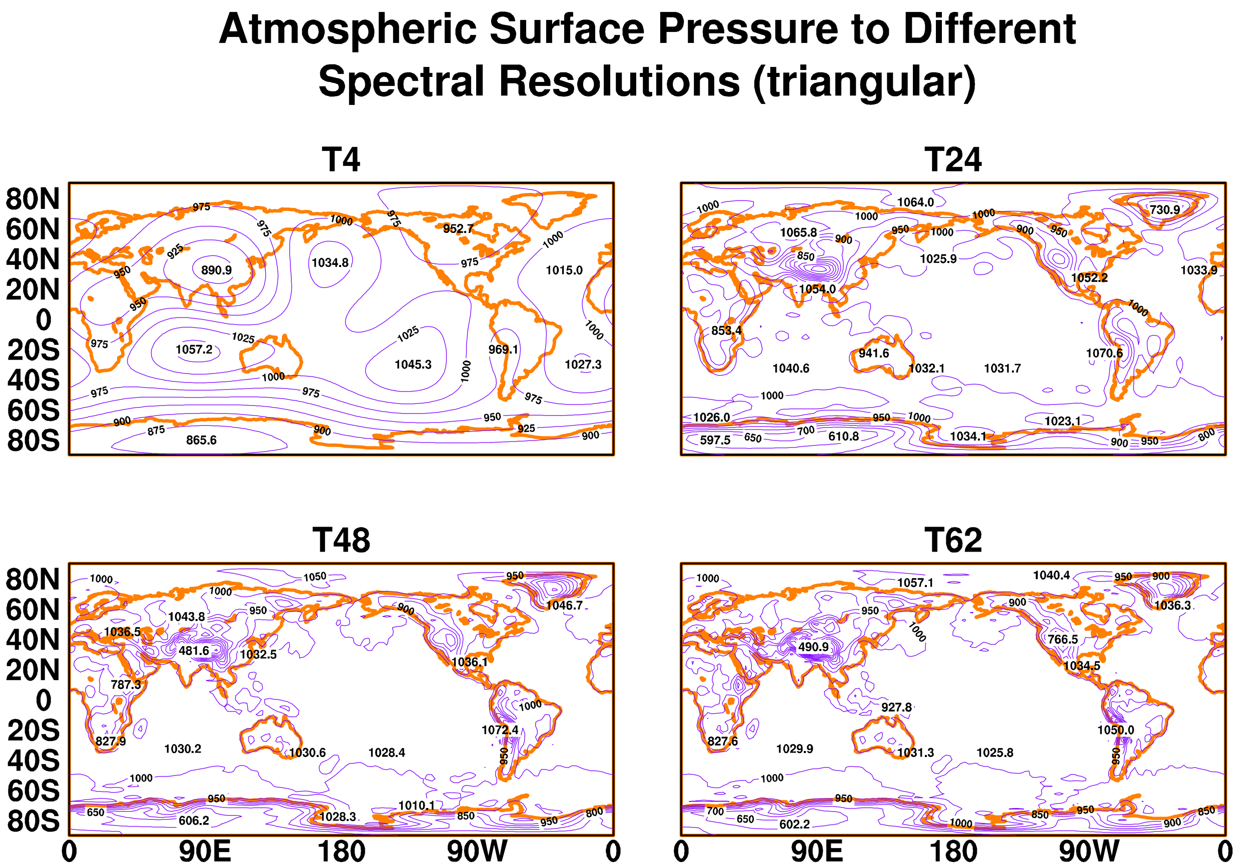

Fig. 1 Atmospheric surface pressure from the NCEP-NCAR reanalysis, for January 1, 2001, using spherical harmonics expanded to four different truncations. Units are hPa.

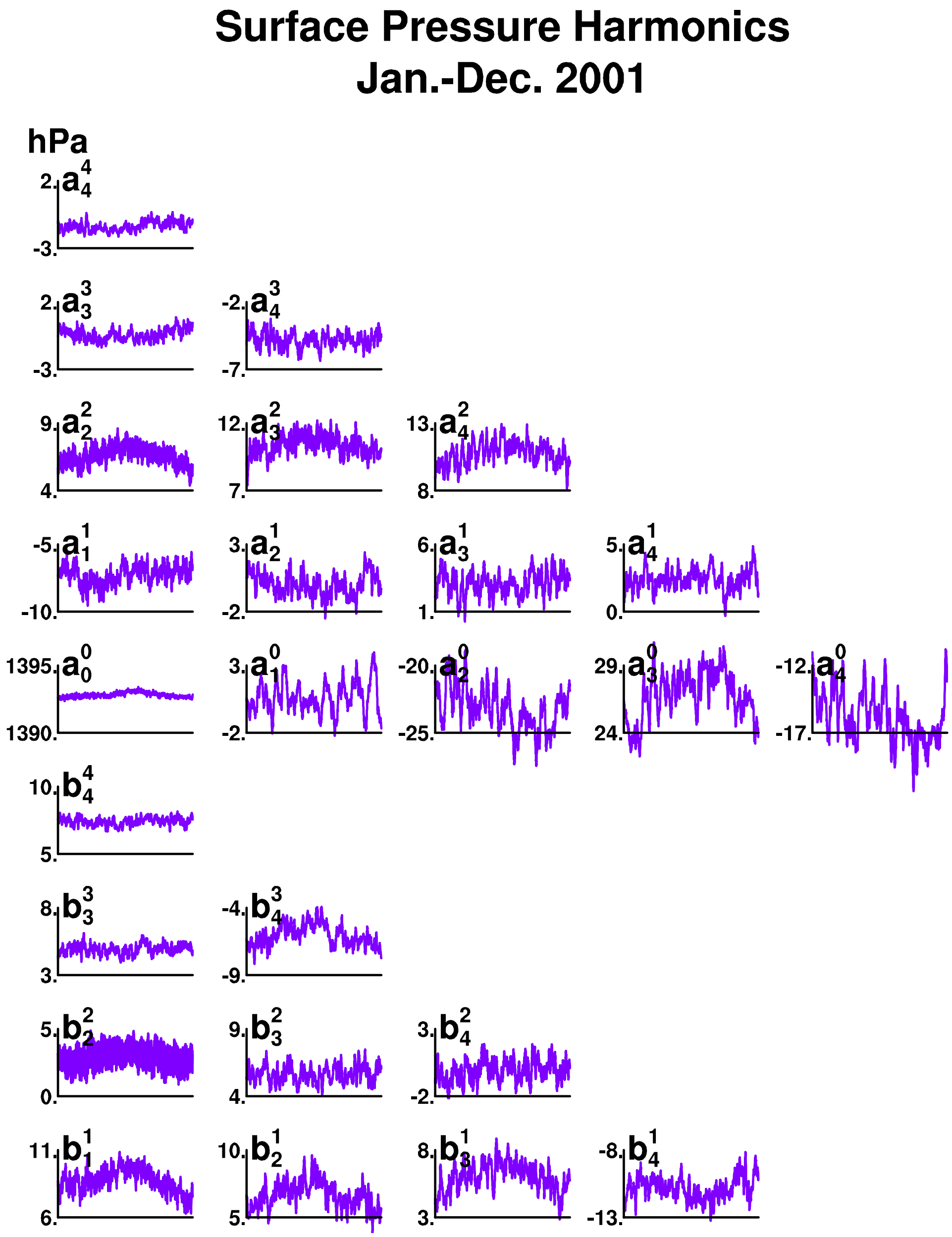

Fig. 2. Time series of surface pressure harmonics from the NCEP-NCAR reanalysis, for 2001, for all spherical harmonics to degree and order 4. Units are hPa.

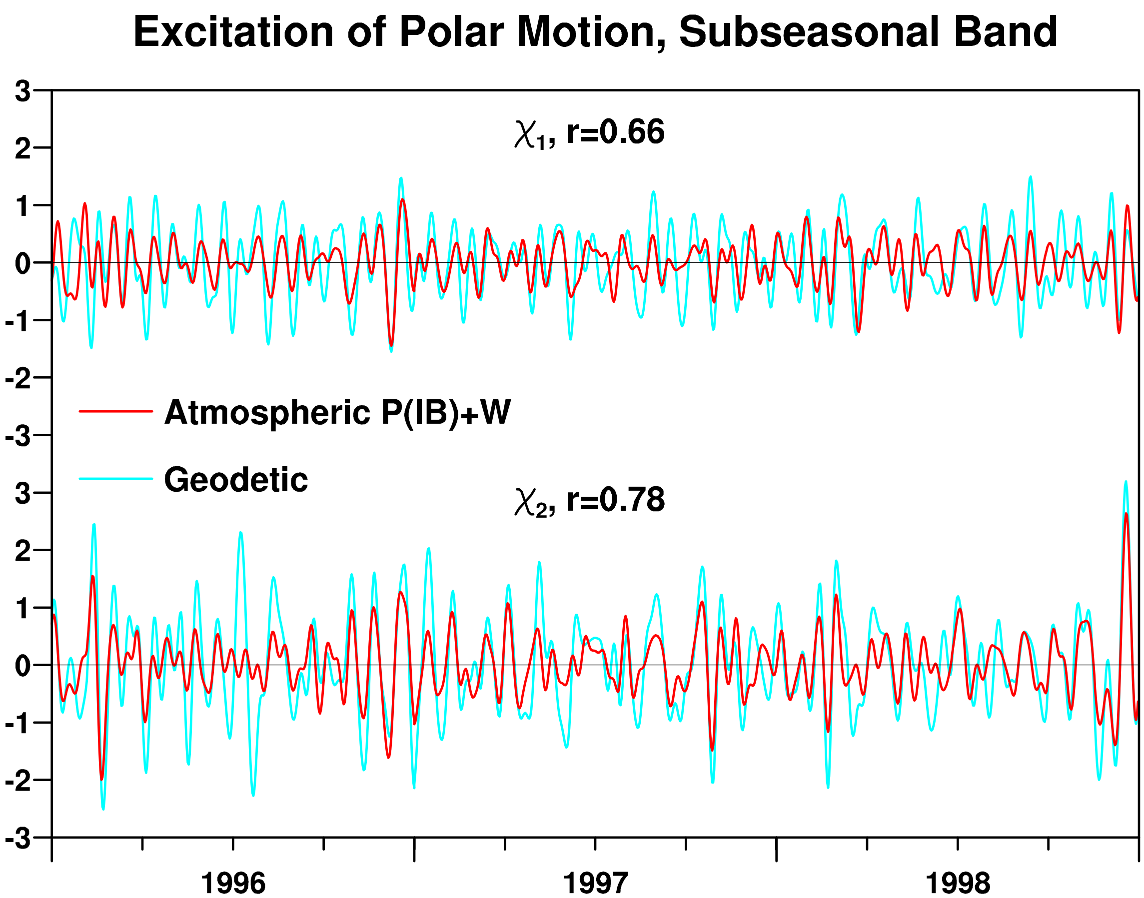

Fig. 3. Series of the two atmospheric excitation terms for polar motion, pointing to 0 and 90 East longitudes, respectively, based on surface pressure as modified by the inverted barometer relationship of ocean isostasy plus the wind term, as compared with the geodetic excitation term for polar motion. Epoch is 1996-1998. The values are filtered to emphasize the subseasonal band. Non-dimensional units are multiplied by 10^{-7}.

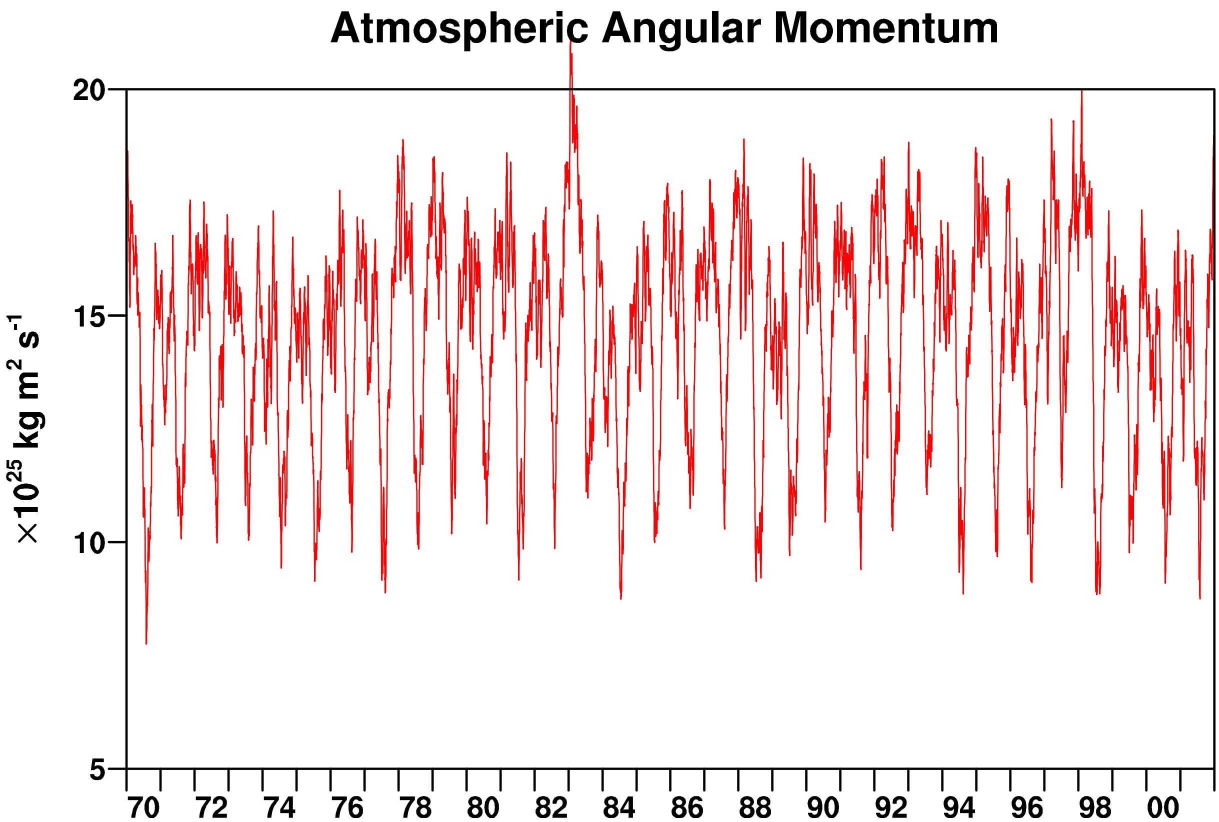

Fig. 4. Time series of relative atmospheric angular momentum 1970-2001, based on NCEP=NCAR reanalysis, based on winds between the 1000 and 10 hPa levels. Note the strong seasonal signature that is modulated by interannual signals.

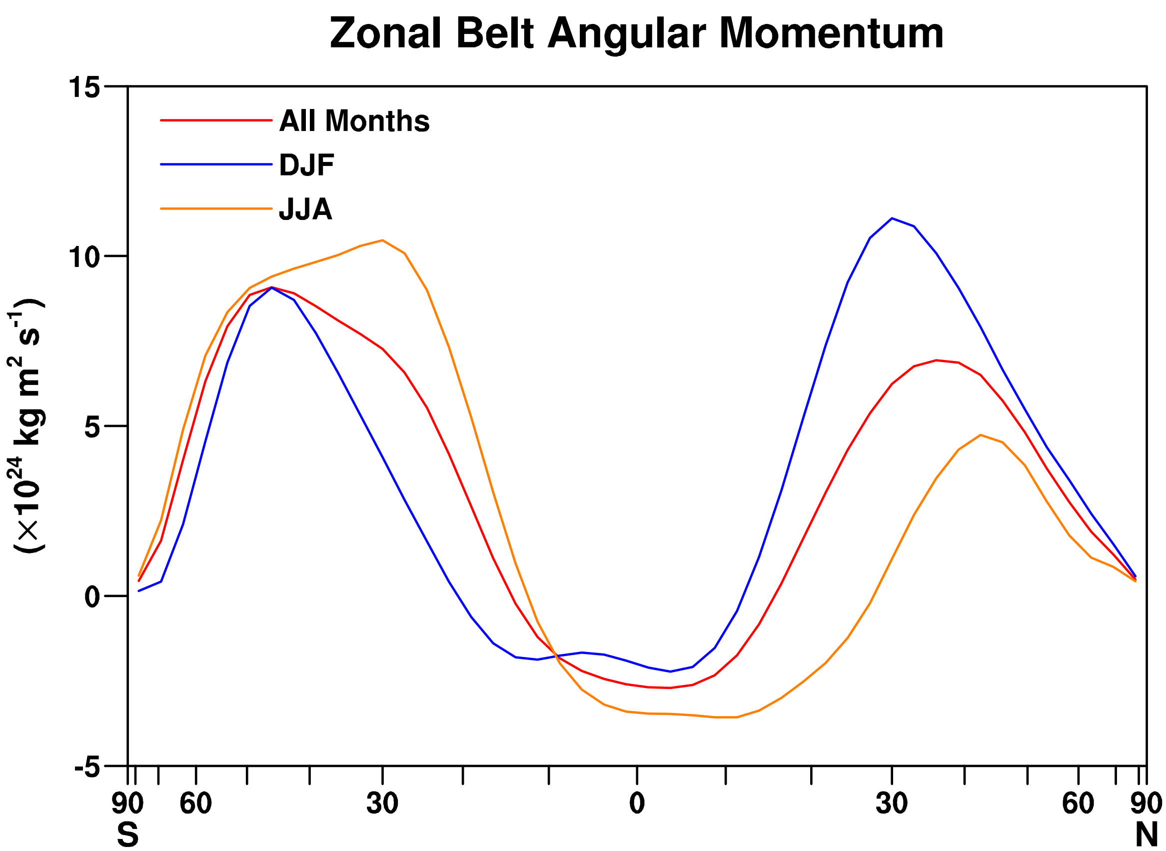

Fig. 5. Angular momentum in zonal belts (Rosen and Salstein 1983) for all months and for the December-January-February and June-July-August means. The stronger annual signal in the Northern Hemisphere compared to the southern Hemisphere is apparent.

Filtered Momentum Belt Values

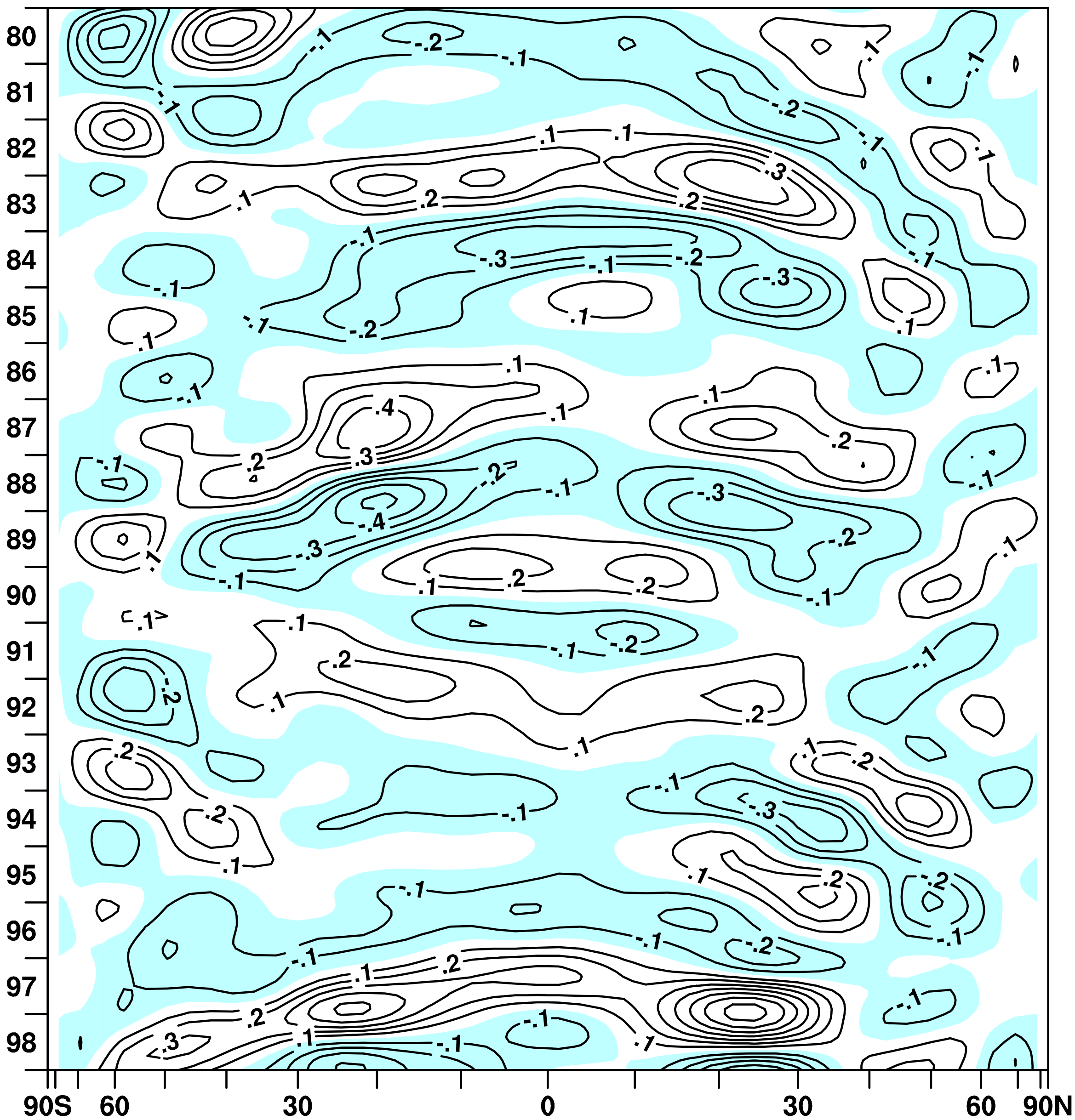

Fig. 6. Band-pass filtered values of atmospheric angular momentum defined in zonal belts, band-passed to emphasize variability of about 2-5 years. Note the strong positive and negative signals (white and blue areas, respectively) during alternating El Niño and Niña events.

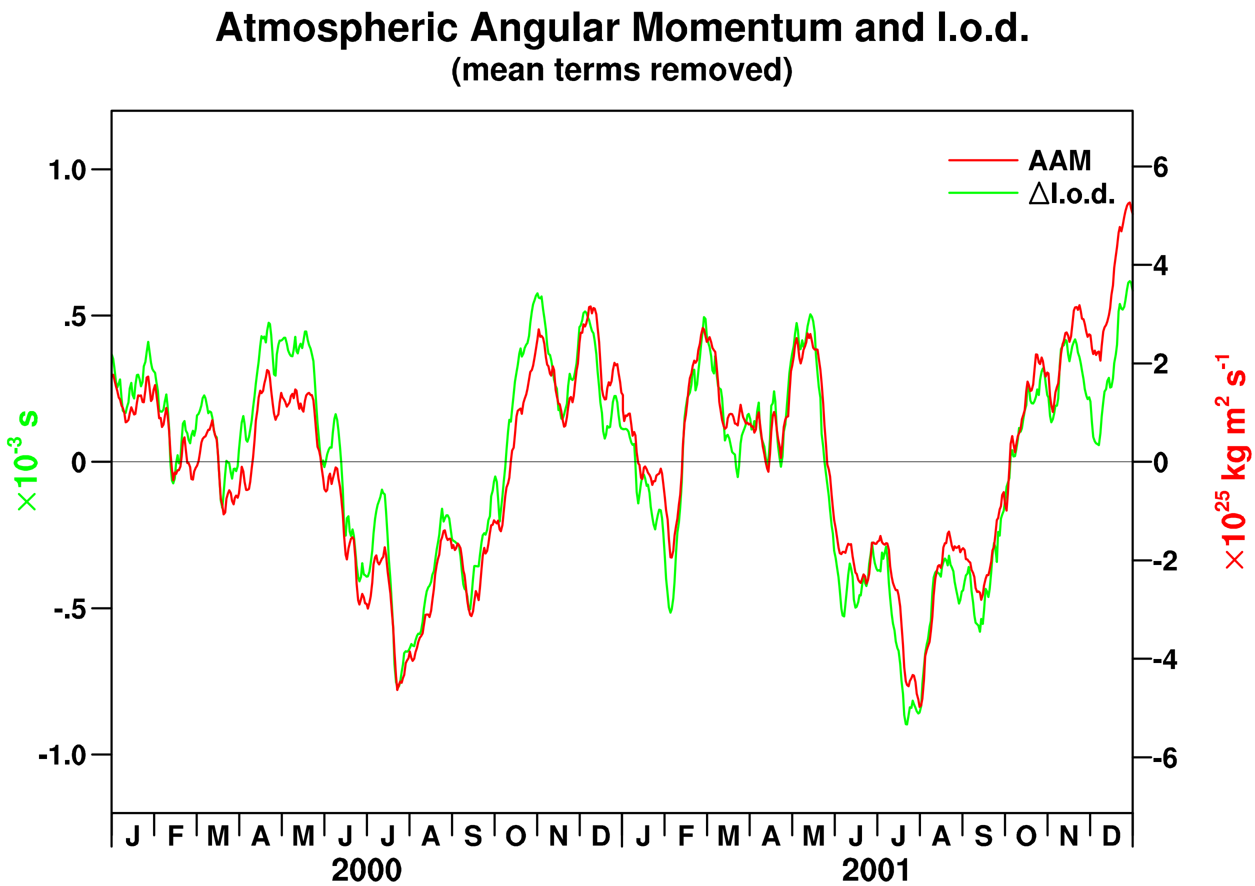

Fig. 7. Comparison of atmospheric angular momentum, between 1000 and 10 hPa, from the NCEP-NCAR reanalysis system, (red; scale on right) and the values of length of day (green; scale on left) for 2000-2001. Mean terms have been removed, and scales indicate equivalent amounts of angular momentum variability.