Impact of climatic variability on atmospheric mass distribution and GRACE-derived gravity fields

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SUMMARY

During the period we calculated the atmospheric data sets related to its mass and angular momentum distribution. For mass, we determined the various harmonics from the NCEP-NCAR reanalysis, especially the low-order harmonics that are useful in studying the gravitation distribution as will be determined from the GRACE mission. Atmospheric mass is also related to the atmospheric loading on the solid Earth; we cooperated with scientists who needed the atmospheric mass information for understanding its contributions to the overall loading, necessary for vertical and horizontal coordinate estimation.

We calculated atmospheric angular momentum from the NCEP-NCAR reanalyses and 4 operational meteorological centers, based on the motion (wind) terms and the mass (surface pressure) terms. These are associated with motions of the planet, including its axial component causing changes in the length of day, more related to the winds, and the equatorial component related to motions of the pole, more related to the mass.

Tasks related to the ocean mass and angular momentum were added to the project as well. For these we have noted the ocean impact on motions of the pole as well as the torque mechanisms that relate the transfer of angular momentum between oceans and solid earth.

The activities of the project may be summarized in the following first manuscript written in December 2002, for a symposium that Dr. Salstein attended on Geodynamics.

We have continued to assess ocean angular momentum (OAM) quantities derived from bottom pressure and velocity fields estimated with our finite-difference barotropic (single layer) model. Three years of output (1993-95) from a run without any data constraints was compared to output from a corresponding run that was constrained by altimeter data using a Kalman filter and smoother scheme. Respective OAM time series were combined with corresponding atmospheric series and compared to observed polar motion. The constrained OAM series provided slightly

better variance reduction than the unconstrained series. Analysis provided a check on the estimation scheme and pointed to further work to improve the determination of OAM using this method. A significant effort was also devoted to quantifying effects of uncertainties in high frequency winds on the mean and seasonal momentum exchange between atmosphere and oceans. This work is summarized in the second manuscript that follows (submitted to the AMS Seventh International Conference on Southern Hemisphere Meteorology and Oceanography Conference).

Atmospheric mass and motion signals in the Earth's orientation and other properties

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1. INTRODUCTION

Mass and angular momentum are, according to fundamental physical principles, conserved in a closed system. For planet Earth, there is extremely small mass interaction with components outside itself. Relatively speaking, somewhat more angular momentum is interchanged due to the tidal influences of the moon and other heavenly bodies, but these effects are regular and can be accounted for.

For angular momentum, therefore, planet Earth can be considered a closed system, and so amounts in one reservoir of the system are exchanged with those in others. If the atmospheric reservoir is considered, the variability in atmospheric angular momentum (AAM) must be compensated for by angular momentum changes in the other reservoirs, including the ocean, but mainly, in the solid Earth. The great mobility of the atmosphere leads to a relatively large variability in AAM, which is measured from global integrals of angular momentum depending on the wind and mass distribution. The resulting amount changing in the solid Earth's rotation as a result was difficult to determine but is now measured with increasing accuracy in the current era of space geodesy.

The angular momentum of the atmosphere is a signal that changes on many climatic time scales due to the motion of winds and to atmospheric mass redistribution. This atmospheric angular momentum signal responds to certain climate influences like an El Niño event, which is one phase of the Southern Oscillation, an atmospheric mass fluctuation across the breadth of the Pacific Ocean.

Currently the large meteorological centers around the world are producing global analyses of the atmosphere, which assimilate the heterogeneous mix of meteorological observations onto a regular horizontal structure, using a model of the atmosphere that accounts for much of its physics. Operational analyses are being performed in real time, mostly for the purpose of weather analysis and forecasting. In addition, centers have produced retrospective analyses of the atmosphere, with as much homogeneity in their system as possible, largely to examine climate variations and trends. Chief among these so-called reanalyses are those performed by the European Centre for Medium Range Weather Forecasts (ECMWF) (Gibson 1997), and by the United States National Centers for Environmental Prediction (NCEP) and National Center for Atmospheric Research (NCAR) (Kalnay et al. 1996). Both these systems capture both mass and angular momentum signals with considerable success; comparisons between them show quite good agreement. We have generally used the NCEP-NCAR system because it is currently the longest in temporal extent, dating from 1948, though its accuracy is variable during the five-decade period.

Besides the general circulation models have been used to simulate past variability and forecast future changes in these quantities. Such models may be forced by the underlying temperature of the sea-surface. Typically, they reproduce the seasonal cycle well, and the interannual and trend signals adequately. (Hide et al. 1997). Such models may also be used to simulate future signals such as those that may result from greenhouse gas changes.

We have considered a number of atmospheric diagnostics relevant to thegeodetic quantities of Earth rotation and polar motion (angular momentum) as well to the Earth's mass distribution and gravitational field. Such diagnostics are calculated, collected, analyzed, and archived by the "Special Bureau for the Atmosphere (SBA)" of the International Earth Rotation Service (IERS); the formal quantities 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.

Originally called the Sub-bureau for Atmospheric Angular Momentum (Salstein et al. 1993), our data center is now one component of the IERS Geophysical Fluids Center.

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 used primarily 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, so a 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. With increasing resolution, the low pressure over high mountain regions, especially those with sharp topography gradient, become better defined. Earlier space-geodetic missions, such as the 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, for the year 2001 is shown in Fig. 2. Interestingly, the a(0,0) term (Fig. 3) 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, though interannual signals may be seen as well in the figure. Also, the large fluctuations in the early part of the record is likely due to data quality issues. Given the March 2002 launch of the GRACE satellite system (B. Tapley, Principal Investigator), which can detect changes in Earth gravity to around degree and order 100, we are collecting such comparable spectral resolution for the atmosphere, and have recomputed high resolution from the NCEP-NCAR reanalysis surface pressure fields. Because the GRACE mission will detect changes in the hydrosphere, such as ground water, from the gravitational signals, but because it must remove the atmospheric signal to do so. Our mission is to collect data related to higher atmospheric variability as well. Point-by-point 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. 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 about 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, 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 that excites both variations of Earth's rotation rate, reckoned as length of day changes, as well as polar motion, were derived by Barnes et al. (1983). An additional element of importance here concerns the so-called inverted barometer (IB) hypothesis, 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 over the oceans for atmospheric surface pressure at every point over the oceans. These excitations for the length of day and polar motion, given for mass, mass as corrected by the inverted barometer, and motion, are the basic angular momentum values collected by the SBA and are reviewed in Salstein et al. (1993; see that paper's fig. 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 Center 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 involving that of planetary spacecraft, because the knowledge of the exact orientation, as well as projections into the future, are necessary and are helped by the angular momentum terms. Besides these operational series, values from reanalyses are collected so that there can be relative consistency among these excitation terms for Earth motions. Based on the NCEP-NCAR reanalysis, atmospheric angular momentum quantities were computed by Salstein and Rosen (1997) staring in 1948. These datasets are available from the Special Bureau for the Atmosphere at http://www.aer.com/groups/diag/sb.html.

We note first that the motions of the pole are related strongly to the pressure (inverted barometer) excitations. Those on subseasonal variations may be seen in Fig. 4, in which moderate correlation exists between the excitations and the polar motion values. Values on longer time scales may be interesting, involving both the seasonal scale, and a natural response of the Earth at around 430 days, known as the Chandler wobble. The polar motions involve both the oceans and 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. 5) 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. 6). 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. 5 occur during occurrences of El Niño when anomalous westerly zonal flow throughout much of the tropics and subtropics occur, sometimes moving as well into higher latitudes; the events in 1983 and 1997-98 contained record high values of the angular momentum index. The global maxima derive from momentum anomalies that often start in the lowest latitudes and propagate poleward (e.g., Dickey et al. 1997) that can be seen in Fig. 7, in the band-pass filtered analysis of a network of zonal belts (Rosen and Salstein 1983), based on NCEP-NCAR reanalysis data. In Fig. 7, 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. 8). The common fluctuations in Fig. 8 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 dynamic link is the subject of a large number of studies that were 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 produced by our data center to geodesists have helped unravel several questions involving excitations of free oscillations, of 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

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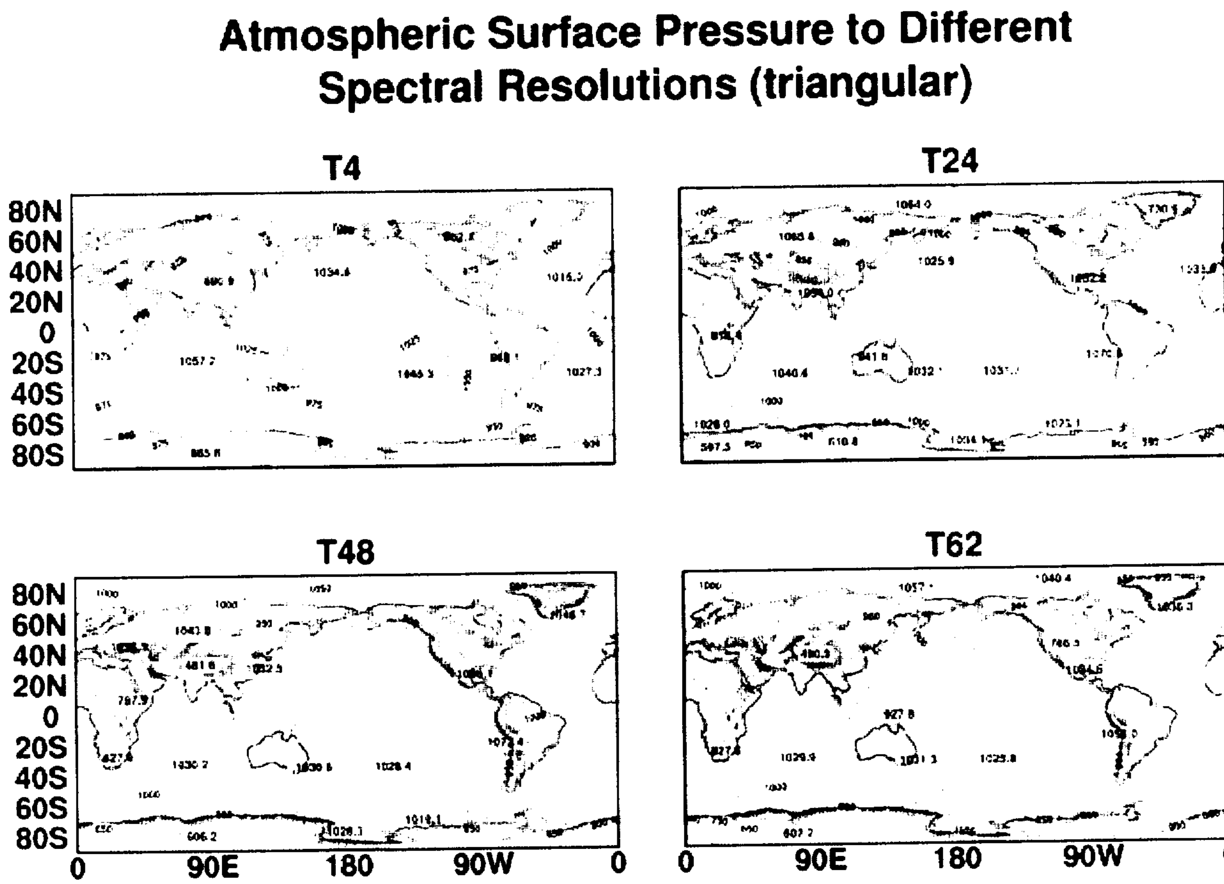

Fig. 1 Atmospheric surface pressure from the NCEP-NCAR reanalysis, for January 1, 2001, using spherical harmonics expanded to four different truncations. Units are hPa.

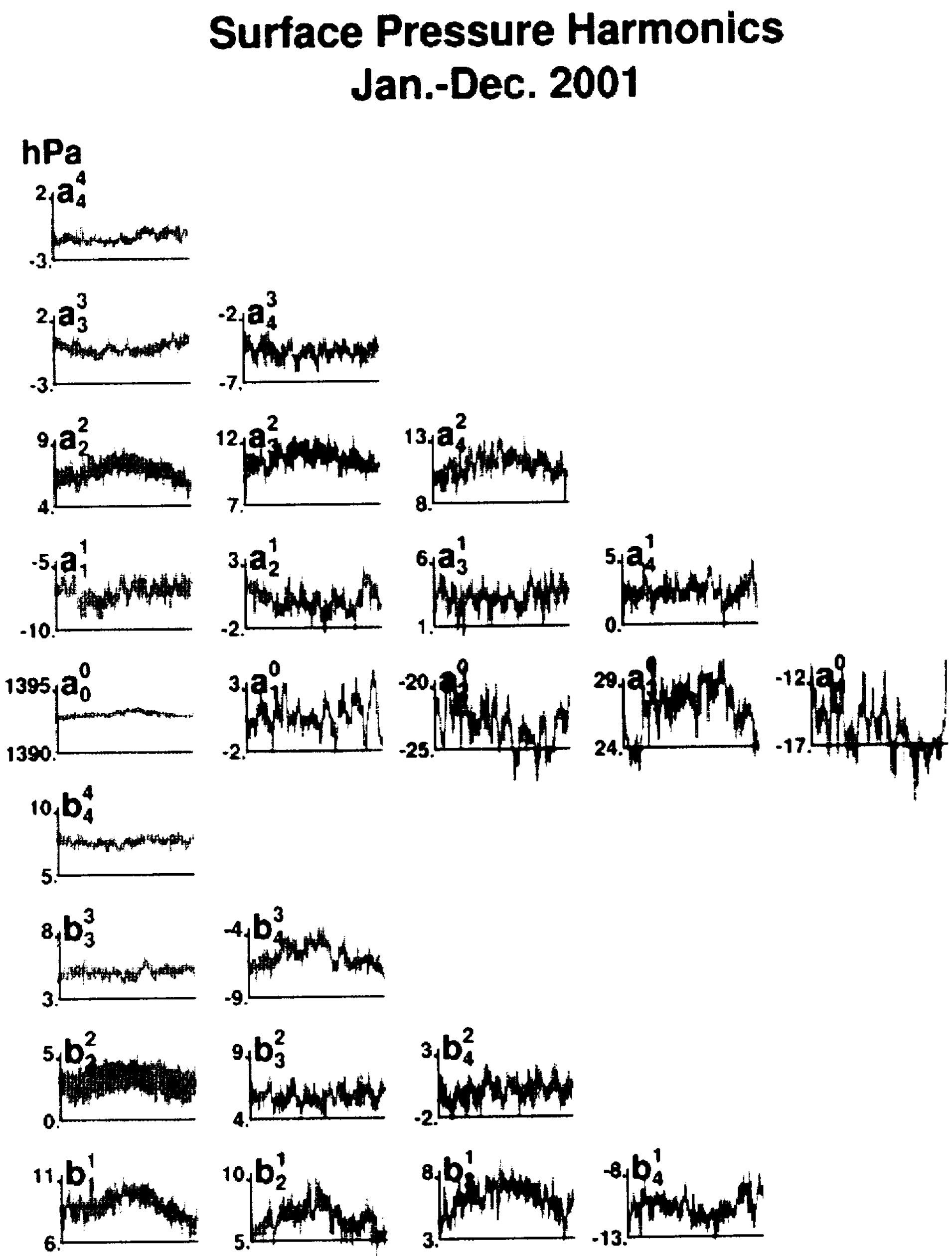

Fig. 2. Time series of surface pressure harmonics from the NCEP-NCAR reanalysis, for 2001, for all spherical harmonics to degree and order 4. Units are hPa.

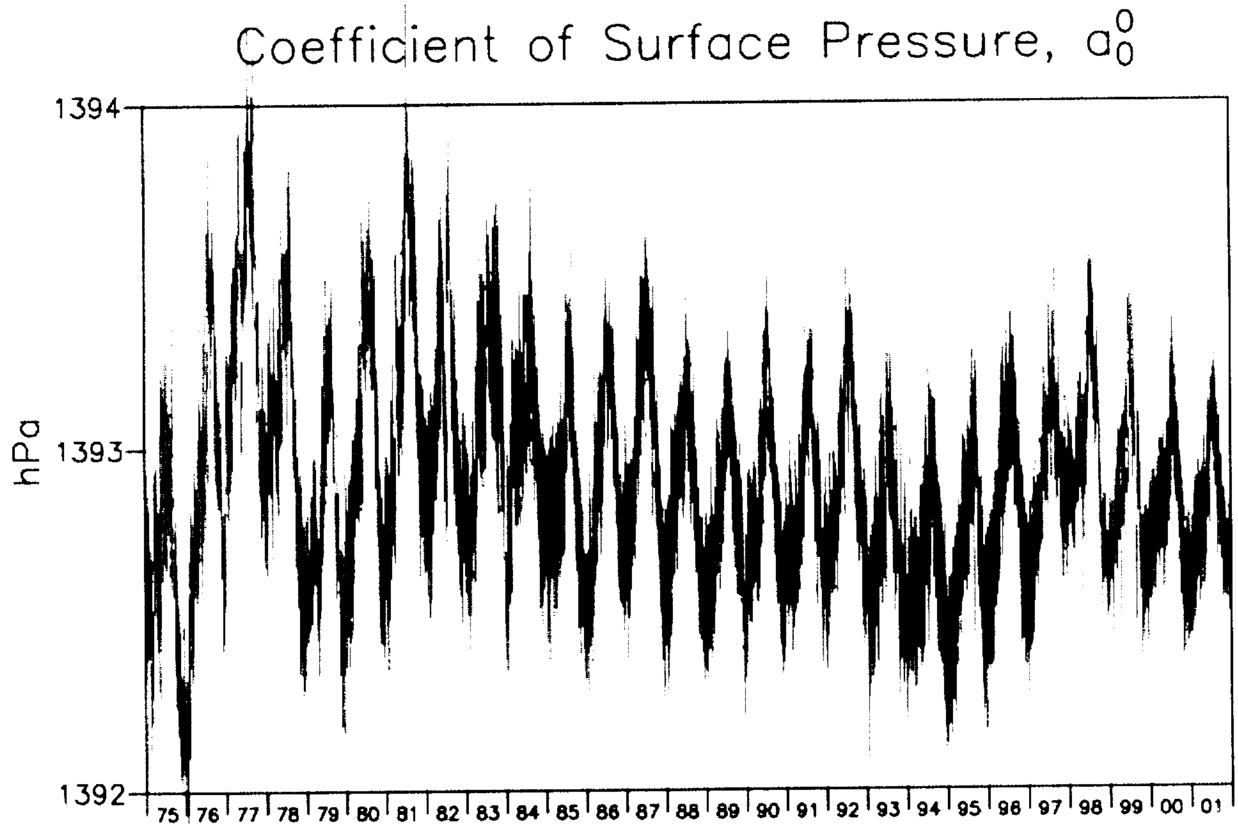

Fig. 3. Time series of the a(0,0) harmonic proportional to the mean surface pressure of the global atmosphere (when multiplied by $2^{-1/2}$). This quantity is also proportional to the mass of the global atmosphere, assuming a hydrostatic relationship.)

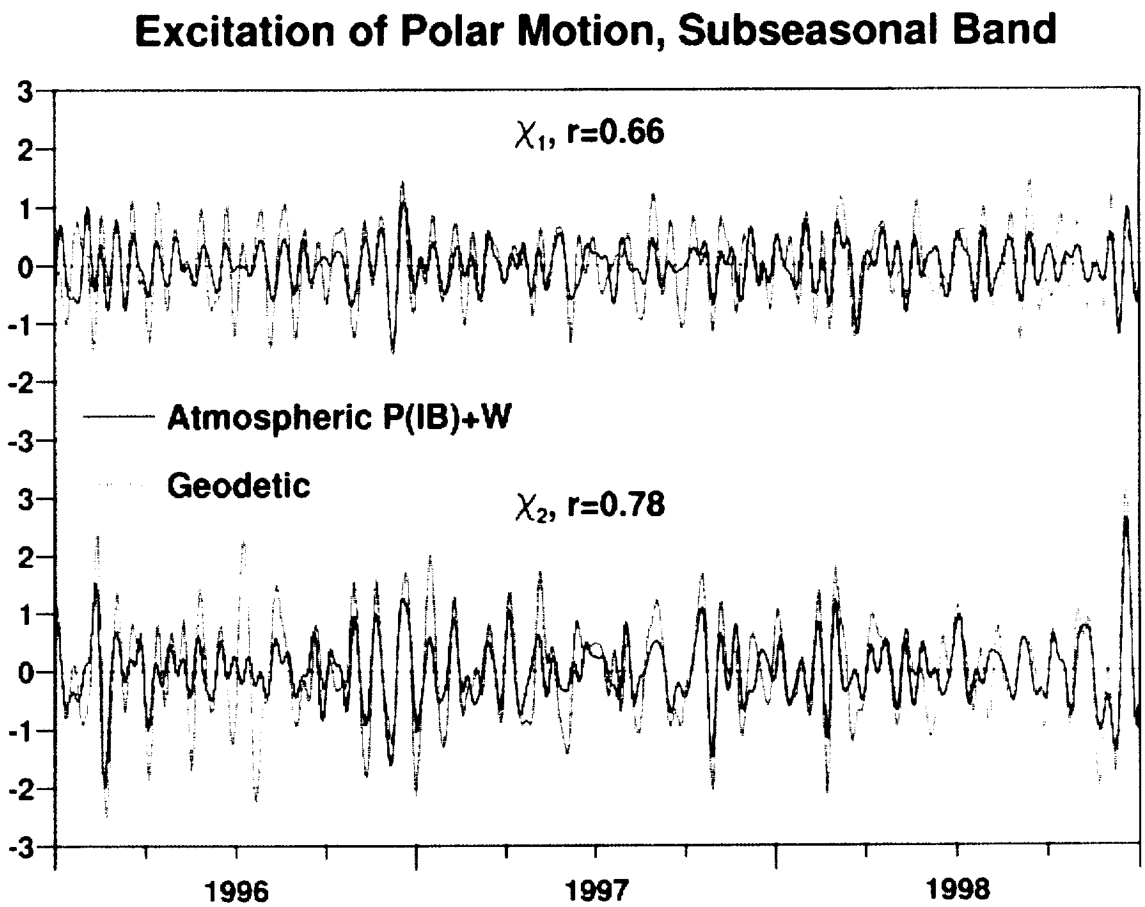

Fig. 4. Series of two atmospheric excitation terms for polar motion, based on surface pressure as modified by the inverted barometer relationship of ocean isostasy plus the wind term, as compared with the geodetic excitation term for polar motion. Period is 1996-1998. The values are filtered to emphasize the subseasonal band. Units are 10^{-7} and non-dimensional.

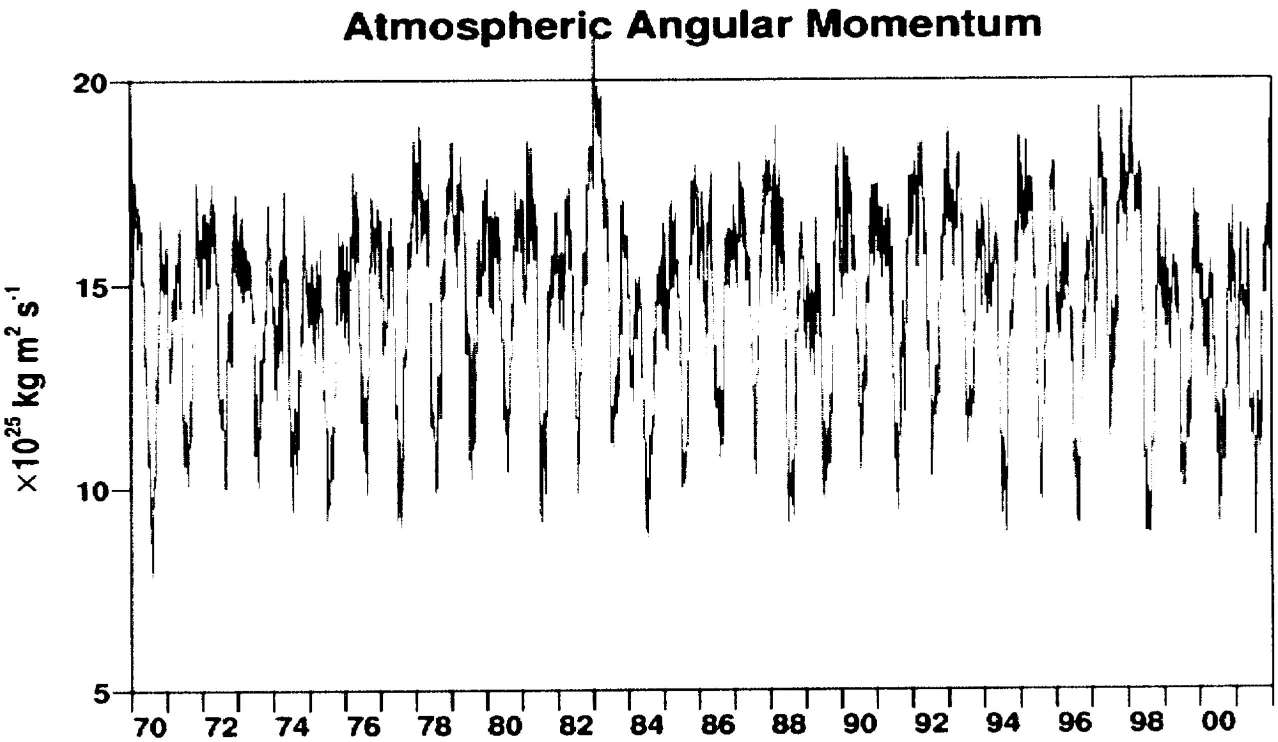

Fig. 5. Time series of relative atmospheric angular momentum 1970-2001, based on NCEP=NCAR reanalysis, based on winds between the 1000 and 10 hPa levels. Note the strong seasonal signature that is modulated by interannual signals.

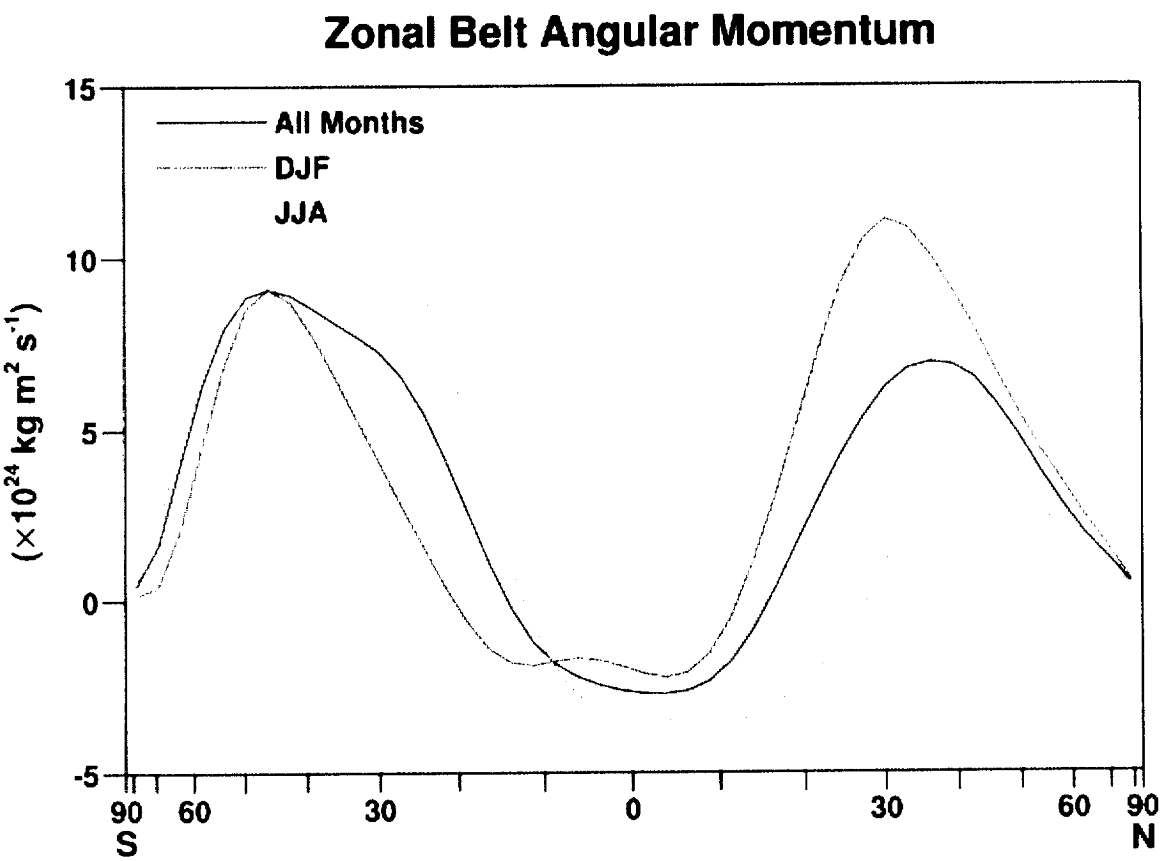

Fig. 6. Angular momentum in zonal belts (Rosen and Salstein 1983) for all months and for the December-January-February and June-July-August means. The stronger annual signal in the Northern Hemisphere compared to the southern Hemisphere is apparent.

Filtered Momentum Belt Values

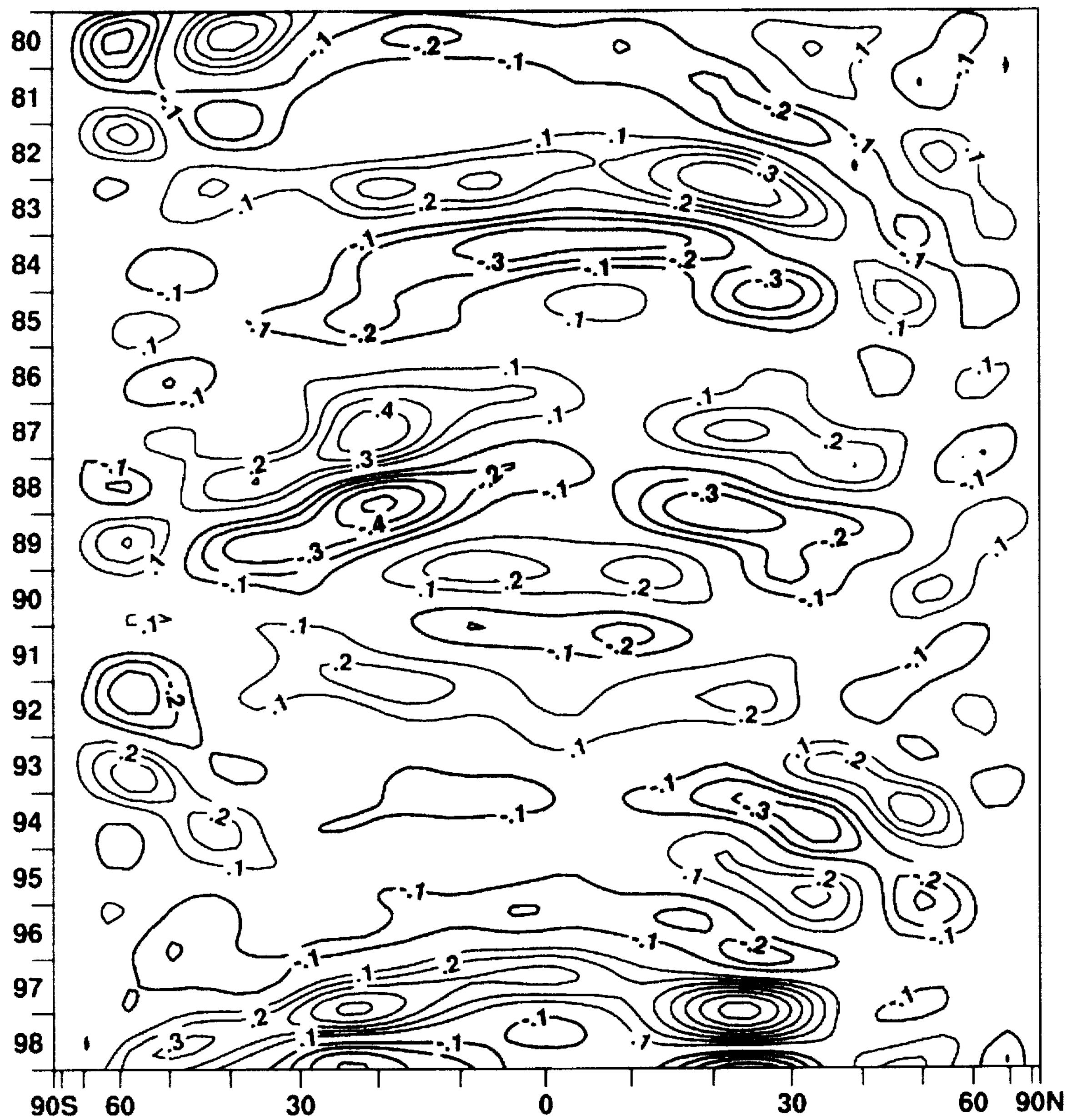

Fig. 7. Band-pass filtered values of atmospheric angular momentum defined in zonal belts, band-passed to emphasize variability of about 2-5 years. Note the strong positive and negative signals (white and blue areas, respectively) during alternating El Niño and Niña events.

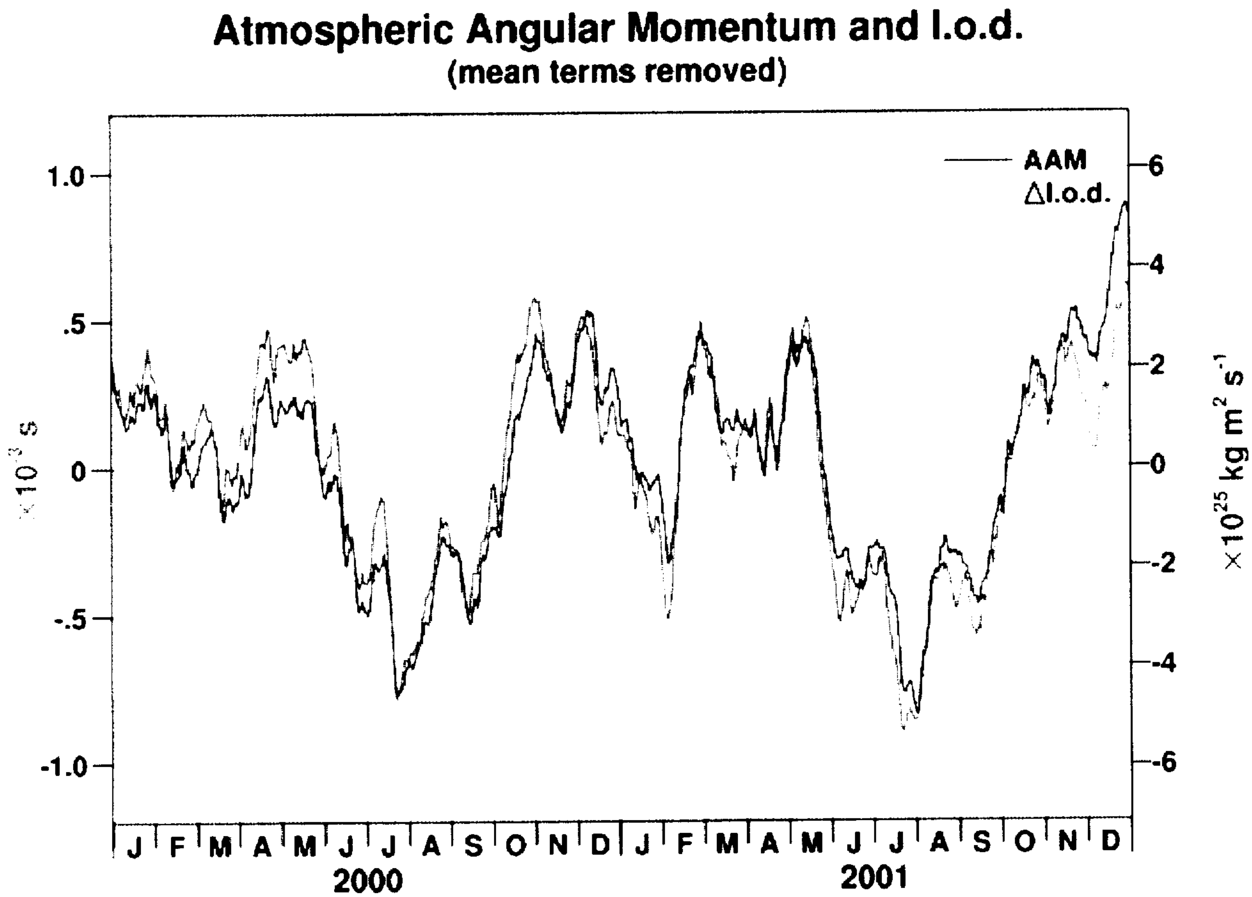

Fig. 8. Comparison of atmospheric angular momentum, between 1000 and 10 hPa, from the NCEP-NCAR reanalysis system, (red; scale on right), and the values of length of day (green; scale on left) for 2000-2001. Mean terms have been removed, and scales indicate equal amounts of equivalent angular momentum variability.

P1.20 IMPACT OF HIGH FREQUENCY WINDS ON THE DETERMINATION OF MEAN AND SEASONAL STRESSES OVER THE OCEAN

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1. INTRODUCTION

Studies of the axial atmospheric angular momentum and torque balance have revealed large uncertainties in the estimated seasonal variability of zonal wind stress over the ocean (Ponte et al. 2003). The zonal stress is given by

$$\tau = \rho C_d U u$$

where ρ is air density, C_d is the drag coefficient, U is the wind amplitude, and u is the zonal wind speed. Because of the nonlinear dependence of τ on the wind, variability at weekly and shorter periods can have an important effect in determining the mean and seasonal cycle in surface stresses (e.g., Hanawa and Toba 1987; Simmonds and Keay 2002). Using available operational and satellite-derived wind products, we explore here the potential for uncertainties in high frequency winds to contribute to errors in the seasonal variability in τ. Focus is on the seasonal cycle of zonal stress fields, as they relate to our original interest on the zonal torques involved in the seasonal axial AAM balance.

2. DATA AND METHODOLOGY

Atlas et al. (1996) have created a multiyear wind dataset by merging European Centre for Medium-Range Weather Forecasts (ECMWF) operational products with satellite observations from the Special Sensor Microwave Imager (SSMI). Here we use both the original ECMWF winds and the Atlas et al. satellite-enhanced winds (hereafter referred to as SSMI) to calculate zonal wind stresses based on the bulk formulation of Large and Pond (1982), as described in detail by Ponte et al. (2003). Both wind products were available on a 1x1 degree grid at 6-h sampling for the period 1988-99.

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The average stress over any period can be written as

$$<\tau> = \tau_M + \tau'$$

where brackets denote time averaging, $\tau_M = <\rho><C_d><U><u>$ denotes the contributions from the mean terms, and τ' includes all the covariance terms (e.g., $<\rho><C_d><U'u'>$) that incorporate the effects of nonlinearities in the stress relation. By comparing $<\tau>$ values based on 6-h quantities with values based on quantities that have been averaged over different periods, we can quantify the importance of τ' on the seasonal and mean stress values as a function of temporal resolution. In addition, using the difference in ECMWF and SSMI winds as a crude proxy for error, we can compare respective τ values to assess the effects of errors as a function of timescale.

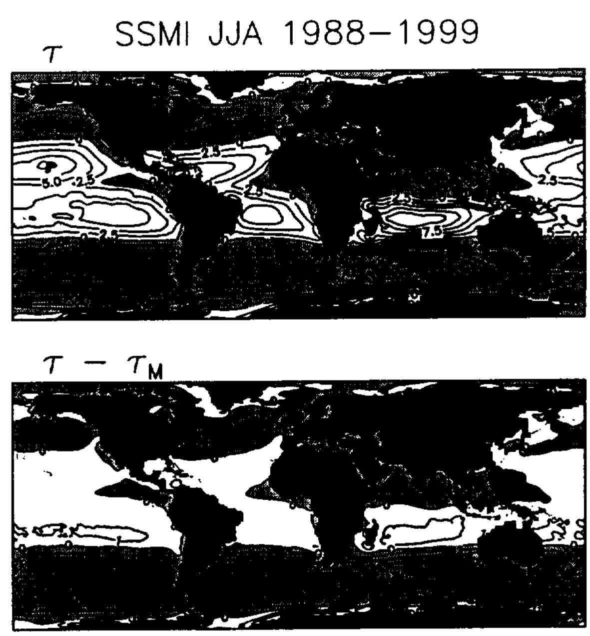

Fig. 1. Values of zonal stress on the atmosphere (positive for surface easterlies) using SSMI winds averaged over JJA season (top) and respective τ' contributions (bottom). Contour interval is 2.5 (top) and 1 (bottom) in units of N m^{-2}. Light shading denotes negative values.

3. CONTRIBUTION OF HIGH FREQUENCIES TO <τ>

Figure 1 shows values of <τ> based on 6-h quantities for the austral winter months of June-July-August (JJA), together with respective contributions from τ'. The latter terms are small but not negligible; typical amplitudes are approximately 10 to 20% of <τ> values. Important contributions by τ' are observed in most of the Southern Ocean, where strong synoptic winter variability is expected, and also in some tropical areas and the northern North Atlantic.

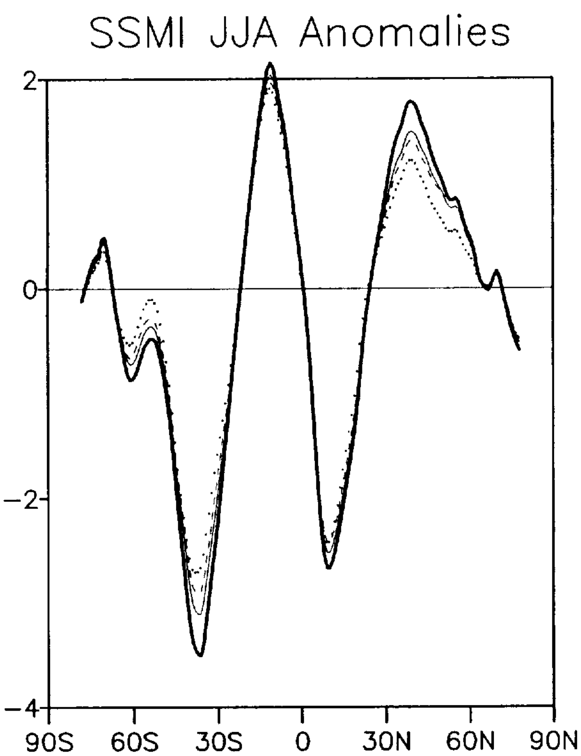

Fig. 2. Zonally averaged stress values (N m^{-2}) based on SSMI winds. Seasonal anomalies for JJA are shown based on 6-h (heavy solid), 3-d (thin solid) and 7-d (dashed) averaged quantities. The dotted line represents values of the mean term τ_M.

Results in Fig. 1 include the effects on τ' of all wind variability at periods longer than 12 h. To examine the importance of the highest frequencies, we calculate JJA stresses based on 3-d and 7-d averaged quantities (Fig. 2). Zonally averaged stress anomalies from the annual mean are shown to focus on the seasonal cycle. The 3-d results indicate that variability at subweekly periods provides a substantial contribution to the JJA stress anomalies, particularly at mid latitudes. Comparison with the values of τ_M confirms the importance of τ' contributions to <τ> found in Fig. 1 when only seasonal anomalies are examined.

4. EFFECTS OF HIGH FREQUENCY ERRORS

Given the importance of relatively short period variability in the determination of seasonal and mean zonal stresses, we explore the effects of possible errors in the wind field at these time scales by forming differences between the various τ curves shown in Fig. 2 for SSMI wind fields and their counterparts based on ECMWF winds. These differences (Fig. 3) are taken here to represent a crude measure of the uncertainty in the zonally averaged stress estimates.

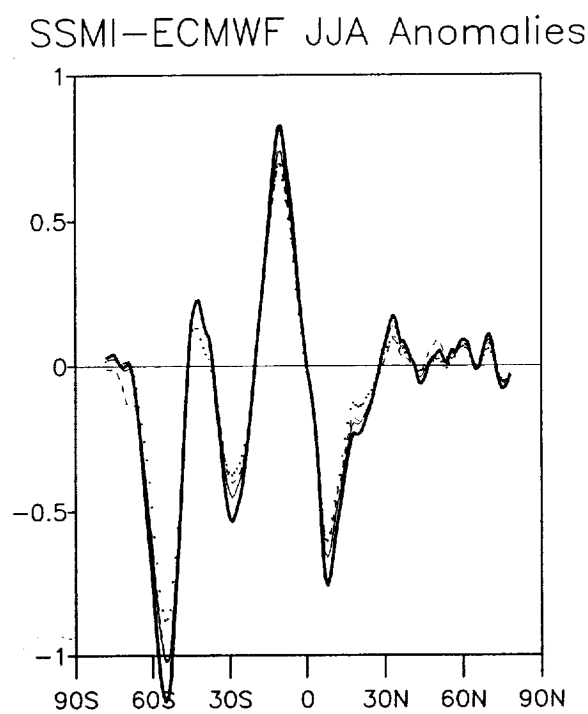

Fig. 3. As in Fig. 2 but curves are the differences between SSMI and ECMWF stresses.

Most of the differences in JJA stress anomalies in Fig. 3 are attributable to errors in the τ_M term, but errors in τ' are not negligible. For example, in the region of maximum difference near 50S-60S, τ' contributions are around 25% of the total difference in the ECMWF and SSMI fields. As seen from the 3-d curve, half of that signal comes from changes in wind fields at period shorter than 6 days.

Our original motivation stemmed from the uncertainty in the available estimates of the seasonal zonal torque *T* over the ocean, where *T* is the integral over the ocean surface of (r cosϕ) τ, with *r* being the radius of Earth and ϕ the latitude. The uncertainty introduced by possible high frequency errors in wind fields is assessed in Fig. 4 for the annual cycle.

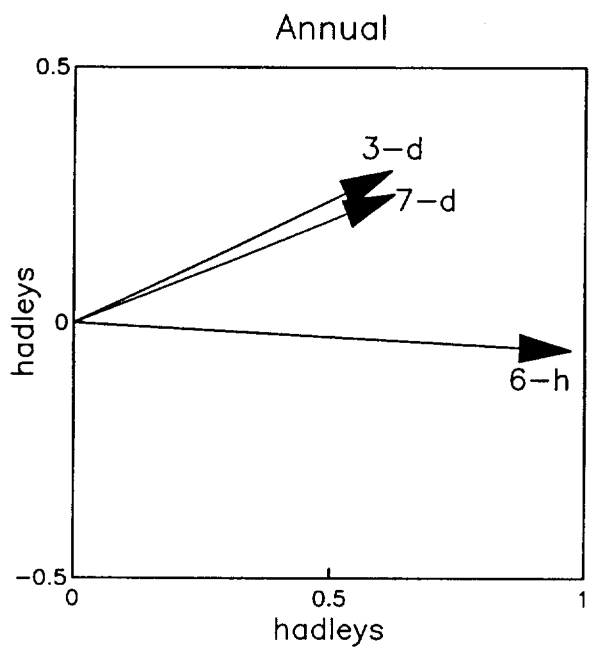

Fig. 4. Annual amplitude and phase of the difference in *T* values based on SSMI and ECMWF fields, in units of Hadleys (1 Hadley=10^{18} kg m^2 s^{-2}). Different vectors are for values derived from 6-h, 3-d, and 7-d quantities. Phase is plotted counterclockwise with 90° corresponding to a vector pointing straight upward. A phase of 0° corresponds to no phase difference between SSMI and ECMWF values.

Values of *T* for SSMI and ECMWF based on 6-h quantities differ in amplitude by 1 Hadley, with little difference in phase. Differences obtained for *T* series based on 3-d stress quantities are comparatively smaller and also show some phase shifting. Results for 3-d and 7-d quantities are very similar. These findings indicate that errors in subweekly wind fields contribute substantially to the differences between the annual cycles of *T* estimated from SSMI and ECMWF products.

5. SUMMARY

By comparing two different wind products and respective stress fields derived from them, we have shown that weekly and shorter period variability in surface winds affects the mean and seasonal cycle of zonal stress over the ocean, and that uncertainties at subweekly periods can lead to substantial errors in the latter. Results point to the need for determining subweekly wind variability as well as possible, both to model the seasonal variability in the ocean circulation and to close the seasonal torque balance of the atmosphere. Satellite wind observations with daily or better temporal resolution thus seem to be important for minimizing uncertainties in stress fields on seasonal timescales.

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