A link between variability of the semidiurnal tide and planetary waves in the opposite hemisphere

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Abstract

Horizontal wind observations over four years from the meteor radar at Esrange (68°N) are analyzed to determine the variability of the semidiurnal tide. Simultaneous global observations of temperature and geopotential from the SABER satellite instrument are used to construct time series of planetary wave amplitudes and geostrophic mean zonal wind. During NH summer and fall, the temporal variability of the semidiurnal tide at Esrange is found to be well correlated with the amplitude of planetary wavenumber 1 in the stratosphere in high southern latitudes (i.e., in the opposite hemisphere). The correlations indicate that a significant part of the tidal variations at Esrange is due to dynamical interactions in the Southern Hemisphere. Other times of the year do not indicate a corresponding robust correlation pattern for the Esrange tides over multiple years.

1. Introduction

Observations from ground-based radar and lidar show that the amplitudes and phases of diurnal and semi-diurnal tides are highly variable with irregular timescales of days to weeks [e.g. *Jacobi et al.*, 1999; *Riggin et al.*, 2003; *Lieberman et al.*, 2004; *Pancheva and Mitchell*, 2004; *Merzlyakov et al.*, 2005]. Sometimes the variation has a regular periodicity for a time and in these cases is normally interpreted as being the result of interaction between the tide and a traveling planetary wave. In some cases it is possible to identify the traveling wave responsible for tidal modulation when it is also present in the observations [e.g., *Pancheva*, 2006]. The variations from different regions can be coherent; in an evaluation of tides from the PSMOS (Planetary Scale Mesopause Observing System) campaign, *Pancheva et al.* [2002] found that the semidiurnal tide from multiple stations distributed over the globe showed a periodicity of around 16 days.

Often there is no indication of what is responsible for tidal variability. Several mechanisms are believed to contribute: variations in the heating that forces the tide, particularly the effect of latent heating in the troposphere on nonmigrating diurnal tides; variations in the background mean wind or temperature, which affect tidal propagation; interactions with large scale waves such as planetary waves or other tides; and interactions with gravity waves or dissipative regions associated with gravity wave breaking [*Fritts et al.*, 2006].

Atmospheric tides are composed of the superposition of global scale modes. For a specific tidal frequency, these can include a number of sun-synchronous (or migrating) components, approximately represented by the classical Hough modes [*Chapman and Lindzen,* 1970], as well as asynchronous (nonmigrating) modes. The migrating modes are forced primarily by solar heating; nonmigrating tides can be forced by longitudinal irregularities in the heating or by dynamical interactions between different tides or between tides and other waves. At any given point on the globe, the observed tide will include a mix of these modes.

One location where nonmigrating tides have received a lot of attention is at the South Pole during summer. Because of the geometry at the site, it is possible to isolate the zonal wavenumber 1 (s=1) nonmigrating mode using the data at this single station. The westward traveling s=1 semidiurnal tide reaches large amplitude there [e.g., *Portnyagin et al.,* 1998]. Modeling by *Angelats i Coll and Forbes* [2002] shows that interactions between the migrating semidiurnal tide and the quasi-stationary planetary wavenumber 1 in the NH stratosphere and lower mesosphere generates this nonmigrating tides and that it reaches large amplitude in high latitudes of the SH. Note that the amplitude of quasi-stationary planetary waves are negligibly small in the summer stratosphere so cross-equatorial coupling is required to explain the observations and is found in the simulations. Simulation of this nonmigrating mode in a general circulation model was reported by *Yamashita et al.* [2002]. They found that this tide in their model originates in the winter hemisphere but propagates across the equator and reaches maximum amplitude in high latitudes during summer, where it is the dominant semidiurnal mode. In their simulations, the NH nonmigrating tide during local summer was quite similar to that seen in the SH six months earlier. A westward propagating s=3 semidiurnal tide is also a product of the same interactions.

Baumgaertner et al. [2006] used data from two instruments at nearly opposite longitudes in high southern latitudes (75˚-78˚S) to look at the variability of the semidiurnal tide. With the two time series, they were able to separate the even wavenumber tides, which they assumed to be dominantly the migrating tide (s=2), and the odd-wavenumber tides (assumed to be s=1). They found that both were correlated with the presence of a planetary wave with wavenumber 1 somewhere in the stratosphere (either hemisphere). During shorter periods of a single season, the amplitude of the odd wavenumber nonmigrating tide was found to be well correlated with the planetary wave in the winter hemisphere.

The present study looks at variability of the semi-diurnal tide at a particular point in high northern latitudes. There is a multi-year record of tidal amplitude and structure from the meteor radar at Esrange, Sweden (68^{o}N, 21^{o}E) that has continued since October 1999 with relatively few gaps of more than a few hours. At this site, it is not possible to separate migrating from nonmigrating tides so we use a different approach to diagnose the tidal activity and variability. We use large scale geopotential height data derived from temperatures measured by the Sounding the Atmosphere using Broadband Emission Radiometry (SABER) satellite instrument to compare the temporal variations of the tide with global fields in the middle atmosphere. The results indicate a strong correlation between the Esrange summer semidiurnal tidal amplitude and planetary wavenumber 1 in high latitudes of the opposite hemisphere. The Esrange tide is also negatively correlated with the mean wind in the SH stratosphere. We interpret these results as indicating that the planetary wave variations are responsible for much of the observed semidiurnal tidal variations during summer.

2. Observations and data analysis

2.1 Esrange Meteor Radar

The radar used in this study is a commercially produced, “SkiYmet” all-sky VHF system, located at Esrange (68^{o}N, 21^{o}E). It has been operating continuously since the beginning of October 1999. Routine data analysis yields hourly-spaced values of the zonal and meridional winds in six independent height intervals centered on heights of 81, 84.5, 87.5, 90.5, 93.5 and 97 km. Further information about this radar, and observations made by it of mean winds and the 12- and 24-hour tides over Esrange can be found in *Mitchell et al*. [2002] and *Pancheva and Mitchell* [2004]. We use data for 2002-2005, when SABER data (see following subsection) are also available.

The basic information used in this study consists of daily estimates of the amplitude and phase of 12-hour period (the semidiurnal tide) for the zonal and meridional wind in each of the height intervals. To estimate the amplitude and phase of the tide as a function of time we applied a linear least-squares fitting algorithm. The fitting algorithm is applied to continuous time segments of 4-day duration, and a superposition of a mean wind and 48-, 24-, 12-, 8- and 6-hour harmonic components was fitted. The segment was then incremented through the zonal and meridional wind time series in steps of 1 day. This process yields daily-spaced values of the mean wind, the amplitude and phase of the quasi-2-day wave, and the amplitude and phase of the four tides in each height interval.

The 4-day segment for radar analysis was chosen after much experience with analysis of radar tidal data. For short time intervals, an even number of days, with a minimum of two, is necessary to avoid contamination of diurnal tidal phases by the 2-day wave. Comparison of various data by *Pancheva et al.* [2002] found that tidal structure was much more stable and reliable with 4-day, as opposed to 2-day, analysis windows.

2.2 SABER Geopotential Height

Observations of the planetary wave structure in the middle atmosphere are derived from observations made by the Sounding the Atmosphere using Broadband Emission Radiometry (SABER) instrument on the Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED) satellite. SABER radiances are inverted using a non-LTE retrieval algorithm to give temperature profiles on pressure surfaces from the upper troposphere through the lower thermosphere [*Mertens et al.,* 2001; 2004]. Altitudes are determined by integrating hydrostatically [*Remsberg et al.*, 2003]. SABER data are available starting in January 2002 with only brief data gaps. We use version 1.06 data.

SABER coverage extends from about 52˚ in one hemisphere to 84˚ in the other. About every 60 days, the latitude ranges flip as the spacecraft yaws to keep the instrument on the anti-sun side of the spacecraft. High latitude structure is therefore available only in 60-day segments, with no information for the 60 days preceding or following. The TIMED orbit precesses to cover 12 hours of local time in each 60-day yaw period; ascending and descending data together give almost 24 hours of local time sampling.

On any day, the SABER measurements at a particular latitude from the ascending portion of the orbit will be at similar local times, although this local time will be different at different latitudes. Likewise, the descending measurements will all be at approximately the same local time (but different from the time of the ascending data). The average over all ascending profiles from any latitude will contain the zonal mean and all of the migrating tides.

The processing of SABER data in this paper determines the planetary wave structure on a daily basis using profiles from 4 consecutive days; multiple days were used to ensure that all grid boxes were populated and to be consistent with the Esrange tidal analyses. Height data from all profiles are interpolated to a uniform pressure grid with spacing of 0.3 in log(pressure) and sorted into longitude and latitude bins of 20˚ and 5˚ respectively for the ascending and descending nodes separately. The mean of each bin is calculated, as well as the zonal means of the ascending and descending bin averages. The zonal means are subtracted from the binned data to create residuals that are combined and Fourier analyzed. This gives planetary wave structure for the day. The resulting daily wave analyses will include nonmigrating tides in the upper mesosphere. However, we are most interested in waves in the stratosphere and lower mesosphere; in this region, tidal contamination will be negligible because tidal amplitudes are small. The longitudinal averages are used to calculate the geostrophic zonal wind. The calculated wind will be contaminated by migrating tides in the upper mesosphere.

Fast-moving planetary waves such as the two-day wave can be distorted in satellite sampling [e.g., *Garcia et al.*, 2005] and will not be accurately determined by the processing of SABER data described here. However, the waves that dominate the winter stratosphere and lower mesosphere are quasi-stationary; this technique will give a reliable measure of their amplitude variations.

3. Comparisons of Esrange tidal variability with SABER global fields

Figure 1 shows a time series of the amplitude of the semi-diurnal tide in meridional wind at Esrange at 81 km and the simultaneous SABER planetary wave 1 at 6 hPa (approximately 35 km) and 50-55S for a period of 150 days spanning NH summer and fall. Points are plotted daily but, as noted in Section 2, each includes data taken over a four day window. There are periods, most striking during 2002 and 2005 but in the other years as well, when the two vary together on short (weekly) time scales. During all years there are similarities in the broader variations (time scale of several weeks to months). Figure 2 shows time series of the phase of the planetary wave for this time period during the two years with continual Esrange observations: 2003 and 2005, together with the Esrange semidiurnal tidal amplitudes repeated from Figure 1. These two winters were quite different: during 2003, wave 1 was traveling eastward until about day 240; after that it maintained a steady phase near the SH climatological position for this latitude and pressure. During 2005, wave 1 was dominated by the quasi-stationary component during the entire period and the phase did not vary strongly.

Figure 3 shows the linear correlation coefficient of the Esrange semidiurnal tidal amplitude with planetary wavenumber 1 amplitude throughout the global middle atmosphere for these dates for all four years. Points where the correlations are not significant at the 90% level are shaded; significance is calculated assuming a normal distribution and reducing the number of independent data points by a factor of four to take into account the 4-day averages used to construct both time series. Note that latitudes greater than 52˚ include only a subset of the data points (SH for days 198-261; NH for other days). The correlations are large and significant in the stratosphere and lower mesosphere in high southern latitudes during all four years. The highest value of the correlation coefficient is over 0.7 in 2002, 2003 and 2005 and over 0.5 in 2004. Analysis using the Esrange zonal rather than meridional winds gives similar results.

Correlations of the Esrange tide with the SABER zonal mean geostrophic wind (Figure 4) are somewhat irregular but predominantly negative in the SH stratosphere. This is expected since a growing planetary wave leads to a decreasing zonal wind [*Andrews et al.*, 1987]. Because of the relation between the wind and the planetary wave, it is not possible to tell solely from the correlations in Figures 3 and 4 whether it is the planetary wave, the wind, or perhaps the two together, that is responsible for the observed relationship.

The analysis was repeated for other times of the year but did not give results that were both statistically significant for at least two out of the four years and had a consistent pattern in those years.

The analysis shown in Figure 3 was repeated with a lag between the two time series (not shown). In most cases, the magnitude of the maximum correlation decreased or was about the same when the tidal time series lagged the planetary wave time series by periods of a week or less. Correlation magnitudes dropped for negative lag times (tidal wind amplitudes leading planetary waves). The exception was for 2003; over this period the magnitude of the correlation was similar with lag times of plus or minus 10 days. This reflects the importance of the low frequency variability in both time series to the correlations during that year.

The results shown use the Esrange tidal amplitude at 81 km. Analysis using the tidal amplitudes at other altitudes (up to 97 km) indicates that the correlation patterns shift and, in some years become negative. This reflects the variable phase structure of the tide [*Mitchell et al.*, 2002]; the period analyzed straddles summer (with on average a weak vertical phase tilt) and autumn (with a more pronounced tilt). The changing vertical structure of the semidiurnal tide can include changes in the balance of which tidal modes contribute to the net semidiurnal variation as well as variations in the structure of each individual mode as the background winds or forcing processes change with time.

4. Discussion and Conclusions

This paper presents observational analysis investigating the summertime variability of the semi-diurnal tide amplitude in the high latitudes of the NH. Analysis shows that the variability is tied to variations in the planetary wave 1 in the opposite (winter) hemisphere. We believe that this is an indication of a causal link. The correlations are strongest with simultaneous time series; no clear indication of a lag was found.

From these observations, it is not possible to separate the effects of the SH planetary wave from those due to the SH mean zonal wind since the two are highly related. However, there is extensive theory indicating that wave-wave interactions play a role in generating nonmigrating tides; a review can be found in *Yamashita et al.* [2002]. In particular, the model study of *Yamashita et al.* [2002] shows that a planetary wave in the SH winter generates nonmigrating semidiurnal tides that have their maximum amplitude in the high northern latitudes. The Esrange observations includes all tides that are present, including interference among both migrating and nonmigrating tides. Our interpretation is that the planetary wave in the SH interacts with the global semidiurnal migrating tide and produces nonmigrating semidiurnal tides that are variable in time, following the planetary wave. The interference between these mode and other semidiurnal migrating and nonmigrating components give the observed variability. Other tidal analyses [e.g., *Baumgaertner et al.*, 2006; *Angelats i Coll and Forbes*, 2002] focus on the planetary wave and its role in the generation of a westward s=1 semidiurnal tide in the SH. However, as noted in this study, the varying planetary wave is linked with a varying mean zonal wind in the winter stratosphere and lower mesosphere; the wind variations can affect the migrating tide itself and that also will contribute to the variability.

If this interpretation is correct, then it is somewhat fortuitous that the variations of the observed tide at the longitude of Esrange are often in phase with the planetary wave; superposition of the same semidiurnal modes at a distant longitude would give a different variability that might not agree with the SABER planetary wave amplitudes. It is perhaps relevant that, during the times that the SH planetary wave and the Esrange tide are correlated, the SH wave phase stays near its climatological position (Figure 2). A shift in the wave phase would affect the phase of any nonmigrating tides generated by wave-wave interactions and therefore would alter the net semidiurnal tide measured at ground-based sites. The apparent role of the phase of the SH wave suggests that at least a significant part of the Esrange tidal variability is due to the nonmigrating contributions; variations in the migrating tide as a result of interaction with the background winds would not be expected to have such a dependence. Additional evidence that nonmigrating tides are important at Esrange during summer is the substantially higher amplitude observed there (seen in [*Mitchell et al.*, 2002] and reinforced by our update of the Esrange amplitudes for additional years) than predicted by the Global Scale Wave Model.

Figure 1 indicates a growth in the amplitude of the Esrange semidiurnal tide within a week or two of day 250 of every year. An amplification of the semidiurnal tide around the time of autumn equinox in the NH (~day 266) has been seen for several NH radar sites [e.g., *Riggin et al.*, 2003] and various mechanisms to account for it have been proposed. From the current results, it is evident that a strong candidate for an explanation of this seasonal tidal growth is the amplification of planetary wave 1 in the SH.

It is noteworthy that we find the strong correlation with the tidal amplitude when the planetary waves are large in the opposite hemisphere but no such persistent correlation pattern during NH winter when the planetary waves are large in the same hemisphere. This is consistent with the South Pole results and the modeling of *Yamashita et al.* [2002], both of which show that the semidiurnal westward wave 1 tide is a dominant feature only in the local summertime. In contrast, *Baumgaertner et al.* [2006] found the SH nonmigrating tide was correlated with the planetary wave in SH winter although the tidal amplitude is much smaller then.

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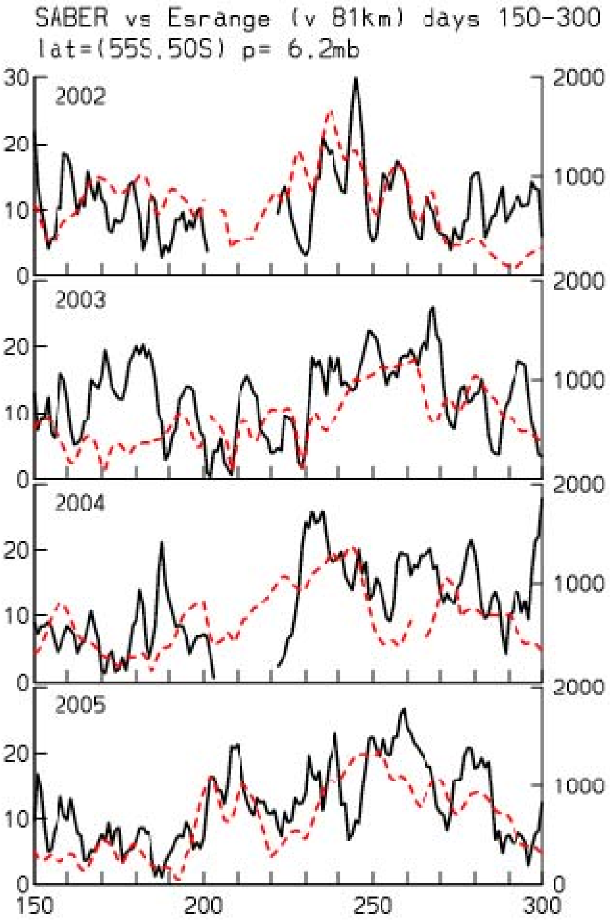

Figure 1: Amplitude of planetary wave 1 for the latitudes 50˚-55˚S at 6 hPa (red dashed line; units are m on right axis) and amplitude of the meridional wind semidiurnal tide at 81 km at Esrange (black solid line; units are m s^{-1} on left axis) for the period 30 May – 27 October during each of four years.

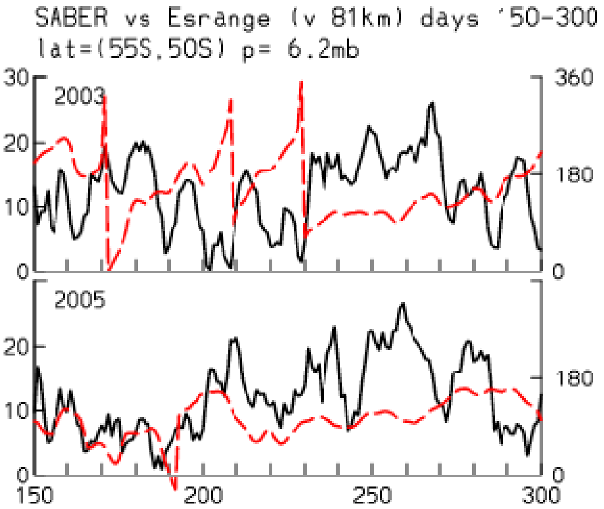

Figure 2: Phase of planetary wave 1 for the latitudes 50˚-55˚S at 6 hPa (red dashed line; units are degrees on right axis) and amplitude of the meridional wind semidiurnal tide at 81 km at Esrange (black solid line; units are m s^{-1} on left axis) for the period 30 May – 27 October during 2003 and 2005.

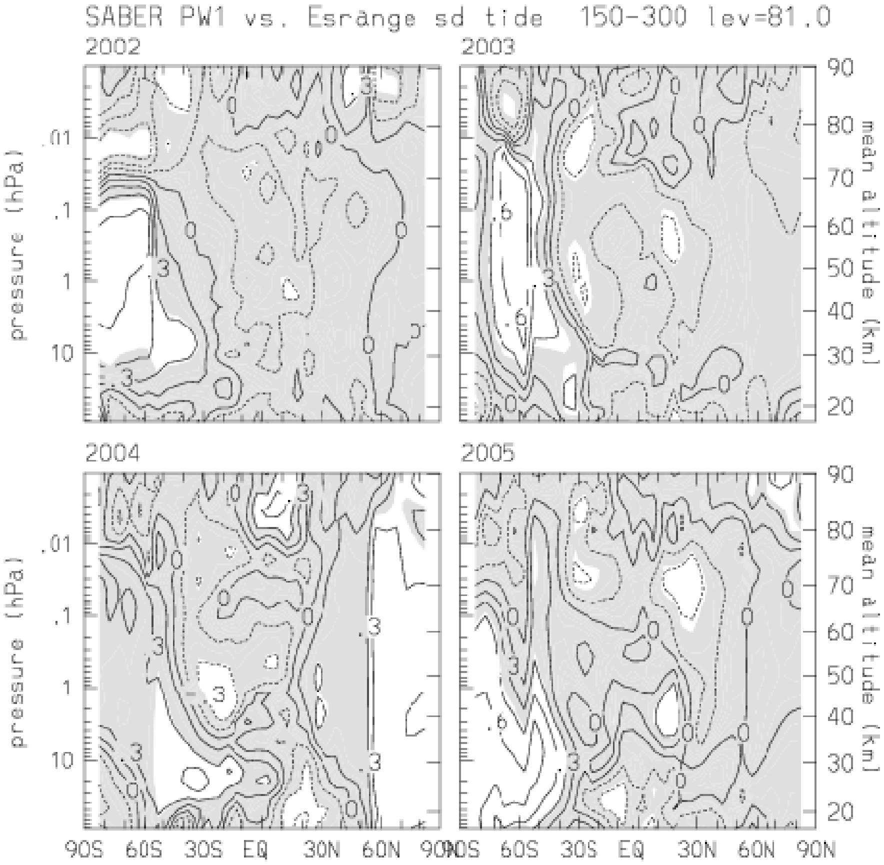

Figure 3: Correlation in time between the amplitude of planetary wave 1 at each latitude and pressure shown with amplitude of the meridional wind semidiurnal tide at 81 km at Esrange for the period 30 May – 27 October during each of four years. Shaded areas indicate that the confidence level is less than 90%.

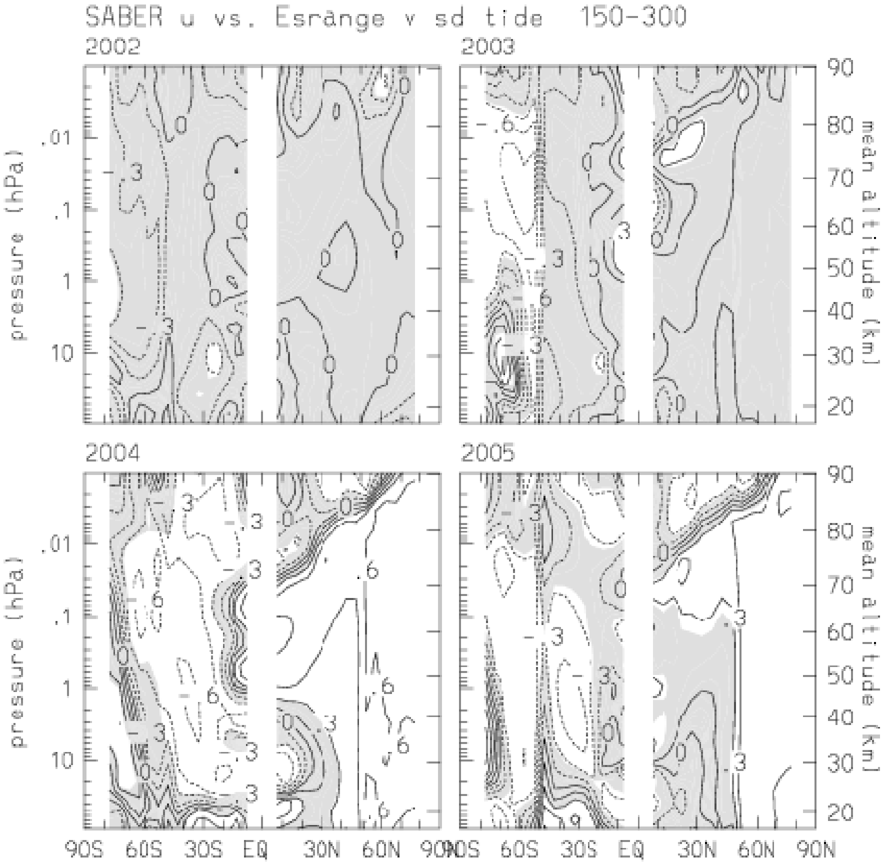

Figure 4: Correlation in time between the geostrophic zonal mean wind at each latitude and pressure shown with amplitude of the meridional wind semidiurnal tide at 81 km at Esrange for the period 30 May – 27 October during each of four years. Shaded areas indicate that the confidence level is less than 90%.