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МОДЕЛИРОВАНИЕ ПЛАНЕТАРНЫХ ВОЛН В СТРАТО- И ТРОПОСФЕРЕ ПОД ВЛИЯНИЕМ ФЛУКТУАЦИЙ СОЛНЕЧНОЙ АКТИВНОСТИ ВСЛЕДСТВИЕ ВРАЩЕНИЯ СОЛНЦА

MODULATION OF PLANETARY WAVES IN THE STRATO- AND TROPOSPHERE BY SOLAR ACTIVITY FLUCTUATIONS DUE TO SOLAR ROTATION

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Из спутниковых наблюдений хорошо известно, что солнечные пятна на вращающемся солнце вызывают периодические колебания стратосферного озона и температуры. Наиболее заметные периоды атмосферных возмущений соответствуют планетарным волнам (ПВ), указывающим на модуляцию волн солнечной активностью. Этот эффект также существует в поле давления волн. Это открытие подтверждает гипотезу, что планетарные волны переносят солнечные возмущения, индуцированные в средней атмосфере, вниз в нижнюю атмосферу. Измерены возмущения, связанные с солнечным вращением, и обсуждаются возможные механизмы распространения возмущений вниз в ПВ, направленных верх.

1 Introduction

Besides the possible impact of the solar sunspot cycle on climate and weather the modulation of atmospheric processes by solar emission fluctuations due to the rotation of the sun is a prominent issue of studies of the impact of solar variability on the atmosphere. Though solar rotation effects are considered to be less efficient than solar cycle effects, they are nevertheless an important feature to be studied for mainly two reasons. Firstly, the rotation period of 27.3 days is short enough for statistical analyses of atmospheric time series where tests of significance have to be performed. Secondly, rotationally induced fluctuations of solar activity exhibit spectral maxima near 27 days and its first two higher harmonics and correspond thus to prominent periodicities of the planetary wave spectrum. This fact suggests itself that planetary waves with periods of about 27 days and less might be sensitive to solar activity fluctuations due to solar rotation and that their investigation might provide clues to the controversially debated mechanisms of sun weather relationships. It has also been speculated that the solar cycle impact on climate might be governed by planetary wave modulation which is itself modulated by the solar cycle [1].

Responses of stratospheric ozone and temperature to solar radiation changes resulting from the sun's rotation have been studied by several authors after reliable satellite observations became available (e.g. [2 - 8, 13]). As a consequence one may speculate that such perturbations affect the dynamical behaviour of the stratosphere and that this should be visible in the variability of the meteorological parameters characterising the temporally changing dynamical state of this atmospheric region. Indications that this is the case have been inferred from statistical analysis of radiosonde observations of pressure and temperature [9] even before reliable satellite observations of direct solar ultraviolet radiation impacts became available. Somewhat later the dynamical response of the stratosphere was confirmed by zonal wind observations in the stratosphere [15]. These findings have been provoking a series of extensive statistical analyses of the spatial and temporal structure of the perturbations of the dynamical field in the stratosphere [10, 11]. Furthermore, model studies have been initiated by these analyses with the aim to explore the processes generating the correlation between solar and atmospheric oscillations. Dameris et al. [12] using a mechanistic dynamical model of the middle atmosphere simulated the penetration of 27-day periodicity from the stratopause region to lower levels. While this disturbance was artificially imposed on the model atmosphere, Krivolutsky et al. [14] applied a realistic perturbation based on UARS UV data in their model and generated wave motions in this way.

Recently Gruzdev et al. ([15] briefly GSB in the following) presented a stimulating model study of the effect of solar rotational irradiance variation on the middle and upper atmosphere using the complex chemistry-climate model HAMMONIA. They imposed a single periodicity of 27 days on the spectral extraterrestrial solar irradiance and found a complex response of their model to this simple sinusoidal forcing. It could be shown that such single frequency forcing spreads to other oscillation frequencies in the model atmosphere with different spatial and temporal structure in the middle atmosphere, in particular in the stratosphere. Though this was a simple design of the experiment in a model atmosphere, it appears to be the most comprehensive simulation study of perturbations induced by solar rotation till now. The results clearly draw the attention to the non-linear aspect of this phenomenon which before has mainly been interpreted on the background of linear wave theory. The present paper is very much motivated by the model study of GSB.

The data employed is derived from statistical analyses as described in the next section. Then some quantitative estimates regarding the intensity and structure of solar-induced stratospheric oscillations with extension to the troposphere are presented mainly looking for signs of non-linearity in the real atmosphere. Some concluding remarks are given at the end.

2 Method

Linear spectral time series analysis [16] has been applied to meteorological parameters as derived from global radiosonde observations on constant pressure surfaces. In this paper we only focus on geopotential height and temperature since we are interested in dynamical effects. The method is described in detail in [1, 9]. The geopotential height and temperature fields have been decomposed in harmonic components as function of latitude. Time series of the sine (A_n) and cosine (B_n) coefficients for zonal wave number n = 1, 2, 3…. are obtained as functions of latitude and pressure. Then coherence spectra have been estimated from the time series of the amplitudes A_n, B_n and solar activity in the period range 3 to 50 days employing the intensity of the solar 10.7-cm radiation as the activity parameter. The 10.7-cm index reveals clear relative maxima of autospectral estimates near periods of 27.3 and 13.6 days, i. e. at the sun's rotation period and its second harmonic.

The spectral methods allow estimates of significance (95% limit applied) and the quantification of phase differences between coherent solar signal and atmospheric parameter oscillations as well as of coherent amplitudes A and B of the zonal harmonics. Zonal wave numbers 1, 2 and 3 have been investigated with respect to their response to activity variations resulting from solar rotation. Here we preferably focus on wave number 1 for the sake of brevity. It is the wave number exhibiting the strongest coherence. An example of coherence spectra obtained from A_1 and B_1 time series is shown in Fig. 1. Artanh of coherence K instead of coherence squared is used for easier statistical interpretation. The bandwidth of the spectral estimates indicated in the figure is 0.0067 day^{-1}. It is employed for all spectral estimates in this study. Two 95%-confidence limits are shown for a priori selection of frequencies or periods where solar rotation effects are expected (27.3 and 13.6 days) and a posteriori selection of periodicities with strong coherence maxima (25 and 15 days in the example).

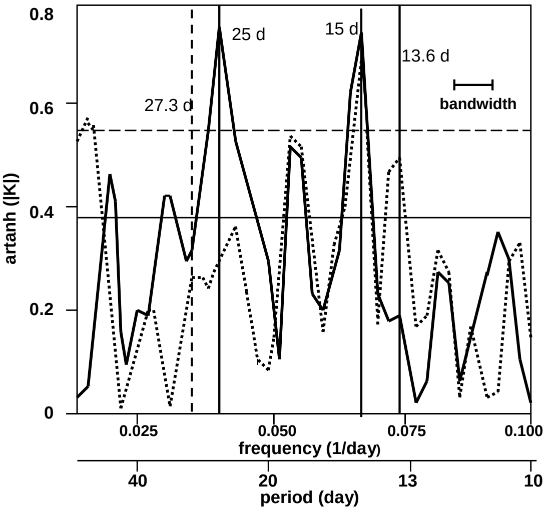

Figure 1: Example of coherence estimates for zonal wave number 1 sine (A) and cosine (B) cofficients of geopotential height at 60 degr. N and 30 hPa and for solar activity (10.7-cm radiation). Rising phase and maximum of weak to intermediate sunspot cycle (1965-1971). Coefficient A: continuous curve. Coefficient B: dotted curve. Horizontal lines show 95%-confidence limits for a posteriori selection (broken line) and a priori selection (continuous line). Frequencies of peculiar interest are indicated by vertical lines.

3 Results and discussion

When checking the coherence spectra of the 10.7-cm index and the sine and cosine coefficients of the Fourier series components one may be surprised to find an at the first glance irregular distribution of frequencies with significant coherence estimates in the analysed spectral range of 0.02 - 0.35 d^{-1}. The sine and cosine coefficient coherence estimates may significantly differ. For instance, this happens around the solar rotation period and its first harmonic in the case shown in Fig. 1, where a significant response has only been obtained for one of the coefficients. This can happen when the response of the standing part of the zonal wave is stronger than that of the transient part. When comparing the spectra at different latitudes in the middle stratosphere one observes a preference of significant values around 27 days, 15 days and 10 days. In certain periods stronger coherence is found around the period of 25 days instead of the solar rotation period. This is the case for the spectrum chosen for demonstration in Fig. 1. Furthermore, the coherence estimates for oscillations around periods of 15 - 16 days are usually stronger than those for the second harmonic of the solar rotation period which is also evident from Fig. 1. Analyzing the spectra at different latitudes and heights it appears that atmospheric dynamics are more sensitive to solar rotational activity fluctuations at larger latitudes and altitudes. Yet this kind of height dependence does not mean that the coherence disappears at lower stratospheric and tropospheric levels as demonstrated in Fig. 2. The distribution of the suspected solar forcing revealed by spectral analysis resembles the findings of GBS in principal regarding the broad band response of their model to single frequency forcing [17]. Yet it should be noted that there is a fundamental difference between their imposed pure 27-day perturbation and the real spectrum of solar activity in the periodicity range of solar rotation. In the latter case a red noise component is underlying the oscillations generated by the sun's rotation.

Though it is evident from spectral time series analysis and the GSB experiment that non-linear processes play a prominent role for the perturbation transfer from a given frequency to other frequencies of atmospheric oscillations, it appears that at the same time naturally existing perturbations themselves, namely free and forced atmospheric waves, play a decisive role for the reaction of the dynamical system to solar activity. This conclusion is based on three strong arguments.

(1) The energy argument: Rotationally induced height and temperature fluctuations of zonal wave number 1 may reach average values of the order 30 gpm and 0.5 K, respectively, at heights around 30 km (10 hPa). Tentatively assuming zonal wave amplitudes for geopotential height and temperature of the order 1000 gpm and 20 K, respectively, one obtains as ratio "solar activity disturbance/average" oscillation values of 0.03 and 0.025, respectively. This is about an order of magnitude larger than the average relative fluctuation of solar irradiance during a rotation period with dips up to a ratio of 0.0025 [18]. Obviously there is more energy contained in the disturbances than it would be expected if strict proportionality between solar forcing and atmospheric response would exist. Naturally existing waves are amplifying weak solar forcing.

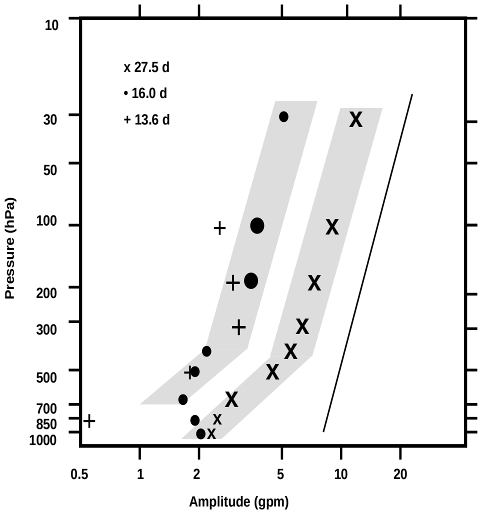

Figure 2: Amplitude estimates (gpm) of planetary waves with zonal wave number 1 coherent with solar activity (10.7-cm solar flux) at periods of 27.5 (solar rotation), 16 and 13.6 days. Latitude range 50 – 60 degrees. Estimated from geopotential height data (rising phase of a strong solar cycle, 1972 -1979) employing spectral analysis. Explanation of symbols and line see text.

(2) The wave structure argument: The temporal and spatial structure of the coherent perturbations of the major zonal wave amplitudes (wave numbers 1 - 3) closely resembles that of PWs [1, 19]. As an example, Fig. 2 exhibits amplitude estimates of coherent zonal wave number 1 oscillations for three prominent periodicities from the middle stratosphere down to the lower troposphere. Bold symbols indicate that at least one of the Fourier coefficients A and B exceeds the 95% confidence limit of the

respective coherence estimates. Light symbols indicate exceedances of the 85% confidence limit. The decrease approximately shows a dependence on pressure (or altitude) as expected for free planetary waves down to about 400 hPa. The theoretically expected dependence of amplitude S at pressure p is given by $\ln(S/S_0) = 0.28\cdot\ln(p_0/p)$ [20]and shown in Fig. 2 by the straight line arbitrarily starting at (p,S) = (30 hPa, 20 gpm). At lower levels the amplitudes decrease faster than expected for free waves. Such behaviour was simulated by Salby [21] studying forced resonant PWs. The grey shaded area approximately represents the relative decrease of wave amplitudes according to Salby's study. It thus appears that free and/or forced waves can act as "carrier waves" for perturbations imposed by solar irradiance variability due to the sun's rotation and transport the solar activity impact on the middle atmosphere generated by UV and EUV variability down to the lower atmosphere.

(3) Based on the hypothesis that resonant atmospheric oscillations should be particularly sensible to solar activity forcing, periods of waves in an isothermal atmosphere at rest with equivalent depth of 10 km have especially been analysed in the coherence spectra in the range where solar rotational forcing is expected [1]. Zonal wave numbers 1 - 3 with 1 - 4 latitudes, where the wave stream function vanishes, were selected. The period range 3.7 - 17.4 d is covered. Coherence estimates quite frequently exceed the 95% confidence limit at these periods in the middle stratosphere, in particular at higher latitudes, thus pointing to increased sensitivity to solar activity fluctuations in the respective period range. It is possible that the relative coherence maximum near 0.06 d^{-1} in Fig. 1 is caused by such resonance (zonal wave number 1, 4 zero points, period 17 - 18 days [20]).

4 Conclusions

Perturbations of atmospheric pressure and temperature induced by solar radiation variability resulting from the sun's rotation have been extracted by means of statistical time series analysis from observed fields of geopotential height and temperature in the middle stratosphere and traced down to the troposphere. The principal main forcing with periods of 27.3 and 13.6 days is also transferred to atmospheric oscillations with other periods indicating the existence of non-linear processes controlling the response of the atmosphere to this type of solar variability. The results of the GSB model experiments regarding the solar 27-day forcing are taken as support of this interpretation of the statistical results. The postulated existence of planetary "carrier waves" for the coherent fluctuations may help to explain also certain features of solar variability and climate relationships.

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ХОЛЛОВСКАЯ МГД МОДЕЛЬ «ФЛЭППИНГ» КОЛЕБАНИЙ ТОКОВОГО СЛОЯ МАГНИТОСФЕРНОГО ХВОСТА

HALL MHD MODEL OF THE “FLAPPING” OSCILLATIONS OF THE MAGNETOTAIL CURRENT SHEET

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Разработана холловская МГД модель «флэппинг» колебаний токового слоя магнитосферного хвоста при наличии малой нормальной компоненты магнитного поля, изменяющейся вдоль слоя. В рассматриваемой модели начальный невозмущенный токовый слой характеризуется заданным одномерным профилем тангенциальной компоненты магнитного поля типа Харриса. Градиент невозмущенной нормальной компоненты магнитного поля направлен к Земле. Для линейных колебаний токового слоя получена дисперсионная зависимость собственной частоты от волнового вектора для несимметричной и симметричной мод. В рамках холловской МГД модели собственная частота «флэппинг» колебаний зависит о направления распространения волны по отношению к вектору тока: она выше для волны, бегущей в направлении тока (в сторону вечернего фланга), и ниже для противоположно бегущей волны (в сторону утреннего фланга) по сравнению с результатом идеальной МГД модели.

Introduction. The term flapping waves was introduced with regard to the up-down motions of the current sheet in the Earth's magnetotail. These flapping wave oscillations were indicated usually by measurements of the corresponding variations of the tangential magnetic field component from negative to positive values. In fact, there exist many observations [1-6] demonstrating existence of the kink-like disturbances of the magnetotail current sheet, which propagate along the plane of the sheet perpendicular to the ambient magnetic field. First statistical studies of Cluster mission [2] yield a conclusion that flapping waves propagate preferably from the tail center to its periphery. This result was also consistent with previous observations. However the dawn-dusk asymmetry aspects were not discussed. Further analysis of Cluster data [3] indicated some evidence of the dawn-dusk flapping propagation asymmetry. Also statistical studies [3,7] proofed a relationship between the flapping oscillations and fast plasma flows in the current sheet.

In spite of large amount of existing observations, a physical nature of the flapping motions is still not understood well. There exist several theoretical approaches for describing the flapping waves in the Earth's current sheet. In particular, a drift kink mode [8] was proposed to explain the flapping oscillations, which is due to a relative drift of electrons and protons. The ion/ion drift kink mode was also considered