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Response of stratospheric circulation at 10 mb to solar activity oscillations resulting from the sun's rotation

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ABSTRACT

Indices, which reflect variations of the zonal geostrophic wind at the 10-mb-surface of the northern hemisphere, are compared with solar activity fluctuations applying methods of statistical frequency analysis. At a frequency corresponding to half the synodic rotation period of the sun, a significant response of the stratospheric circulation to solar activity is found for nearly all latitudes between 10 and 80° N. Considering the detailed coherency spectra it is suggested that a stratospheric "system", e.g. a high or low pressure belt with an average position near 50° N, oscillates with the synodic period of the solar rotation. The periodic variations are probably modulated by annual, semiannual and 4-monthly oscillations of the solar radiation or of stratospheric quantities. Satellite measurements of the stratospheric radiance (temperature) indicate that the response to solar activity fluctuations resulting in quasiperiodic changes of stratospheric properties with half the rotation period of the sun, is a global phenomenon.

1. Introduction

The problem of meteorological and climatic responses to solar activity variations has stimulated many controversial discussions about the existence and meteorological relevance of such processes. Especially older publications on this subject mostly suffer from the lack of significant results normally based on the application of statistical methods (Berg, 1957). Yet more recent investigations (King, 1975; Wilcox, 1975; compare also the working document on solar-terrestrial physics issued by the SCOSTEP Secretariat, World Data Center A, 1975) give strong evidence that it might be possible to identify solar activity effects in temporal and spatial variations of meteorological elements applying improved observational and analytical techniques. One of the main tasks of such investigations is to find out the physics and energetics of middle and lower atmospheric responses to solar activity. Apart from the study of special solar-terrestrial events, this requires large scale—global or hemispheric—investigations of the whole complicated atmospheric system with respect to solar activity effects.

This study may be regarded as a small contribution to such a laborious project. The paper is concerned with 10-mb-height variations in the northern hemisphere in connection with solar activity oscillations in a frequency range between roughly 1/80 and $1/10\,d^{-1}$, including the solar rotation frequency and its first harmonic. Unexpected phase and amplitude correlations between solar activity and 10-mb-circulation fluctuations as derived from the isobaric surface heights, were found when the global characteristics of stratospheric and ionospheric interactions were investigated. As will be shown below, an important fraction of the correlations can be explained by hemispheric, perhaps global, oscillations connected with solar activity changes due to the rotation of the sun.

We have compared daily 10-mb-circulation indices and solar activity changes, as indicated by the flux of the 10.7-cm-radiation of the sun, by means of spectral analysis methods (Jenkins and Watts, 1968). The circulation indices (I) have been derived from the geopotential height (h) of the 10-mb-pressure surface by definition:

$$I(\phi_1, \phi_2, \lambda_1, \lambda_n) = \frac{1}{n} \sum_{i=1}^{n} h(\phi_1, \lambda_i) - h(\phi_i, \lambda_i)$$

where ϕ_1 and ϕ_2 represent the southern and northern boundary of a latitude belt. $\phi_1 - \phi_2 = 20°$ was chosen. I is proportional to the average of the approximate zonal component v of the geostrophic wind in the area (ϕ_1, ϕ_2, λ_1, λ_n), with $v \approx 0.03\, I/\sin((\phi_1 + \phi_2)/2)$ where I and v are given in gpm and m/s, respectively. The 10-mb-data were supplied from the Institute of Meteorology, FU Berlin. They are available for the northern hemisphere ($10 \times 10°$ gridpoints) from Nov. 1964–Oct. 1971.

2. Results and discussion

The time series thus obtained have been prefiltered to subtract long-term variations with periods of more than about 80 d. This has been done by applying the elementary filter W_0 (smoothing by equally-weighted running means) after Kertz (1966) with the frequency response $R(f) = (1/2\,m) \sin(2\pi f m \Delta t) \cot(\pi f \Delta t)$ where $2m + 1$ is the number of the discrete weights of the filtering function and Δt (= 1 day) the distance of the values in the time series. $m = 20$ has been chosen for this study. Then, spectra of different kind (auto-, cross-, amplitude, phase, coherency spectra) have been estimated using circulation indices for latitude belts from 10–20° N up to 60–80° N, with the longitude normally ranging from 0–360° E (zonal indices). In a few cases sectorial indices for a longitude range of less than 360° E have been investigated.

The coherency estimates show strong responses of all selected indices to the solar activity in various frequency intervals which seem to be irregularly distributed over the entire range studied. Yet in at least one case, there exists a consistent significant response of the 10-mb-circulation in most of the northern latitude belts to solar activity oscillations. This response was found in a frequency band centred at $f = 2/27.3\ \mathrm{d}^{-1}$, that is two times the frequency f_0 corresponding to the sun's synodic rotation period. The coherency spectra of six zonal indices ($0 \leqslant \lambda \leqslant 360°$) and two sectorial indices ($\phi_1 = 50°$ N, $\phi_2 = 70°$ N, 0° E $\leqslant \lambda \leqslant$ 90° E and 150° E $\leqslant \lambda \leqslant$ 240° E) are shown in Fig. 1 for periods between roughly 10 and 66 days.

The computation of the spectra has been carried out following the rules given by Jenkins & Watts (1968). The estimates are smoothed using the Tukey window. This leads to a spectral bandwidth

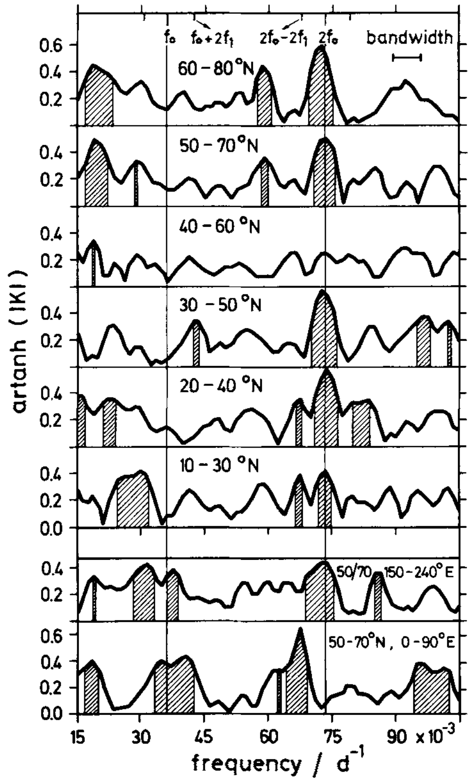

Fig. 1. Coherency spectra for time series of the solar activity (10.7-cm-flux of the solar radiation) and 10-mb-circulation indices. Upper six curves: Zonal indices. Lower curves: Sectorial indices for 50–70° N. Hatched areas indicate values which exceed the 95 % confidence limit (0.34). Bandwidth 0.0067 d^{-1}, time lag 200 d, daily values from November 1964 to October 1971.

of $b = 1.333/L\ \mathrm{d}^{-1}$. L is the lag (in days) chosen for the cross and autospectral estimate. When a time series contains T daily values, $\nu = 2b \cdot T$ degrees of freedom are associated with the spectral estimate. The confidence limit of the squared coherency estimate, K^2, can be obtained from the confidence limit of artanh ($|K|$), given by $c = \pm r/\sqrt{\nu}$ (90 %-limit: $r = 1.64$, 95 %: $r = 1.96$). 95 %-confidence limits for the phase and autospectral estimates (Table 1) have been taken from diagrams after Jenkins & Watts (1968).

Characteristic parameters of the time series and spectra discussed in this study are $L = 200$ d and $T = 2500$ d. Therefore one has $b = 0.0067\ \mathrm{d}^{-1}$, $\nu \approx 33$ and c (95 %) ≈ 0.34. For the autospectral estimate (spectral density) C_{xx} the 95 %-confidence limits are $\langle 0.75, 1.7 \rangle \times C_{xx}$.

Table 1. *Spectral estimates (10.7-cm-flux, 10-mb-indices) for frequencies f near 0.073 d^{-1} and 0.059 d^{-1}. p: Period. C_{xx}: Autospectral estimate of the 10-mb indices in gpm²d. K^2: Squared coherency. ϕ: Phase. h^*: "Amplitude" of the 10-mb-height oscillation related to solar activity, defined as $(K^2C_{xx})^{1/2}$. v': Corresponding amplitude of the zonal geostrophic wind oscillation; the width of the spectral lines for which v' is calculated, has been taken to be* 0.0067 d^{-1}

Latitude (degrees N)	f (d^{-1})	p (d)	C_{xx} (gpm²d)	K^2	ϕ (degrees)	h^* (gpm $d^{1/2}$)	v' (cm/s)
60–80	0.0725	13.8	0.1546×10^6	0.28	229 ± 24	208	54
50–70	0.0738	13.6	0.4050×10^5	0.22	201 ± 28	94	27
40–60	0.0738	13.6	0.6770×10^4	0.06	88 ± 60	20	6
30–50	0.0725	13.8	0.4895×10^4	0.27	21 ± 24	36	14
20–40	0.0738	13.6	0.3356×10^4	0.27	2 ± 24	30	15
10–30	0.0738	13.6	0.1623×10^4	0.15	36 ± 35	16	11
50–70, 0–90 E	0.0675	14.8	0.1170×10^6	0.32	196 ± 22	193	55
50–70, 150–240 E	0.0713	14.0	0.1486×10^6	0.17	180 ± 33	159	45
60–80	0.0588	17.0	0.1588×10^6	0.18	-23 ± 33	169	44
50–70	0.0588	17.0	0.6155×10^5	0.12	-15 ± 38	86	24
10–30	0.0588	17.0	0.2010×10^4	0.10	158 ± 40	14	10

The coherency estimates for certain frequencies are partly selected "a priori" and partly "a posteriori". The latter is the case for $2f_0$ in Fig. 1, where at least one value should exceed the significance limit for posteriori selection (Julian, 1975). For the sake of simplicity we use as this limit $c^* = \sqrt{2}\, c$ for artanh (K) (based on considerations on white noise spectra). c^* appears to be a somewhat more stringent test than the values quoted by Julian. With $c = 0.34$ one has c^* (95%) = 0.48. This limit is not exceeded by the curves 40–60° N and 10–30° N at $2f_0$ in the upper part of Fig. 1. The latter curve only reaches c^* (90%) = 0.40 at $2f_0$. Another value above c^* (95%) is found for 50–70° N at $f = 0.019$ d^{-1} and for the sector 50–70° N, 0–90° E near $f = 0.07$ d^{-1}. The investigation of the spectra around the rotation frequency of the sun, f_0, and near some modulation frequencies ($mf_0 \pm nf_1$), which are discussed below, may be regarded as a case of prior selection. The intervals where the coherency estimates exceed the prior confidence limit c (95%) are hatched in Fig. 1. Briefly, "significant" in the following text means that in the case of posteriori selection at least one value of the spectra in Fig. 1 exceeds c^* (95%) at a fixed frequency when a group of spectra is discussed whereas the other significant values may range between c and c^*. In the case of prior selection the estimate exceeds c (95%).

Thus one has significant responses of the zonal—and partly sectorial—10-mb-indices to solar activity oscillations around $2f_0$ except for 40–60° N. The corresponding phases are given in the table. One finds circulation oscillations which between 10 and 50° N appear to be in phase with the solar activity oscillations, and which show a phase difference of 180° or approximately 7 d north of 50° N. With the values given in the table, an estimate can be made concerning the amplitudes of the velocity changes resulting from the response to solar activity around $2f_0$. With a width of the spectral "lines" of 0.0067 d^{-1}, amplitudes between 11 and 55 cm/s are obtained when the coherency values are significant. The corresponding momentum at 10 mb north of 50° N nearly equals the momentum in the opposite direction south of 50° N. Yet this may be an accidental result since the errors of the amplitude estimate are very large (Fig. 3). Regarding the sectorial spectral estimates around 60° N (lower curves in Fig. 1) the following differences with respect to the zonal estimates can be stated. The frequency intervals with significant coherency values near $2f_0$ are shifted to lower frequencies, especially for 0–90° E. The autospectral estimate for the indices I yields appreciable larger values than for the zonal indices. Strong coherency appears around f_0 whereas the zonal indices show a marked minimum near the synodic rotation period of the sun.

The autospectra in Fig. 2 clearly show that the

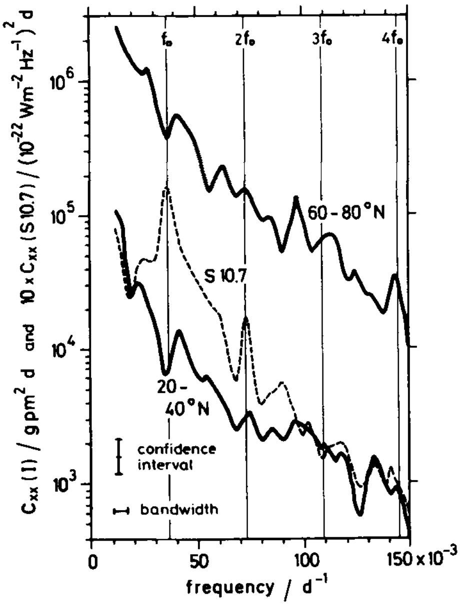

Fig. 2. Autospectral estimates C_{xx} for filtered time series of the 10-mb-indices (I, in gpm) and solar activity (10.7-cm-flux of the solar radiation, S10.7, in units of 10^{-22} W m^{-2} Hz^{-1}). The curves are corrected with respect to the frequency response of the applied filter W_0 (see text). Total variance of the filtered time series: 1082 gpm^2 (I, 20–30° N), 42,370 gpm^2 (I, 60–80° N), 358 [10^{-22} W m^{-2} Hz^{-1}]^2 (S10.7).

variance of the zonal 10-mb-index is appreciably reduced near f_0 and slightly increased near $2f_0$. The decrease and increase both correspond to an increase of the spectral density of the activity parameter. In principle, it is possible that these "lines" formally produce enlarged coherency estimates. Yet considering the systematic behaviour of the phases in the northern hemisphere at $2f_0$, the reduced coherency near $2f_0$ in only one latitude belt (40–60° N) and the diminished values near f_0 in spite of the strong activity line, it seems very unlikely that they have been generated by chance.

The apparent relationship between the 10 mb circulation and the rotation frequency of the sun encourages a more detailed discussion of other spectral peaks near f_0 and $2f_0$, some of which also exceed the 95% confidence limit. The zonal indices for 10–30° N and 20–40° N show such maxima at $2f_0 - 2f_1$ with $f_1 = 1/365$ d^{-1}. Additional maxima are indicated at $2f_0 + 2f_1$ and $2f_0 + 4f_1$ in several coherency estimates. Furthermore, in some cases increased values are found around $f_0 + nf_1$ ($n = 1$, 2, 3) with n preferably equal to 2. Frequency shifts of $1f_1$ seem to appear less often. This is certainly due to the bandwidth of the spectral estimate which is roughly $2f_1$. Only the strongest maxima in a sequence f_0 (or $2f_0$) $\pm nf_1$ have the chance to appear as separate maxima in the spectra.

Summarizing these results, it can be said that strong evidence exists for a response of the zonally averaged circulation at 10 mb to solar activity oscillations with periods of half the synodic rotation of the sun and that this response is modulated by variations with the frequency f_1 (annual variation), $2f_1$ (semiannual) and perhaps $3f_1$ (4-monthly). This modulation may also exist around f_0 (full rotation period) where the circulation response is completely suppressed in the zonal indices, yet is clearly present in the sectorial indices.

Another interesting frequency seems to be 0.0588 d^{-1} where large coherency values show up for the zonal indices of 50–70° N and 60–80° N. (Values exceeding c^* (95%) are obtained when magnetic activity instead of solar activity is used.) The value for 10–30° N in Fig. 1 nearly exceeds the 95% confidence limit. These cases are included in the table. One finds a similar behaviour as for $2f_0 = 0.073$ d^{-1}. Yet the phases with respect to the solar activity oscillation differ by about 180° compared with the cases at $2f_0$.

3. Interpretation

Coherency spectra obtained from the summer and winter portions of the time series yield no significant seasonal differences at f_0 and $2f_0$. Though the spectral resolution of such short time series is appreciably reduced, this may be taken as an indication that the oscillations near the frequency $2f_0$ occur on a global scale. Seasonal effects apparently result in modulated oscillations when long time series are regarded.

If the oscillations with the frequencies f_0 and $2f_0$ at 10 mb are treated separately, it may be suggested that the variations near f_0 resemble global oscillations on the rotating earth with latitudinal structure (wave number > 0; Longuet-Higgins, 1968). Such oscillations will show up in sectorial but not in zonal averages. Then the oscillations near $2f_0$ have an important component with wave number 0, leading to strong coherency estimates for zonal averages, and perhaps also

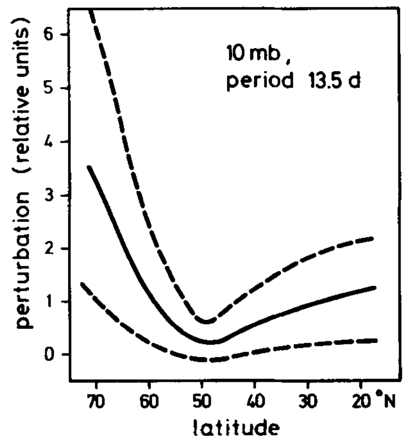

Fig. 3. Sketch showing the amplitude of the periodic height perturbation of the 10-mb-pressure surface corresponding to solar activity oscillations at a frequency $f \approx 0.074\ d^{-1}$. The middle curve is based on the values h^* in the table. Other curves represent estimates of the upper and lower limit of the perturbation according to the 95% confidence intervals of the coherency and autospectra.

show a longitudinal structure which may explain the different behaviour of the sectorial indices compared with the zonal means. It may be noted that the latitudinal profile of h^* (for zonal indices, Fig. 3) is very similar to the eigenfunction of the height perturbation of a thin oscillating layer as derived by Longuet-Higgins for the lowest modes with zonal wave number 0.

On the other hand, the oscillations around f_0 and $2f_0$ may be ascribed to a common source, for which a simple—preliminary—model can be designed. With the aid of h^*, which is an estimate of the fraction of the height perturbation at 10 mb correlated with the solar activity fluctuations (Table 1 and Fig. 3), a belt of high or low pressure with an average position of its centre at 50° N can be constructed. The meridional cross-section of the belt is asymmetric about its centre. This is thought to change its position periodically with a peak amplitude at fixed longitudes λ^* and $\lambda^* + 180°$. The deviations from its central position might vary, to a first approximation, as $\delta \sim \cos(2\pi f_0 t + \alpha) \cos(\lambda - \lambda^*)$. t, α and λ are the time, a phase angle and the longitude, respectively. (δ defines a standing wave with zonal wave number 1; higher wave numbers are possible.) The shape of the belt can be chosen in such a way that the main results of the coherency spectra at f_0 and $2f_0$ can be explained simultaneously. These are (1) the strongly reduced response of the zonal indices near 50° N, (2) the vanishing response of zonal indices near f_0, (3) the strongly increased response of sectorial indices near f_0, (4) the predominant coherency maxima near $2f_0$, (5) frequency and phase shifts in the sectorial spectra depending on the choice of the sector boundaries, (6) an increase of the spectral densities of sectorial indices when compared with zonal indices at the same latitude.

The essential point of the adopted model is the introduction of variations due to the synodic period of the sun's rotation as the basic process for the generation of an appreciable fraction of the zonal wind oscillations near the frequency f_0 as well as $2f_0$. This implies two consequences. (1) A good deal of the solar activity oscillations with frequencies around f_0 and $2f_0$ must be correlated with respect to phase and amplitude. This can be expected because of the general dependence of the activity fluctuations on the average level of the solar activity and only small changes of this level during one rotation period. (2) The latitudinal position of the oscillation axis of the stratospheric pressure belt, which is controlled by solar activity fluctuations due to the solar rotation, should not deviate too much from an average value during the observation period. Otherwise the coherency values near $2f_0$ or $2f_0 - 2f_1$ of the sectorial spectra would be markedly reduced. At this point we would like to emphasize that the "pressure belt" may be replaced by any other stratospheric system with similar spatial and temporal characteristics which is able to produce the observed oscillations. For instance, this system could be a general time-varying function describing the height structure of stratospheric wind or pressure field.

There remain to be explained (in the frame of the model) the coherency maxima, which occasionally show up near $f_0 \pm nf_1$ and $2f_0 \pm nf_1$. As already indicated, the simplest assumption is that the amplitude, phase or frequency of the principal oscillation (δ) are modulated by annual, semiannual, seasonal and other long-periodic variations. According to the latitudinal and longitudinal variations in the spectra, important spatial structures of the modulation function may exist. The coherency maxima near $f = 0.0588\ d^{-1}$ (period $=$ 17 d) probably may not be explained by the above adopted simplified model though $0.0588\ d^{-1} \approx 2f_0 - 5f_1$. The coherency spectra for the geomagnetic activity and the circulation indices also show significant maxima near $f = 0.0588\ d^{-1}$, especially at higher latitudes. Therefore, a combined effect of different processes, to which both activity parameters are related, seems possible. As a marginal result of the spectral analysis we state that ultralong waves ($P >$ 35 d) in the stratosphere may be correlated with the solar activity.

4. Concluding remarks

Several attempts have been made to get further information on the possible causes and source regions of the stratospheric oscillation at $2f_0$. The separate treatment of years with low (1964–1967) and moderate (1968–1971) solar activity yielded generally larger coherency values for the latter years. In addition, a better response of the 10-mb-indices to magnetic activity fluctuations (*Ap*) with frequencies around $2f_0$ was found at low and middle latitudes (20–50° N), but the corresponding autospectral densities are considerably less than the values connected with solar activity variations. Probably, the oscillations at $2f_0$ correlated with *Ap* are different from the index fluctuations correlated with solar activity, for the only significant response to *Ap* variations, which is obtained from the total 10 mb series, shows up at 50° N where the response to solar activity is less prominent.

Relatively short time series (April 1970–June 1971) of stratospheric radiance measurements (Nimbus 4, Satellite Infrared Spectrometer Experiment –SIRS–, channel 8, centred at 669 cm^{-1} of the CO_2-band, maximum of the weighting function near 25 km; Wark & Hilleary 1969) have also been analyzed with respect to responses to solar and magnetic activity variations at frequencies f_0 and $2f_0$. The zonal averages of the radiances between 80° S and 80° N exhibit oscillations around $2f_0$ which are significantly correlated with solar radiation changes, at nearly all latitudes. The latitudinal profile of the amplitudes is slightly different in both hemispheres. This is probably due to seasonal effects or to the existence and superposition of different modes of oscillations in the stratosphere. Again, the response to geomagnetic activity variations at $2f_0$ is much weaker than to solar activity fluctuations. Regarding activity oscillations, which correspond to the full rotation period of the sun, one might expect a better response in the case of radiance (or stratospheric temperature) than in the case of circulation at 10 mb, since the solar activity line at $f_0 - 1/27.3\ d^{-1}$ is very strong and direct absorption of fluctuating UV radiation by stratospheric ozone may be thought to cause the above assumed oscillations of a "pressure system" with the period of the solar rotation. Yet the response at f_0 is normally very weak, especially at low latitudes, or absent (at middle latitudes), whereas at high latitudes significant or nearly significant coherency values have been obtained (70° N, 80° N and S). Surprisingly large coherency estimates near f_0—$>c$ (95%)—showed up at 60–80° N and 80° S, when geomagnetic activity and stratospheric radiances were compared.

The problem of the stratospheric f_0-oscillation with zonal wave number 0 requires further investigation, for instance with respect to ozone variations which have also been measured by the satellite Nimbus 4 (Heath et al., 1973) but were not available in sufficiently long time series until now. The response of ozone to geomagnetic and solar activity fluctuations should be different at high and low latitudes if photochemical reactions due to cosmic rays significantly contribute to the NO production in the stratosphere (Ruderman & Chamberlain, 1975). Perhaps these data make it possible to decide if 27.3-d-oscillations connected with both kinds of activity are coupled or not, especially at high latitudes. On the whole, the solar activity appears to be the more important component near the frequency f_0 and acts on stratospheric temperature preferably at high and probably also at low latitudes. The relatively stable latitudinal position of the oscillating "system" as evident from the sectorial 10-mb-index variations can be ascribed to the influence of stationary pressure systems, e.g. the Aleutean high. The auto- and cross spectra of the stratospheric radiance again indicate that the oscillations at $2f_0$ strongly depend on dynamical processes. From the autospectrum "S10.7" in Fig. 2 one would expect the ratio 10 for the spectral densities of the radiance at f_0 and $2f_0$ if the stratospheric temperature directly reacted upon solar activity variations. Yet normally, the ratio is less than 5 (for instance 2.5 at 0° lat.).

The amplitudes of the zonal wind oscillations connected with solar activity fluctuations, which are given in the table for the frequency $2f_0$, show that these oscillations are of minor importance for actual meteorological wind changes. However, we think that they are of principal physical importance, especially with respect to the dynamics and energetics of the atmospheric circulation responses to solar activity, since they give strong evidence that the earth's stratosphere reacts like thin layers on a rotating sphere (Longuet-Higgins, 1968) to quasi-periodical disturbances generated by external energy sources. Certainly, it is necessary to find out more on the spectral (frequency as well as horizontal and vertical wave number) characteristics of these oscillations before a definite theoretical approach, for instance on the basis of the theory of atmospheric tides, is attempted. Perhaps the full spectrum of oscillations controlled by external sources will show that they are yet more meteorologically relevant than now realized. For climatological applications it will be worthwhile to investigate if such oscillations can cause accumulation or transfer of energy gained from solar activity fluctuations to climatologically more effective circulation or pressure systems in the middle and lower atmosphere.

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ВЛИЯНИЕ КОЛЕБАНИЙ СОЛНЕЧНОЙ АКТИВНОСТИ, ВЫЗВАННЫХ ВРАЩЕНИЕМ СОЛНЦА, НА СТРАТОСФЕРНУЮ ЦИРКУЛЯЦИЮ НА ПОВЕРХНОСТИ 10*МБ*

Параметры, отражающие изменения зонального геострофического ветра на поверхности 10 *мб* северного полушария, сравниваются с флюктуациями солнечной активности, причем применяются методы спектрального анализа. При частоте, отвечающей полупериоду вращения солнца, обнаружена значимая реакция стратосферной циркуляции на солнечную активность почти ве всех широтах между 10 и 80° с.ш. Особенности спектров когерентности для солнечной активности и параметры дают основание предполагать, что какая-то стратосферная "система", например, пояс высокого или низкого давления в среднем положении при 50° с.ш. колеблется с периодом вращения солнца. Периодические изменения, по всей вероятности, модулируются вследствие годовых, полугодовых и четырехмесячных волн в солнеуной активности или в параметрах стратосферного состояния. Спутниковые наблюдения радиации из стратосферы показывают, что реакция на колебания солнеуной активности в виде стратосферной волны с полупериодом вращения солнца представляет собой глобальное явление.