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MODELING THE IMPACT OF SOLAR ACTIVITY VARIATIONS ON GLOBAL ATMOSPHERIC CIRCULATION

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Abstract. In this study, we continue a series of works devoted to modeling and studying the sensitivity of global atmospheric dynamic processes to variations in solar emissions during the 11-year solar activity (SA) cycle. We focus on studying the response of meridional atmospheric circulation in the middle atmosphere to changes in thermosphere characteristics with changes in SA. For this purpose, numerical simulations of the general atmospheric circulation were carried out using the nonlinear numerical circulation model of the middle and upper atmosphere MUAM. The main mechanism of the influence of thermospheric disturbances on the underlying layers is assumed to be a change in the conditions of propagation and reflection of planetary waves (PWs) due to changes in SA. Changes in temperature, zonal and meridional wind are shown to localize along waveguides, demonstrating the significant role of PWs in transmitting thermospheric disturbances, caused by changes in SA, to the middle atmosphere. The magnitude of changes in meridional circulation can reach 10 % in the northern stratosphere between SA maxima and minima.

Keywords: general atmospheric circulation, numerical simulation, solar activity, thermosphere, residual circulation.

INTRODUCTION

The main mechanism for the global transport of gas species between different atmospheric layers [Fishman and Crutzen, 1978] is the Brewer—Dobson meridional circulation (BDC) [Dobson, 1956; Brewer, 1949]. In general, BDC is a global mass transfer including upwelling of tropospheric air in the tropics, poleward transfer of air masses, and downwelling in the middle and high latitudes. In the upper stratosphere and mesosphere, it is common to observe the summer-winter meridional circulation transferring mass from one hemisphere to another [Holton et al., 1995]. BDC studies are reviewed extensively in [Butchart, 2014]. In the last two decades, there has been a surge of interest in studying global meridional circulation, including BDC. This is mainly due to exploring and predicting possible changes in the transport of atmospheric species due to climate change, as well as due to active development of general circulation models [Gerber et al., 2012; Pawson et al., 2000] and chemical and climatic models [Eyring et al., 2005; SPARC CCMVal, 2010].

According to the downward control principle proposed in [Haynes et al., 1991], wave disturbances are an agent transporting energy and momentum and affecting meridional circulation, so the study of meridional transport in all atmospheric layers directly concerns atmospheric waves — both mesoscale gravity and macroscale planetary waves. Due to the rapid development of numerical modeling of general atmospheric circulation, the interest in the dynamic and thermal effects caused by wave motions, such as planetary waves (PWs), in different atmospheric layers has been growing. Noteworthy among the works dealing with numerical modeling of thermal and dynamic effects on atmospheric circulation of planetary waves are [Liu et al., 2018; Chang et al., 2014; Wang et al., 2017; Forbes et al., 2018; 2020].

Conditions of PW generation and propagation depend on solar activity (SA). Incoming solar radiation and atmospheric heating are driven by SA, which undergoes cyclical changes with a period of about 11 years [Hathaway, 2010]. SA variations affect temperature and circulation flows, changing conditions of PW propagation in the upper atmosphere [Arnold, Robinson, 1998; Geller, Alpert, 1980]. In turn, a change in the PW structure due to the exchange of momentum has an effect on zonal circulation, and wave dissipation also contributes to acceleration of the meridional circulation. In particular, Krivolutsky et al. [2015] have used numerical modeling to investigate the effect of SA cycles on the zonal wind and the temperature in the middle atmosphere and have pointed out the important role of PWs in realizing the Sun's effect on climate due to the transfer of disturbances between the upper and lower atmospheric layers.

A change in the space-time characteristics of PWs under different SA conditions can also be caused by wave reflection in the lower thermosphere [Lu et al., 2017]. One of the causes for the PW reflection may be significant temperature and wind velocity gradients in the lower thermosphere due to its direct solar heating, which increases with SA [Koval et al., 2019]. As has been shown in [Koval et al., 2019], these gradients change the ratio of upward and reflected wave energy, which, in turn, alters the middle atmosphere circulation.

This study is a sequel to the cycle of works devoted to modeling and studying the sensitivity of global atmospheric dynamic processes to thermospheric variations caused by solar radiation variations with the 11-year SA cycle. Changes in structures of westward PWs (normal atmospheric modes) have been examined in [Koval et al., 2018]; simulated PW spectra have been compared with ionospheric critical frequency variations from ionosonde data in [Koval et al., 2022]. The effect of SA variations on stationary PW structures and related variations in zonal circulation are discussed in [Koval et al., 2019]. Numerical experiments and statistical data processing when studying long-period PWs at different SA levels are presented in [Koval, 2019].

In this paper, we explore the effect of changes in thermosphere characteristics, which occur during SA variations, on the meridional atmospheric circulation in the middle atmosphere. For this purpose, through ensemble numerical simulations of atmospheric circulation, we have obtained Eliassen—Palm (EP) wave activity fluxes, as well as components of residual meridional circulation (RMC), using the Transformed Eulerian Mean (TEM) approach [Andrews, McIntyre, 1976]). The RMC components thus calculated result from merging of stratospheric BDC with the mesosphere summer-winter circulation.

METHODOLOGY

MUAM

The mechanistic nonlinear numerical model of the general circulation of the middle and upper atmosphere (MUAM) [Pogoreltsev et al., 2007] is actively used for studying large-scale wave processes [Koval et al., 2018, 2019, 2022]. This finite-difference model is based on solving the complete hydrodynamic equations in a spherical coordinate system with a 36×64 horizontal grid in cell latitude and longitude and in a log-isobaric coordinate system with 56 vertical levels from Earth's surface to ~300 km.

The SA dependence of solar radiation is taken into account in the MUAM radiation block; the main indicator of SA is the solar flux $F10.7$. The flux $F10.7$ varies in the 11-year SA cycle [Tapping, 1987]. By analyzing observations of $F10.7$ in six solar cycles, we have selected the values of $F10.7$=70, 130, 220 sfu (1 sfu = 10^{-22}W/(m^{2}Hz)) as characteristics of low, medium, and high SA levels respectively. Parameterization of thermospheric heating in the area of extreme UV radiation gives due consideration for solar fluxes and absorption coefficients for each spectral UV range and each component, calculated by the model [Richards et al., 1994]. In this work, we deal with the effect of SA variations exclusively on the thermosphere and its extension to the middle atmosphere; different $F10.7$ values in the MUAM radiation block are therefore set only at altitudes above 100 km. Below 100 km, a constant value of $F10.7$=130 sfu corresponding to the medium SA level is used in all numerical simulations. To account for the effect of charged particles on the neutral gas motion in the ionosphere, MUAM specifies the ionospheric conductivity for different SA levels, including its latitude, longitude, and temporal variability. Consideration of SA in MUAM is detailed in [Koval et al., 2018]. This formulation of the problem allows us to avoid taking into account the direct effect of solar radiation on the middle atmosphere [Kodera, Kuroda, 2002] and to identify patterns in the dynamic relationship between the thermosphere and the middle atmosphere due to upward propagating and reflected PWs and their interaction with the mean flow.

The lower boundary conditions in the model are defined at the level of 1000 mb as temperature and geopotential height distributions averaged over 10 years (2005–2014) from JRA-55 reanalysis data [Kobayashi et al., 2015]. As shown in [Scaife et al., 2000], ten years of data are sufficient for a reliable climatology of meteorological fields. This approach makes it possible to exclude the possible effect of natural tropical oscillations, such as El Niño—Southern Oscillation or the quasi-biennial oscillation of the equatorial zonal wind [Labitzke et al., 2006], and to consider the effect of SA variations in its pure form.

To achieve sufficient statistical significance, we have calculated two ensembles of 16 pairs of model simulations of the MUAM general circulation for low and high SA. Features of creating ensembles in MUAM to obtain averaged distributions, initialization stages of the model, and statistical processing are described in detail by Koval [2019]. Initial conditions in all runs of MUAM were the same. All simulations of MUAM circulation were made for January.

Residual meridional circulation

RMC in this study is understood in the context of the transformed Eulerian mean circulation [Andrews, McIntyre, 1976]. The RMC meridional and vertical components can be obtained with the formulas [Andrews et al., 1987; Holton, 2004]

$$\bar{v}^* = \bar{v} - \rho^{-1}\frac{\partial}{\partial z}\left(\rho\frac{\overline{v'\theta'}}{\frac{\partial\bar{\theta}}{\partial z}}\right), \qquad (1)$$

$$\bar{w}^* = \bar{w} + \frac{1}{a\cos\varphi}\frac{\partial}{\partial\varphi}\left(\frac{\cos\varphi\,\overline{v'\theta'}}{\frac{\partial\bar{\theta}}{\partial z}}\right), \qquad (2)$$

where the overbar indicates zonal averaged values; strokes, deviations from the zonal averaged values; v

and w are meridional and vertical winds; ρ is the atmospheric density; z is the vertical coordinate; θ is the potential temperature; φ is the latitude; a is the Earth radius. RMC is widely used for analyzing the global mass transfer and passive/long-lived atmospheric species, as well as the thermodynamic regime of the atmosphere. Moreover, the RMC dependence on planetary waves makes the transformed Eulerian approach a convenient method for analyzing and interpreting nonstationary interactions of PWs with the mean flow [Bal et al., 2018; Koval et al., 2023].

An important characteristic that allows us to analyze PW and to interpret the interaction of the wave with the mean flow is the Eliassen—Palm (EP) flux $\mathbf{F}_\mathrm{m} = \left(F_\mathrm{m}^{\varphi}, F_\mathrm{m}^{z}\right)$ [Jucker, 2021]. For quasigeostrophic conditions with a log-isobaric vertical coordinate, the EP-flux components, divided by the atmospheric density and the Earth radius, are represented as follows [Andrews et al., 1987]:

$$F_\mathrm{m}^{\varphi} = \cos\varphi\left(\bar{u}_z \frac{\overline{v'\theta'}}{\bar{\theta}_z} - \overline{u'v'}\right), \tag{3}$$

$$F_\mathrm{m}^{z} = \cos\varphi\left(\left(f - \frac{(\bar{u}\cos\varphi)_\varphi}{a\cos\varphi}\right)\frac{\overline{v'\theta'}}{\bar{\theta}_z} - \overline{w'u'}\right), \tag{4}$$

where u is the zonal wind; f is the Coriolis parameter; a is the Earth radius. It is believed that the main contribution to the vertical component of the wave activity flux is made by an eddy heat flux [Kodera et al., 2008], and the upward EP-flux vector corresponds to the northward wave heat flux. The EP-flux divergence reflects zonal flow acceleration/deceleration due to the exchange of momentum with PW. In general, positive values of the EP-flux divergence correspond to positive (eastward) acceleration of the mean wind and to the PW momentum transfer to the mean flow.

RESULTS AND DISCUSSION

To study the SA effect on the global circulation, we examine the differences between fields of atmospheric parameters modeled by MUAM for January. We have analyzed two ensembles of 16 pairs of model runs corresponding to high and low SA. The analysis shows that the temperature, pressure, and density fields modeled by MUAM are consistent with those obtained by the empirical atmospheric model NRLMSIS 2.0 [Emmert et al., 2020] for the same time interval and the same levels of F10.7. In addition, we compare distributions of temperature, zonal and meridional winds with the MERRA-2 reanalysis data.

The SA effect is illustrated in Figure 1, which demonstrates altitude-latitude distributions of zonal-mean temperature and RMC components for January under low SA (Figure1, *a*), as well as differences between these parameters for high and low SA (Figure 1, *b*). Figure 1, *b* indicates that SA-driven variations in the thermodynamic regime of the thermosphere can lead to statistically significant variations in temperature and RMC components below 100 km. The RMC differences can reach 10 % in the northern stratosphere, and with increasing altitude the significant RMC increments cover a larger latitude range. In the lower thermosphere, above 95 km, statistically significant variations in residual circulation occur in both hemispheres (Figure 1, *b*), with the SA effect increasing at altitudes above 100 km, which is explained by the direct effect of solar radiation in MUAM above 100 km (see Section "Methodology"). The analysis shows that the region of maximum RMC and temperature variations roughly coincides with the waveguide, i.e. with the region of positive refractive index for stationary PW in Figure 2, *a* (calculation of refractive indices is described in [Gavrilov et al., 2015]). This once again confirms the importance of PW's contribution to atmospheric dynamics.

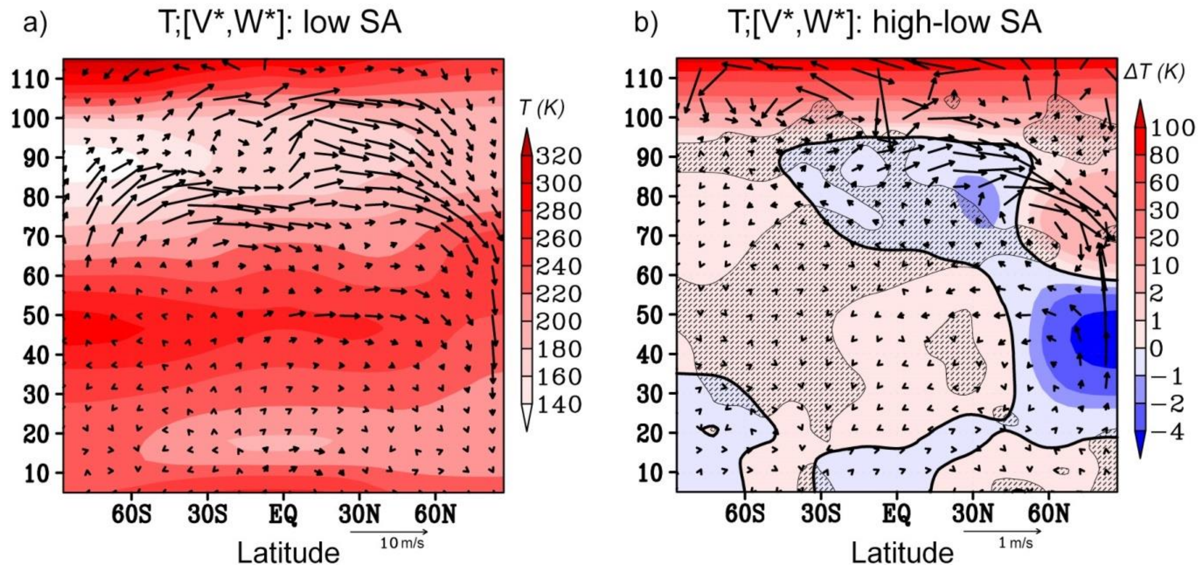

Figure 1. Altitude-latitude distribution of zonal-mean temperature (K, fill) and RMC components (m/s, arrows): during low SA (left); differences between given parameters for high and low SA (right). The RMC vertical component is multiplied by 200. Shaded areas indicate statistically insignificant data at 95 %

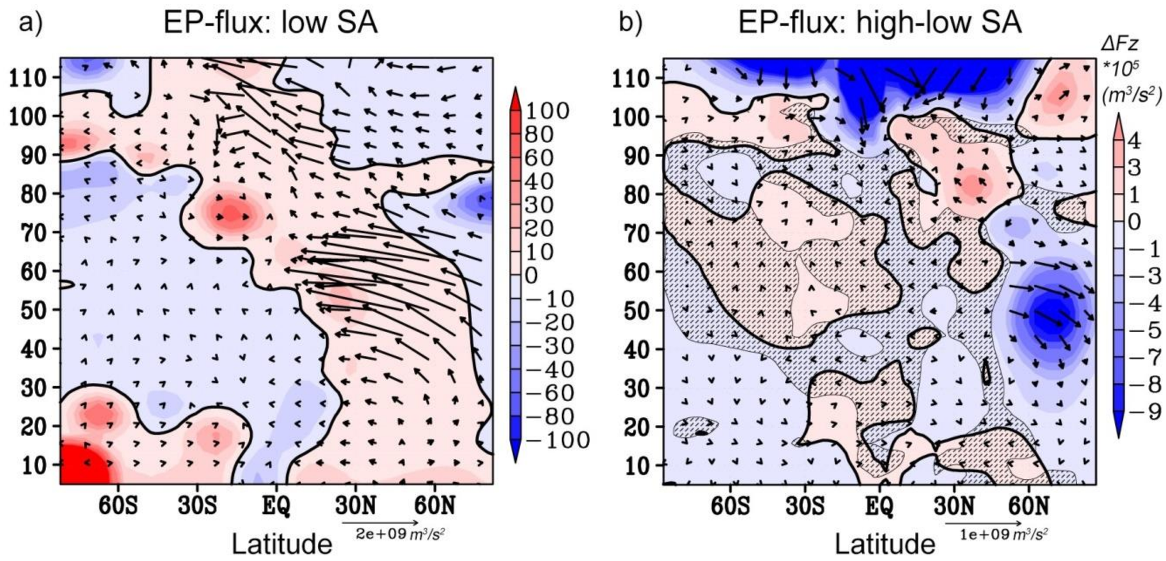

Figure2. Altitude-latitude distribution of Eliassen—Palm flux components (m^3/s^2, arrows): data collected during low SA (left), differences between given parameters during high and low SA (right). The vertical component is multiplied by 200. Filling on the left shows the refractive index of the atmosphere for stationary PW with zonal number 1; on the right, the difference in the vertical flux component. Shaded areas indicate statistically insignificant data at 95 %

It has previously been suggested that wave disturbances generated in the thermosphere directly by solar influence are not able to significantly affect the dynamics of the middle and lower atmosphere since their amplitudes should decrease rapidly as they propagate downward. This is explained by a quasi-exponential decrease in pressure with increasing altitude. By contrast, SA-driven variations in vertical temperature gradients and wind shifts can affect the amount of downward reflected energy of PWs propagating from tropospheric sources. These reflected waves can change the proportion of vertical traveling and standing PWs and other characteristics of global waves in all underlying layers of the atmosphere, having an effect on circulation and thermal regime of the stratomesosphere.

The wave reflection effect can be demonstrated by the example of changes in the structure and direction of the Eliassen—Palm wave activity flux in the lower thermosphere under changes in SA (see Figure 2). Figure 2, *a* shows that during low SA the wave activity flux vectors are directed from the northern lower stratosphere upward and southward, hence the trajectory of PW propagation expands with altitude, as is typical for January. Figure 2, *b* indicates that in the lower thermosphere EP-flux increments during increasing SA are oppositely directed, i.e. mainly downward, which suggests that upward PW propagation weakens and wave fluxes even reverse in this region during high SA. Moreover, the EP-flux weakening also occurs in the stratosphere (Figure 2, *b*).

Other researchers have recently demonstrated similar results. For example, Gan et al. [2017] have analyzed the EP flux in the stratosphere and have found that under maximum SA conditions PW activity is weaker, which causes an anomaly in the westward zonal wind in the upper winter stratosphere and the lower mesosphere. At the same time, the annual and seasonal average variations in the temperature response to the 11-year solar cycle in the mesosphere have been studied using both modeling and broadband radiometry data from TIMED/SABER satellites. According to Expression (3), a weakening of the vertical EP-flux component leads to a weakening of the poleward heat flux; this factor explains cooling of the high-latitude stratosphere during high SA (Figure 1, *b*).

To analyze the wave effect on RMC, we have calculated the eddy RMC component, which is the difference between components of residual circulation and transfer by advection: $v_{\text{eddy}} = \overline{v}^* - \overline{v}$, $w_{\text{eddy}} = \overline{w}^* - \overline{w}$. The eddy circulation component and its SA-driven variations are illustrated in Figure 3. Comparing Figures 2, *a* and 3, *a* shows that the eddy RMC component extremes are located along PW waveguides (in the northern lower stratosphere and further, with increasing height, the waveguide expands toward the Southern Hemisphere). Figure 3, *b* indicates that the eddy component decreases significantly in the winter stratosphere during high SA. Thus, a weakening of wave activity in the stratosphere not only contributes to the cooling of the circumpolar region, but is also the main factor in the RMC decrease during high SA.

An interesting feature of the distribution of the EP-flux components in Figure 2, *b* is the intensification of wave activity in the 80–100 km layer in the 10–50° N latitude range. Under high SA, RMC increases in the same region (see Figure 1, *b*) and hence changes in the eddy circulation component (Figure 3, *b*), which make an important contribution to the RMC increase. Thus, an increase in the meridional transfer of cold air masses from the summer mesosphere to the winter hemisphere can cause the low- and mid-latitude mesosphere to cool. On the contrary, the high-latitude winter mesosphere can heat up, and the key role in this is played by the strengthening of the RMC descending branch and hence by the adiabatic heating of the medium. At the same time, the cold summer (southern) mesosphere is not very

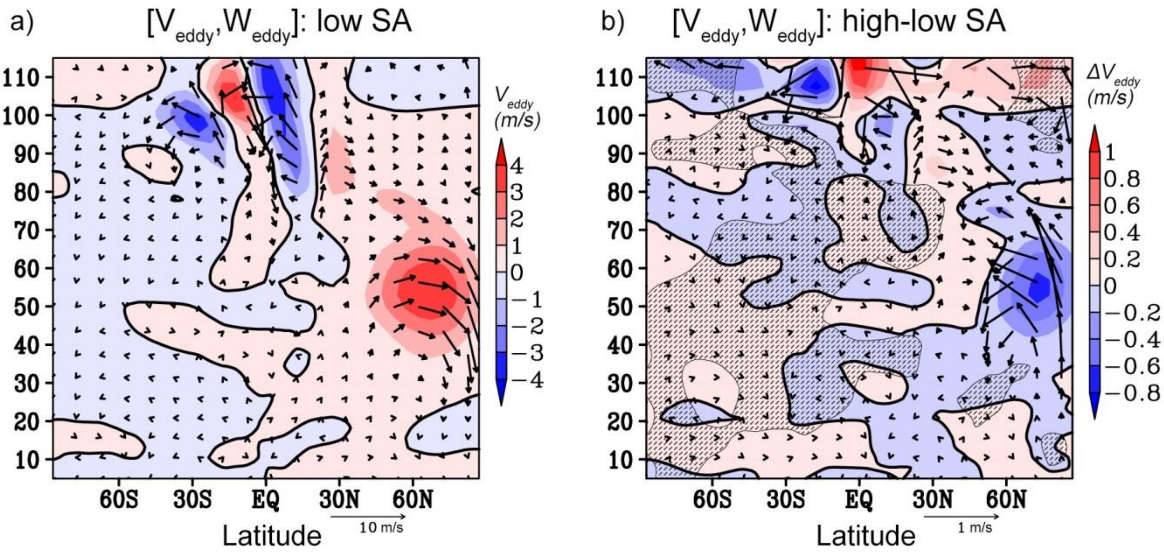

Figure 3. Altitude-latitude distribution of the eddy meridional circulation component (m/s, arrows): data obtained during low SA (left); differences between given parameters for high and low SA (right). The vertical component is multiplied by 200. Filling represents the meridional component. Shaded areas indicate statistically insignificant data at 95 %

sensitive to SA variations due to the absence of PW even with an increase in the direct radiation effect at high latitudes, as observed, for example, in [Karlsson, Kuilman, 2018].

In the Northern Hemisphere, positive accelerations of the meridional RMC component, according to the motion equation, produce eastward increments of the zonal flow in 70–100 km the altitude range. Figure 4, *b* clearly shows a strengthening of the zonal wind at these altitudes, except for the circumpolar region above 80 km, where, according to Figure 4, *a*, the zonal wind changes direction. An increase in the meridional temperature gradient plays a dominant role in strengthening the wind according to the classical theory of thermal wind [Gill, 1986].

Eastward PW momentum transfer to the mean flow is described by the EP-flux divergence and causes a strengthening of the zonal wind in the Northern Hemisphere. This effect is observed in Figure 4, *b*, where there is an increase in the EP-flux divergence (contours) in the northern mid-latitude stratosphere and a corresponding strengthening in the zonal wind. Similar trends in the zonal wind and temperature variations in January are detailed in [Karlsson, Kuilman, 2018] based on numerical modeling by the Canadian Middle Atmosphere Model. Note, however, that in the model simulations we maintained the radiation balance and composition below 100 km unchanged for all SA levels. It is, therefore, not quiet correct to compare the results we have obtained with the results of the above-mentioned

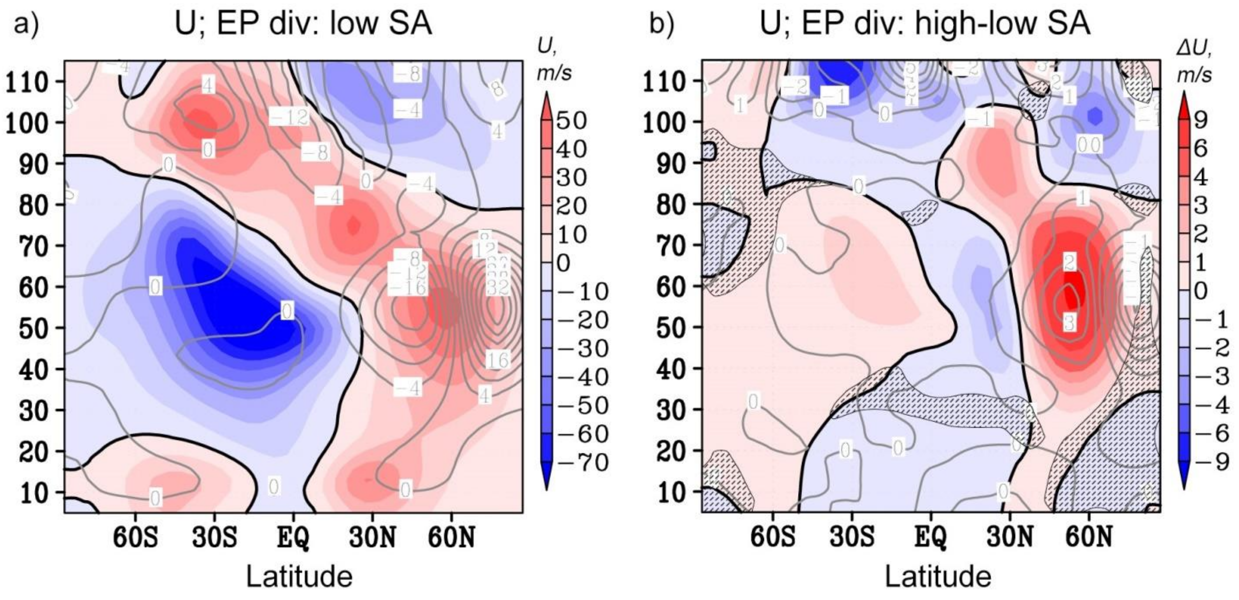

Figure 4. Altitude-latitude distribution of zonal wind (m/s, fill) and Eliassen—Palm flux divergence (10^2 m^2/s^2/day, contours): data obtained during low SA (left); changes of given parameters with increasing SA (right). Shaded areas indicate statistically insignificant data at 95 %

studies. Nevertheless, our simulation results show that the SA-induced disturbances of atmospheric parameters above 100 km can produce statistically significant effects in the middle atmosphere, which are comparable to the direct effect of solar radiation below 100 km.

Modifications of the mean wind and temperature can change wave propagation conditions in the atmosphere, for example, the structure of waveguides, which contributes to a change in PW characteristics. At the same time, changes in the EP-flux components can cause wave accelerations and heat inflows, leading to circulation and temperature changes in the middle atmosphere. Hence, the interaction between the mean flow and PW is a non-stationary process with a complex cause-and-effect relation.

Another cause for variations in the mean wind and temperature in the atmosphere may be the dynamic and thermal effects of gravity waves. Numerous studies show that characteristics of gravity waves depend on SA in the thermosphere [Klausner et al., 2009; Yiğit, Medvedev, 2010]. Solar activity affects atmospheric temperature, density, dissipation, and static stability, which can have an effect on conditions of gravity wave propagation [Vadas, Fritts, 2006]. Analysis of wave drag and heat inflows, taken into account by parameterizations of gravity waves in MUAM, has revealed that they are significant at altitudes above 80–100 km. Changes in SA lead to changes in wave accelerations and heat inflows in the thermosphere, similar to those considered in [Yiğit, Medvedev, 2010]. These changes can modify the average temperature, wind, and PW waveguides, especially in the lower thermosphere. At the same time, increments of atmospheric parameters are localized along PW waveguides, confirming the important role of their impact on global circulation.

CONCLUSION

In order to study the SA effect on changes in the meridional circulation and temperature regime of the middle atmosphere, we have made numerical simulations with a mechanistic nonlinear numerical model of the middle and upper atmosphere MUAM. We have analyzed two ensembles of 16 pairs of model runs corresponding to high and low SA. Different SA levels in MUAM were set at altitudes over 100 km since we dealt only with thermospheric disturbances under SA changes and the transfer of this effect to the middle atmosphere.

Changes in the conditions of PW propagation and their reflection in the lower thermosphere are the main mechanisms for transmitting the effect of SA changes from the thermosphere to the underlying atmospheric layers. We have analyzed and interpreted PW interactions with the mean flow by calculating Eliassen — Palm fluxes and their divergence, as well as residual meridional circulation, using the transformed Eulerian mean approach. RMC, which significantly affects the atmospheric temperature, in this context is the result of a superposition of eddy and advective air-mass transport in the meridional plane.

We have analyzed variations of EP fluxes and demonstrated a change in the reflection conditions of PWs propagating from the troposphere due to a significant increase in the vertical temperature gradient in the lower thermosphere during high SA. To analyze the wave effect on RMC, we have calculated the eddy RMC component. The calculations suggest that the eddy RMC component decreases significantly in the winter stratosphere during high SA. This decrease not only contributes to the cooling of the circumpolar region, but also makes a major contribution to the RMC weakening in the stratosphere.

We have demonstrated an increase in wave activity in the mesosphere—lower thermosphere of the Northern Hemisphere, which occurs with an increase in RMC during high SA. The intensification of the meridional transport of cold air masses from the summer mesosphere to the winter hemisphere causes the low- and mid-latitude mesosphere to cool. The high-latitude winter mesosphere is heating up, and a key role in this is played by the strengthening of the RMC descending branch and hence by the adiabatic heating of the medium.

Changes in atmospheric parameters are localized mainly along PW waveguides, confirming the extremely important role of PWs in forming the global circulation. Statistically significant non-zero increments of mean zonal and meridional winds and temperatures below 100 km confirm that changes in the characteristics of the thermosphere due to the SA effect can affect the circulation of the middle atmosphere, and PWs provide an effective mechanism for the interaction between various atmospheric layers.

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