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Influence of thermospheric effects of solar activity on the middle atmosphere circulation and stationary planetary waves

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OVERVIEW

Large-scale wave processes in the atmosphere play an important role in the formation of the dynamical and temperature regimes, as well as the composition of the atmosphere.

The most important sources of energy in the middle and upper layers of the atmosphere are:

- **solar radiation**
- **energy flux** from the underlying atmospheric layers, created **by internal atmospheric waves**.

A significant influence on the generation and propagation of planetary waves have changes in the incoming solar radiation. Solar radiation depends on solar activity (SA), which undergoes cyclic changes with a period of about 11 years.

In turn, atmospheric oscillations of a planetary scale are the main driving force of the meridional circulation, which determines both the energy balance of the atmosphere and the transport of atmospheric impurities.

MAIN POINTS

- The main purpose of this study is to perform numerical investigation of the effects of solar activity (SA) changes in the thermosphere (above 100 km) on general atmospheric circulation and stationary planetary waves (SPW) amplitudes with zonal wavenumbers *m*=1,4 in the middle atmosphere (below 100km).
- We used 3-dimensional GCM "Middle and Upper Atmospheric Model" (MUAM) and obtained 2 sets of model "runs" with initial conditions typical for high and low solar activity (HSA and LSA, respectively). To improve the statistical confidence of the results, two ensembles of calculations were obtained, consisting of 16 model runs (Koval, 2019).
- Changes in the SA were set in the MUAM model only at altitudes over 100 km. At lower altitudes, the same conditions were used in all simulations.
- We calculated differences in zonal, meridional and vertical wind components below 100km between ensembles of model runs for HSA and LSA.
- Amplitudes and phases of SPW modes having zonal wavenumbers m = 1 – 4 at zero frequencies were estimated using Fourier transform with the least squares fitting longitude-time structure of geopotential height fields.

The “MUAM” general circulation model

Middle and upper atmosphere model “MUAM” model (Pogoreltsev et al., 2007).

- 3-dimension nonlinear mechanistic model based on a set of primitive equations in aspherical coordinates.
- The horizontal grid of the model has 36 x 64 nodes. As the vertical coordinate the model uses the log-isobaric non-dimensional height with 56 vertical levels at the altitudes from the ground up to 300 km.
- The MUAM model can reproduce SPWs and travelling NAMs. Amplitudes of stationary planetary waves are estimated from the geopotential heights in the lower atmosphere obtained from the Japanese 55-year Reanalysis (JRA-55, Kobayashi et al., 2015) of meteorological data for the month of January averaged over years 2005-2014.
- The MUAM includes standard radiation schemes (Fröhlich et al., 2003) for the rates of solar heating and infrared cooling due to the main absorbing and emitting atmospheric gas species.
- MUAM accounts for turbulent and molecular viscosity and thermal conduction, as well as ion drag.
- In the thermosphere, the MUAM includes an extended parameterization of ultraviolet heating with fluxes of solar radiation and absorption coefficients for different gas species and different spectral intervals taken from the model by Richards et al. (1994).
- The MUAM involves different GW parameterizations. For GWs with different phase speeds (5–125 m/s), (Lindzen, 1981; Yigit & Medvedev, 2009); stationary orographic gravity waves (Gavrilov and Koval, 2013).
- The main equations and peculiarities of the model adjustment one can find here: (Pogoreltsev et al., 2007; Gavrilov et. al., 2018; Koval et al., 2018)

Solar activity accounting in the MUAM

- The MUAM radiation subroutines take into account the dependence of solar radiation on the SA, as an indicator of which the solar radio flux at a wavelength of 10.7 cm ($F_{10.7}$) is used. $F_{10.7}$ is characterized by cyclicity with a period of the main 11-year solar activity cycle.

- To take into account SA in MUAM The time series of solar flux F10.7 observations for the last 6 solar cycles were analyzed. To characterize the low and high SA level, F10.7 values of 70 and 220 SFU (Solar Flux Unit) were selected. These values, corresponding to solar minima and maxima, were set in the MUAM at altitudes higher than 100 km.

- To correctly take into account the influence of charged particles on the motion of a neutral gas at ionospheric heights, ionospheric conductivities are specified in MUAM including their latitudinal, longitudinal and temporal variability at altitudes higher than 100 km.

- The calculation of ionospheric conductivities is performed using formulas that include atmospheric and ionospheric parameters taken from semi-empirical models of the neutral atmosphere of the NRL-MSISE and the ionosphere of IRI-Plas.

Zonal wind and temperature

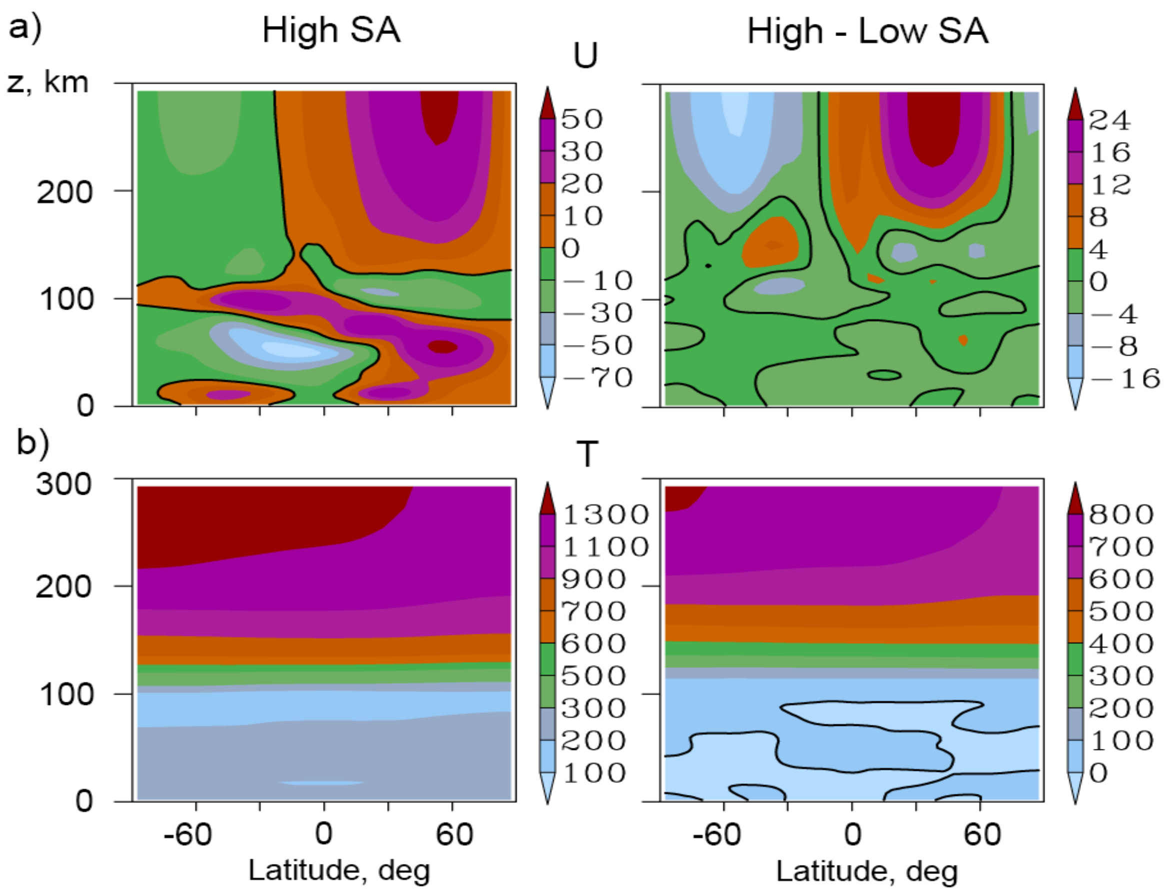

Figure 1. Altitude-latitude distributions of the mean zonal wind in m/s (a, left) and temperature in K (b, left) at high SA, also their differences from the low SA (right panels) in middle December – February averaged for 16 MUAM runs. Solid lines show zero levels.
The altitude range: 300 km

The right panel of Figure 1a shows that magnitudes of the mean zonal wind are stronger (up to 50%) at altitudes higher than 180 km and weaker at 140 – 180 km at high SA level in both hemispheres. This is associated with solar flux influence on meridional temperature gradients. For example, in the Northern hemisphere, increasing northward temperature gradient between 140 and 180 km at high SA corresponds to decrease in the eastward wind speed and to negative wind differences in the right panel of Figure 4a. This corresponds to classical theory of “the thermal wind”.

Zonal wind and temperature in the middle atmosphere

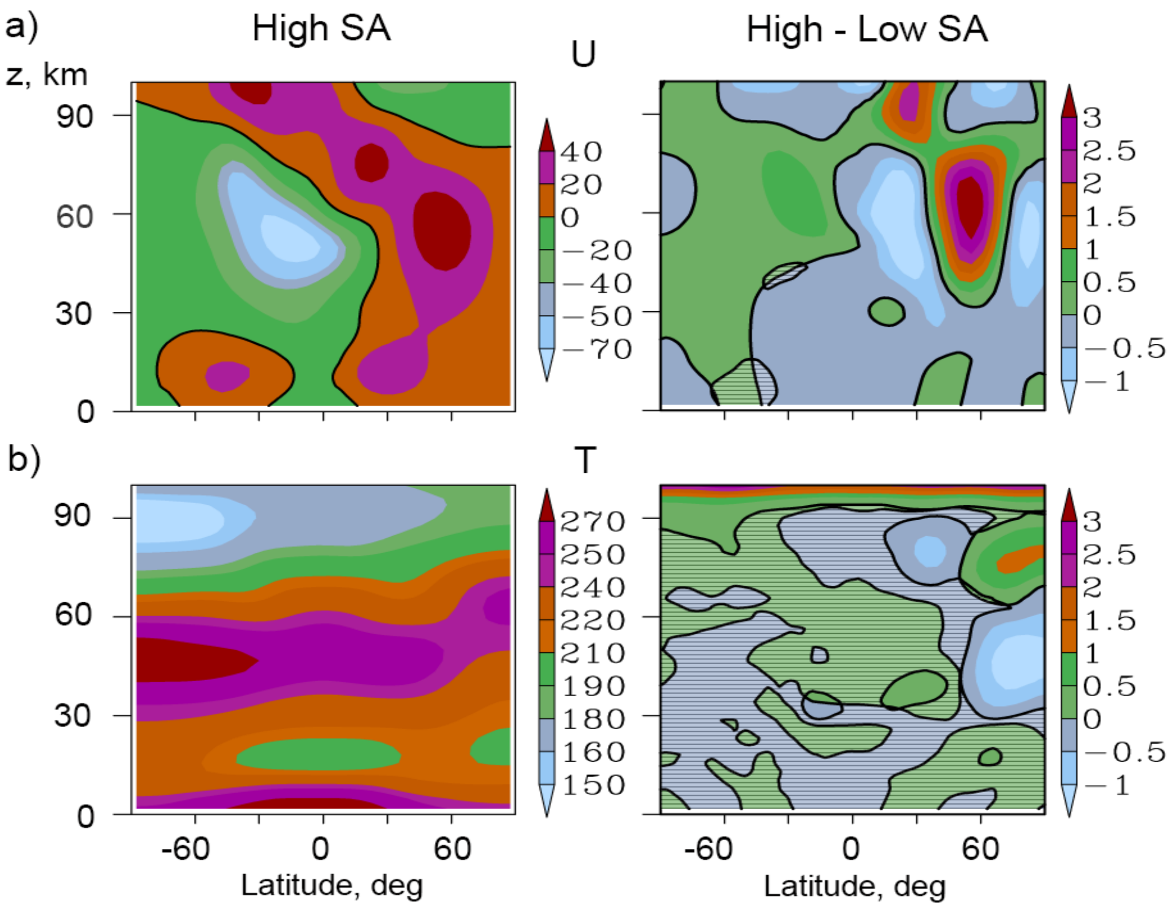

Figure 2. Altitude-latitude distributions of the mean zonal wind in m/s (a, left) and temperature in K (b, left) at high SA, also their differences from the low SA (right panels) in middle December – February averaged for 16 MUAM runs. Solid lines show zero levels. Hatched areas indicate statistically insignificant data at level 5 % according to the paired t-test (Koval et al., 2019).

The mean differences of the zonal wind and temperature due to thermospheric SA impacts (right panels) are smaller at heights below 100 km than those above 100 km in Figure 1. They can reach 3 – 4 m/s and 3 K at altitudes 40 – 100 km at high northern latitudes. **This illustrates that variations of thermospheric parameters at heights above 100 km due to SA variations can influence the mean flow in the middle atmosphere as well.** At heights 40 – 100 km, average temperature differences have maximum magnitudes in the Northern Hemisphere. This is associated with the features of SPW propagation in the winter/summer hemisphere (see Figure 3).

SPW amplitudes in the middle atmosphere

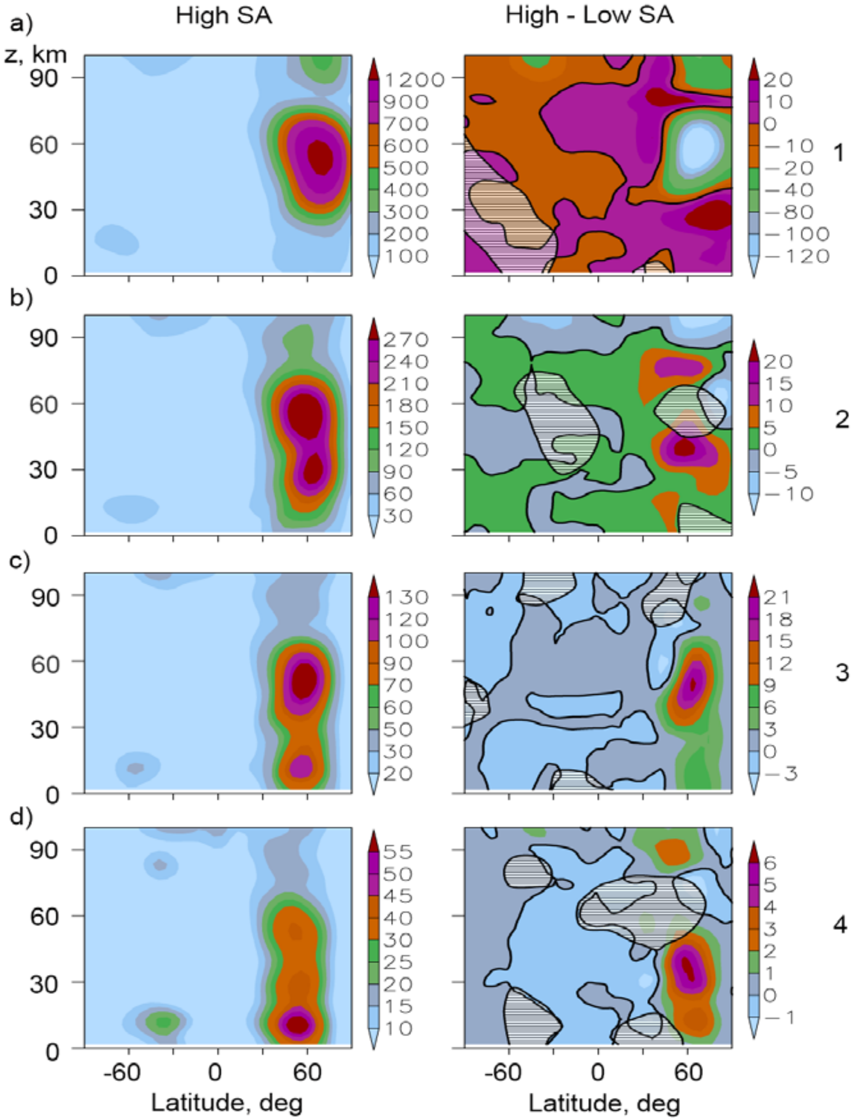

Figure 3. Altitude-latitude distributions of geopotential height amplitudes (in g.p.m.) at high SA (left) and their differences from those at low SA (right) for SPW modes with zonal wavenumbers m = 1 – 4 (a-d, respectively) averaged for eighty 15-day intervals taken from 16 pairs of the MUAM runs. Solid lines show zero levels. Hatched areas indicate statistically insignificant data at level 5 % according to the paired t-test.

In the middle atmosphere in January SPWs have larger amplitudes in the Northern (winter) Hemisphere, than those in the Southern Hemisphere, because the background zonal circulation has eastward directions at all altitudes, which corresponds to waveguides for SPW propagation in winter. At altitudes above 90 km SPW propagate to the Southern hemisphere along the waveguides.

The right panels of Figure 3 reveal that **SA impacts in the thermosphere can make modifications of SPW amplitudes at altitudes below 100 km**. Magnitudes of the differences in the right panels of Figure 3 can reach up to **10 – 15 %** of the peak values in the respective left panels of Figure 2 in the northern middle atmosphere depending on wavenumber.

Meridional circulation in the middle atmosphere

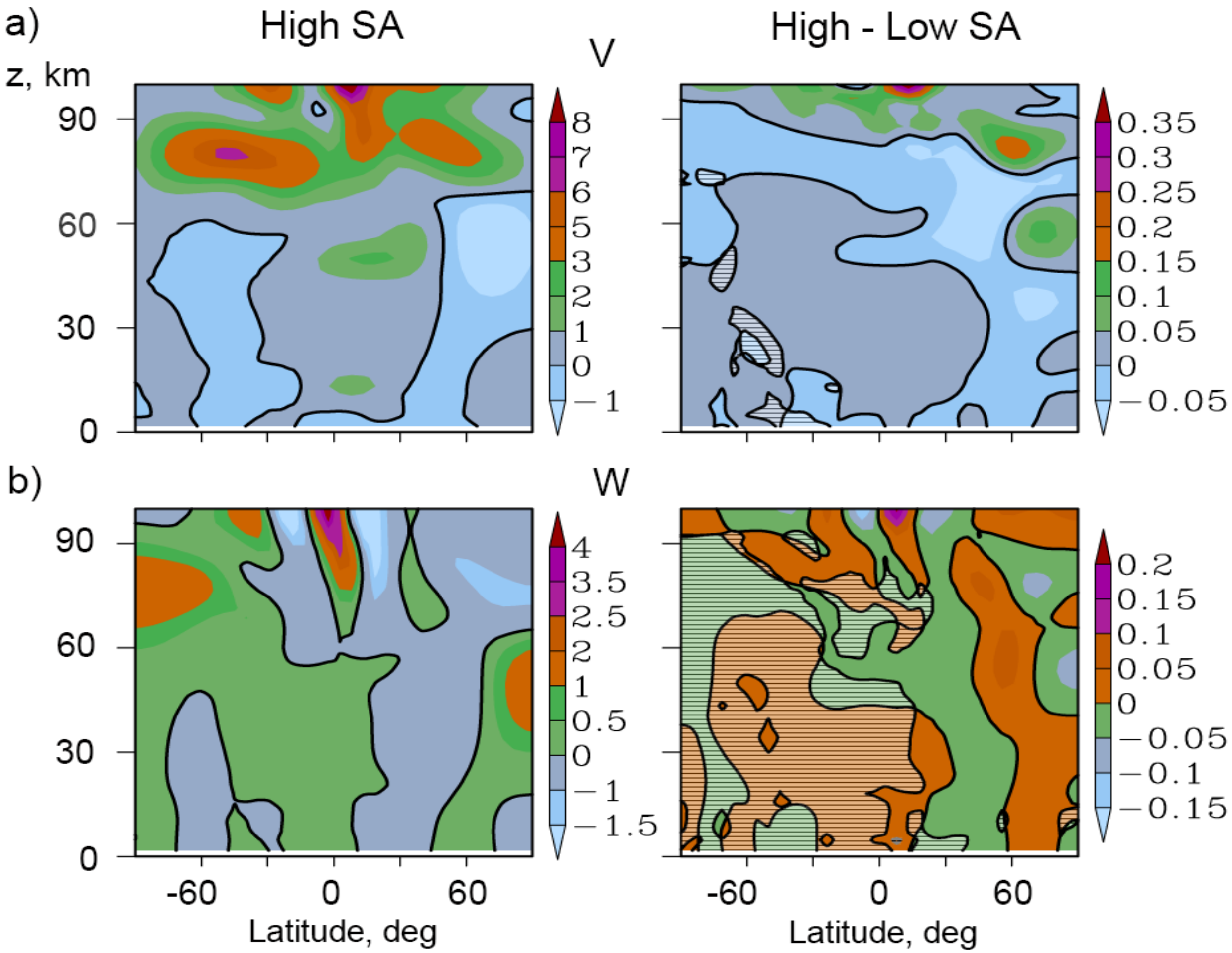

Figure 4. Altitude-latitude distributions of the zonal-mean meridional wind in m/s (a, left) and vertical wind in cm/s (b, left) at high SA; their increments due to change of SA in the thermosphere (right panels) in middle December – February averaged for 16 MUAM runs. Solid lines show zero levels.
Hatched areas indicate regions of statistically insignificant results at 5 % level.

Changes in zonal-mean circulation are closely connected to the meridional-mean circulation through the Coriolis force. One can see that changes in meridional and vertical velocity (right panels) occur at middle and high latitudes of the Northern hemisphere and in both hemispheres above 70 km. Differences can reach p to 3-5 % of the corresponding peak values.
Vertical wind increments have massive insignificant areas in the Southern hemisphere where they are close to zero.

Residual mean Meridional circulation

The consideration of the classical Eulerian-mean meridional circulation is ineffective from the point of view of the analysis of the study of transport of long-lived atmospheric impurities. (Because of the appearance of eddy flux terms in both mean momentum and thermodynamic energy equations, and the near cancellation of eddy and mean flow processes. (Holton, 2004))

For this purpose was developed alternative theory of Transformed Eulerian-mean (TEM) approach (e.g. Andrews and McIntyre, 1976).

Meridional and vertical components of the residual mean meridional circulation:

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

The time-averaged residual mean meridional circulation approximates the average movement of air masses and, therefore, in contrast to the conventional Eulerian circulation, is an approximation of the mean advective movement of gas components.

Residual mean Meridional circulation

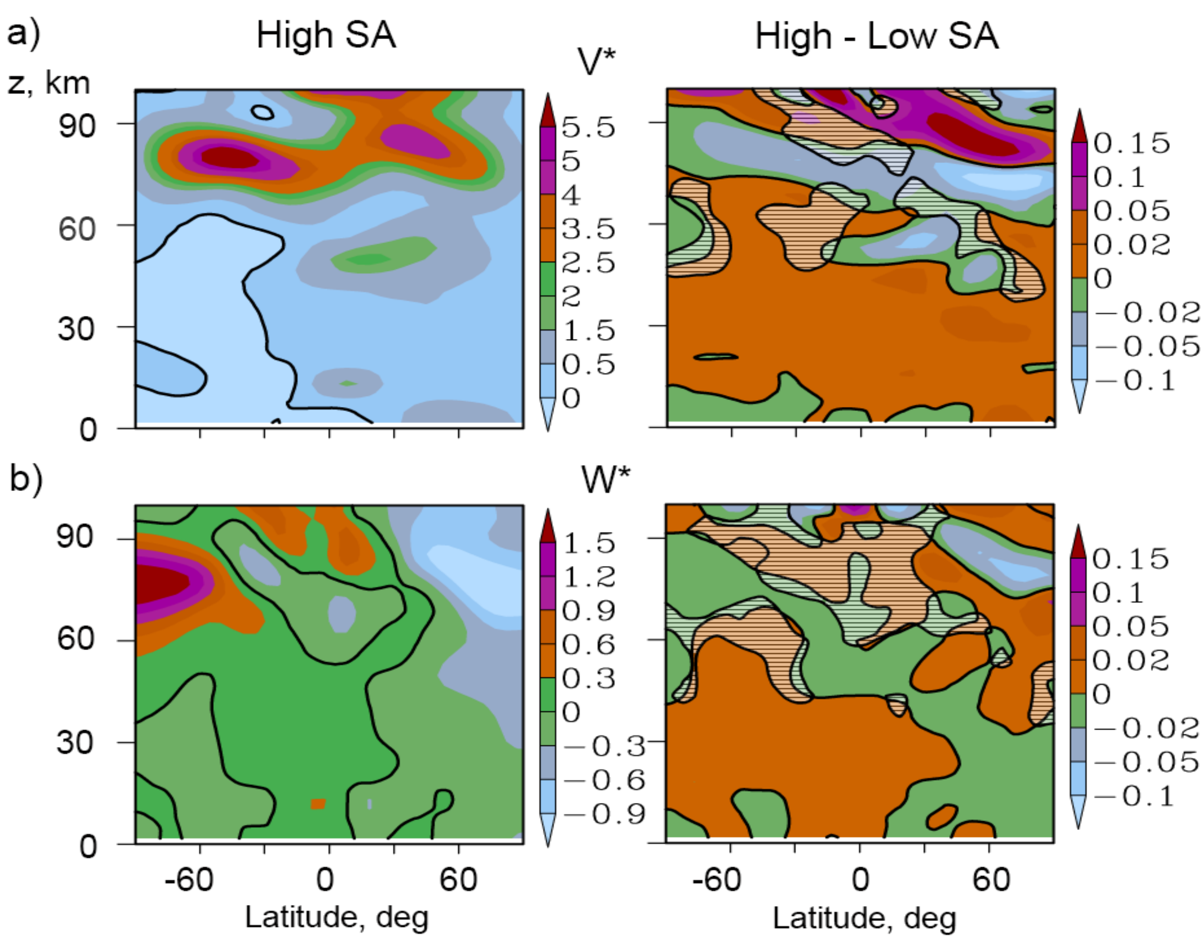

Figure 5. Zonal-mean components of the residual mean meridional circulation: meridional wind in m/s (a, left) and vertical wind in cm/s (b, left) at high SA; their increments due to change of SA in the thermosphere (right panels) in middle December – February averaged for 16 MUAM runs. Solid lines show zero levels. Hatched areas indicate regions of statistically insignificant results at 5 % level.

Joint consideration of the left panels reveal two global residual circulation cells below 60 km with upward flow north from equator and downward flows at middle and high latitudes;
Areas of significant W* and V* increments due to thermospheric SA impact are seen mainly in the Northern hemisphere below 60 km and in both hemispheres above this level.

Conclusions

- ✓ Changes in temperature and circulation in the thermosphere with a changing in SA can significantly affect the SPW propagation in the atmosphere. The increase in SA at altitudes above 100 km leads to a statistically significant changes in the amplitudes of the SPW up to 10-15% in the middle atmosphere.
- ✓ Significant effect on the propagation of SPW at high SA has reflection of SPW at MLT altitudes, leading to an increase in the amplitudes of these waves in the middle atmosphere of the Northern hemisphere and to a decrease in the amplitudes at the thermospheric heights.
- ✓ This study give statistically confident evidences that variations of thermospheric parameters caused by changing SA at altitudes above 100 km can influence the global circulation (zonal mean, meridional mean as well as residual meridional circulation) in the middle atmosphere below 100 km.

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