Mesospheric wind and temperature trends simulated with MUAM

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Summary: The Middle and Upper Atmosphere Model (MUAM) was used for the period from 1979 to 2015 and for January and July to analyze the interannual and long-term development of the horizontal wind and temperature in the middle atmosphere. Above the troposphere, for each season a long-term temperature decrease was observed, with maxima in the polar stratosphere in winter. In the zonal wind, a weakening and slight northward displacement of the mesospheric westerly wind could be observed in the respective winter hemisphere. On the southern hemisphere in January there was a slight weakening of the wind jets, while in the northern hemisphere a slight increase could be observed in July. For the meridional wind, especially for the mesospheric branch of the meridional wind jet, the southerly wind was intensified in January, while the northerly wind weakened particularly in the southern hemisphere in July. Possible reasons for the long-term trends are discussed.

Zusammenfassung:

Mit dem Modell für die mittlere und obere Atmosphäre MUAM wurden Berechnungen über den Zeitraum von 1979 bis 2015 für Januar und Juli durchgeführt, um die Entwicklung des Zonal- und Meridionalwindes sowie der Temperatur zu analysieren. Dabei zeigte sich ganzjährig ein Temperaturrückgang oberhalb der Troposphäre, mit einem Maximum in der polaren Stratosphäre während des Winters. Beim Zonalwind ließ sich in der jeweiligen Winterhemisphäre eine Abschwächung und leichte Nordverlagerung des mesosphärischen Westwindjets beobachten. Auf der Südhemisphäre im Januar kam es zu einer leichten Abschwächung der Starkwindbänder, während im Juli auf der Nordhemisphäre eine leichte Verstärkung festgestellt werden konnte. Für den Meridionalwind, insbesondere für den meridionalen mesosphärischen Windjet zeigte sich im Januar eine Intensivierung des Südwindes, während sich der Nordwind im Juli besonders auf der Südhemisphäre abschwächte. Gründe für diese Trends werden diskutiert.

1. Introduction:

The anthropogenic climate warming leads to changes not only in the troposphere, but also at upper atmospheric layers. The effects of climate warming in the mesosphere and the lower thermosphere have so far been insufficiently explored. Interactions between increasing CO_2 in the atmosphere and the MTL are known. Lübken et al. (2013) showed

that an increase of CO_2 leads to a cooling in the mesosphere. It is to be investigated, if measurements from the last years and decades can be reproduced using model calculations from a middle and upper atmosphere model. The concentration of CO_2 in the atmosphere has increased in the last century. In 1979, the CO_2 mixing ratio was 335 ppm and it was rising to 408 ppm in 2016. The pre-industrial level of CO_2 was 280 ppm (IPCC, 2001), so that the current year is about 130 ppm above the pre-industrial level. There is an increase of about 15 ppm between 1980 and 1990, but of 20 ppm from 2005 to 2015. An increase in emissions is also expected in the coming years. In Fig. 1 it is shown how the CO_2 concentration has developed in the last 40 years.
Roble and Dickinson (1989) investigated the effects of changes in CO_2 and methane on the structure of the mesosphere and thermosphere with a global circulation model. A doubling of the CO_2 led to a cooling in the mesosphere and a warming in the mesopause. With the “Leibniz-Institute Middle Atmosphere” (LIMA) model, Lübken et al. (2013) considered the effects of the trends of CO_2 and ozone on the MLT region. They found that CO_2 has a larger effect than ozone on the cooling in the middle atmosphere. But the warming effect of ozone was stronger in the mesopause. This also confirmed the simulations of Marsh et al. (2013).
Also important for middle atmospheric variability are changes in ozone concentration, which have a large effect on temperatures in the stratosphere. The time series of global ozone mass as calculated from MERRA reanalyses (Rienecker et al., 2011) is shown in Fig. 2. The ozone mixing ratio has decreased with time, but owing to the to the ban of chlorofluorocarbons, there is a slight increase in the ozone concentration since the 1990s (Solomon, 1999; Bodeker et al., 2001).

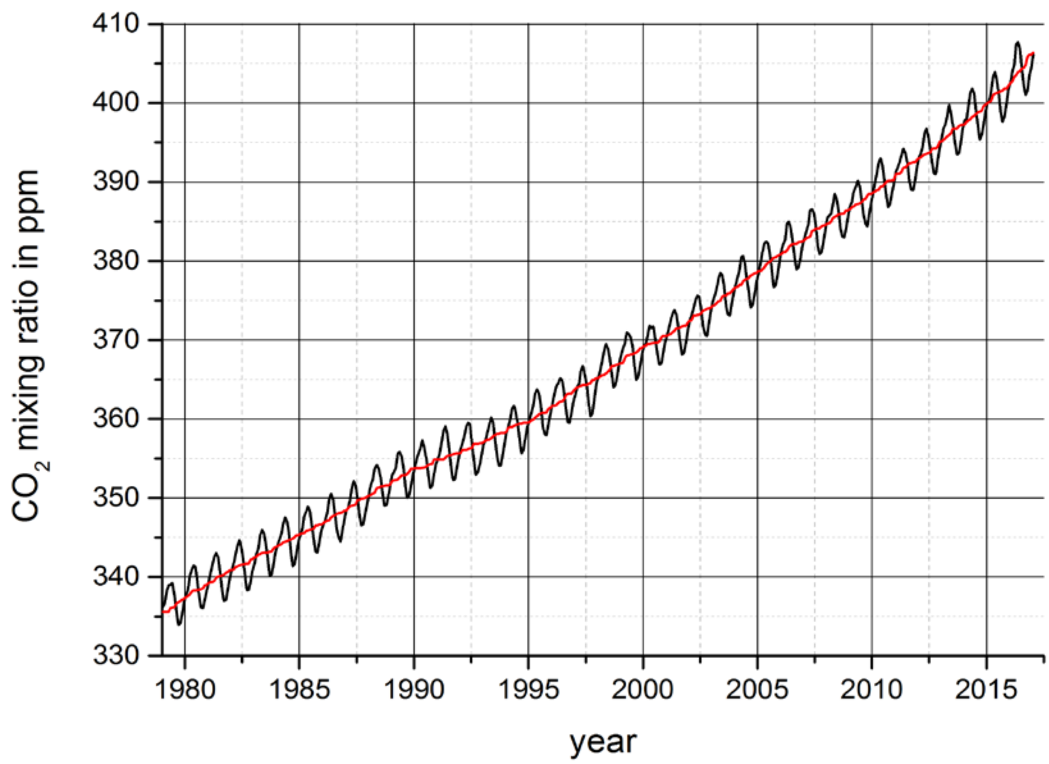

Fig. 1: CO_2 *mixing ratio from 1979 to 2016 at Mauna Loa Observatory. The red line corresponds to a sliding five-year mean. Data: NOAA, (Tans and Keeling, 2017).*

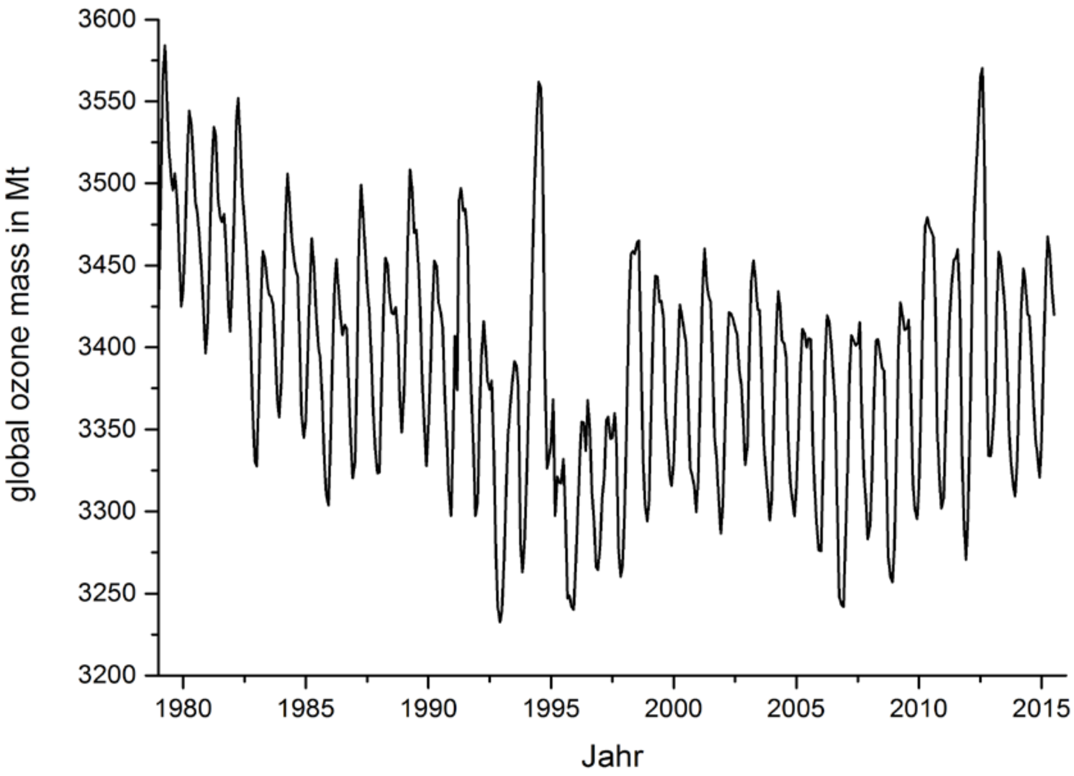

Fig. 2: Global ozone mass in megatons from MERRA (Rienecker et al., 2011) data from 1979 to 2015.

Some model simulations on middle atmosphere wind trends were performed by Jacobi et al. (2015a). An intensification of the westerly wind in January in the mesosphere was observed, as well as a weakening of the wind jet in July. This was also seen by Marsh et al. (2013). The meridional wind in the upper mesosphere increased in both January and July.
Measurements were analyzed by Bremer and Berger (2002) and a review of long-term temperature trends can be found at Beig et al. (2003) and, more recently, Beig (2011). These confirm the model results with regard to the cooling in stratosphere and mesosphere and the weaker cooling or small warming in the mesopause. Satellite measurements were analyzed by Funatsu et al. (2016). These measurements also show the temperature drop in the stratosphere which was stronger in the middle and higher latitudes during winter.
Various wind measurements from the mesosphere were compared in Jacobi et al. (2015a). Measurements in Collm (51°N, 13°E, Germany), Saskatoon (52°N, 107°W, Canada) and Obninsk (55°N, 37°E, Russia) were compared. For the zonal wind in winter there is an increase (more eastward) until 2005, after that year there is a decrease (less eastward) in Collm and Saskatoon. The meridional wind in winter shows a decrease until 2005 (less northward) and an increase (more northward) after that in Collm and Obninsk. In summer the westerly wind intensifies until 2005 and then decreases slightly. The meridional wind in the summer shows a decrease of the northerly wind until 2005. After that time, there is a slight increase in the northerly wind, especially over Obninsk.
To summarize, there are obvious long-term trends in the middle and upper atmosphere, but still some details are missing. Therefore we calculated with MUAM time series over 37 years of zonal wind, meridional wind and temperature and examined these for trends.

The remainder of the paper is organized as follows: in section 2 the model will be introduced, section 3 shows the model results and section 4 summarized the results.

2. Model Description and Experimental Setup

The MUAM 3D mechanistic global circulation model of the middle atmosphere was used. It based on the Cologne Model of the Middle Atmosphere-Leipzig Institute for Meteorology (COMMA-LIM, Fröhlich et al., 2003; Jacobi et al., 2006). The model is based on the primitive equations. It has a horizontal resolution of 5 × 5.625° and it reaches to an altitude of 160 km in log-pressure heights $x = ln\ (p_s/p)$ with p as pressure, p_s = 1000 hPa as a reference pressure. The step size is 2.842 km in log-pressure height $h = x \cdot H$ and H = 7 km as the scale height. Pogoreltsev et al. (2007) described the model in detail. The model uses a time step of 225 s in the 56-level version following a Matsuno integration scheme (Matsuno, 1966). Zonal means of temperature and geopotential as well as their stationary planetary waves of zonal wavenumbers 1-3 derived from ERA-Interim reanalyses are used at the lower boundary of the model (1000 hPa). To correct the climatology in the troposphere and lower stratosphere, also zonal mean temperature up to an altitude of 30 km was nudged to the model.
Parameterizations of CO_2 and ozone radiative effects are important for the radiation balance in the model. The CO_2 mixing ratios are assumed to be globally constant, the database is the measurements of the Mauna Loa Observatory on Hawaii. A CO_2 reference profile is created in the model where the volume mixing ratio remains constant up to 85 km and decreases to 0 at 140 km (Lange, 2001). CO_2 absorbs most strongly in the near infrared at 15µm, thereby overlapping the absorption bands of water vapor (Lange, 2001). The CO_2 cooling rates are larger than heating rates so that the CO_2 has a cooling effect in the middle atmosphere. The model uses ozone fields as monthly and zonal mean based on MERRA (Modern-ERA Retrospective Analysis for Research and Applications) data (Rienecker et al., 2011). Ozone absorbs ultraviolet radiation resulting in heating of the stratosphere. The amount of the ozone infrared cooling rates is smaller than heating rates so that the ozone has a warming effect in the middle atmosphere. The heating (Strobel, 1978) and cooling (Fomichev and Sheved, 1985) rates of CO_2 and ozone are calculated in the model.
Some model experiments were carried out for the period from 1979 to 2015. The lower boundary conditions, ozone and CO_2 data were changed from year to year, resulting in a time series of winter winds from 1979 through 2015.

3. Model results

The results for January are shown in Fig. 3. The colored background represents the 37-year mean of the MUAM simulations from 1979 to 2015 for January as zonal means. Trends can be seen as contour lines in the left panels. Hatched areas indicate positive trends. The standard derivations of the zonal means for temperature (top), zonal wind (middle), and meridional wind (bottom) are shown on the right panels. The climatology of MUAM simulations shows good consistency for zonal mean of temperature and wind jets to other climatologies, such as CIRA (Fleming et al., 1990), UARS Reference Atmospheric Project (Hays et al., 1993, Swinbank and O'Neill, 1994) and the Global Empirical Wind Model (GEWM) of the middle atmosphere by Portnyagin et al (2004) and extended by Jacobi et al. (2009). Compared to climatologies, it can be seen that in

the January the mesospheric wind reversal in the MUAM is near 80 km at midlatitudes, and thus is lower than measurements show.
For the temperature standard derivation (top, right side) high values can be seen at high latitudes of the northern hemisphere from the troposphere up to the mesopause with maxima in the polar tropopause and stratopause. Higher values can also be found at the lower thermosphere. This broadly corresponds with the maxima of trends, which are shown on the top left panel. A maximum of positive trends is located in the troposphere and tropopause with over 0.1 K/y in the northern polar region of tropopause. Large negative trends can be seen in the northern polar stratosphere and stratopause with up to -0.2 K/y. Above 100 km in the thermosphere there is a strong decrease of temperature (-0.1 K/y to -0.4 K/y).
The standard derivation of zonal wind (Fig. 3, middle row, right panel) shows a maximum in the middle at higher latitudes of the northern hemisphere, especially in the midlatitude jets. Positive zonal wind trends, i.e. a decline of the easterly winds or an increase of the westerly wind, are seen in the area of the mesospheric westerly wind jet between 30°N and 50°N (larger than 0.1 $ms^{-1}y^{-1}$), which means an intensifying of the mesospheric westerly wind jet, because the stronger cooling at high latitudes caused an increase of horizontal temperature gradients. A positive trend of zonal wind in the northern polar (decrease of easterly wind) or southern midlatitude mesopause (increase of westerly wind jet with 0.1 ms^{-1} y^{-1}), but in the east wind maximum there is an intensification of the east wind up to over 0.12 ms^{-1} y^{-1}. Positive trends can be observed at middle and high northern latitudes in the stratosphere and mesosphere with up to 0.2 ms^{-1} y^{-1}, which indicates a southward shift and a strengthening of mesospheric westerly wind jet. Also negative trends can be seen in the mesospheric easterly wind jet (increase of this jet) in northern and in the southern midlatitude mesosphere.
On the bottom right panel, the standard derivations of the meridional wind are shown. The maximum of the standard derivation is in the region of the meridional wind jet in the middle and lower latitudes of the mesosphere and mesopause. Notable positive trends (up to 0.02 ms^{-1} y^{-1}) can be identified in the range of the meridional wind jet in mesosphere and mesopause. This means an intensification of this circulation from the southern hemisphere to the northern hemisphere during January. Reasons could be that the zonal wind increase implicates larger gravity wave amplitudes and stronger gravity waves divergence in the MLT and this caused a stronger meridional wind through gravity wave forcing.
In Fig. 4 the results for July are presented. The colored background shows the climatology of MUAM simulations from 1979 to 2015 for July as zonal mean. Trends can be seen left, the standard derivations on the right panels as zonal mean for temperature (top), zonal wind (mid), meridional wind (bottom). Hatched areas indicate positive trends.

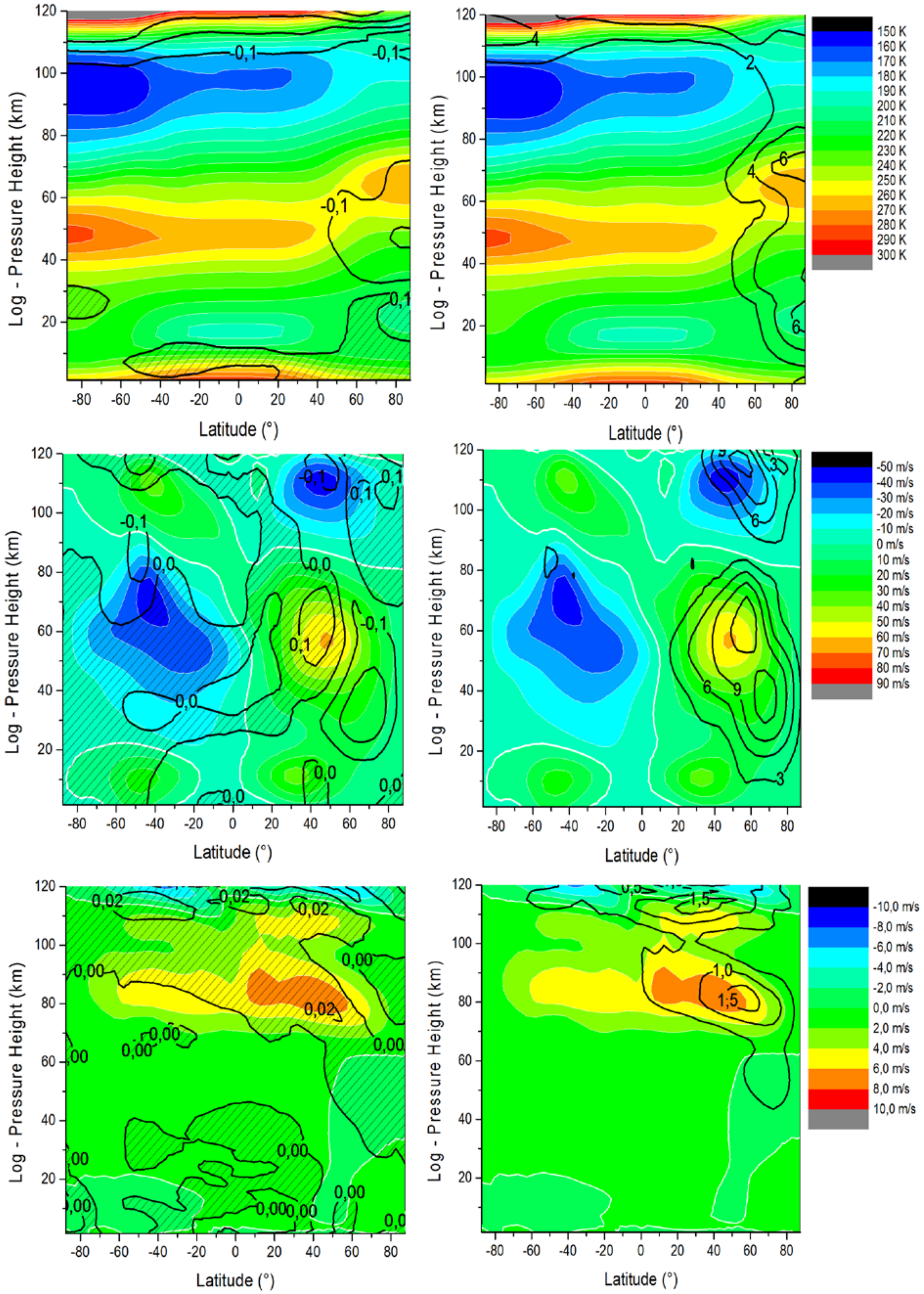

Fig. 3: Climatology of MUAM simulations from 1979 to 2015 for January (background) as zonal mean. Trends (left) as zonal mean per year and standard derivation (right) for temperature (top), zonal wind (mid) and meridional wind (bottom). Hatched for positive trends.

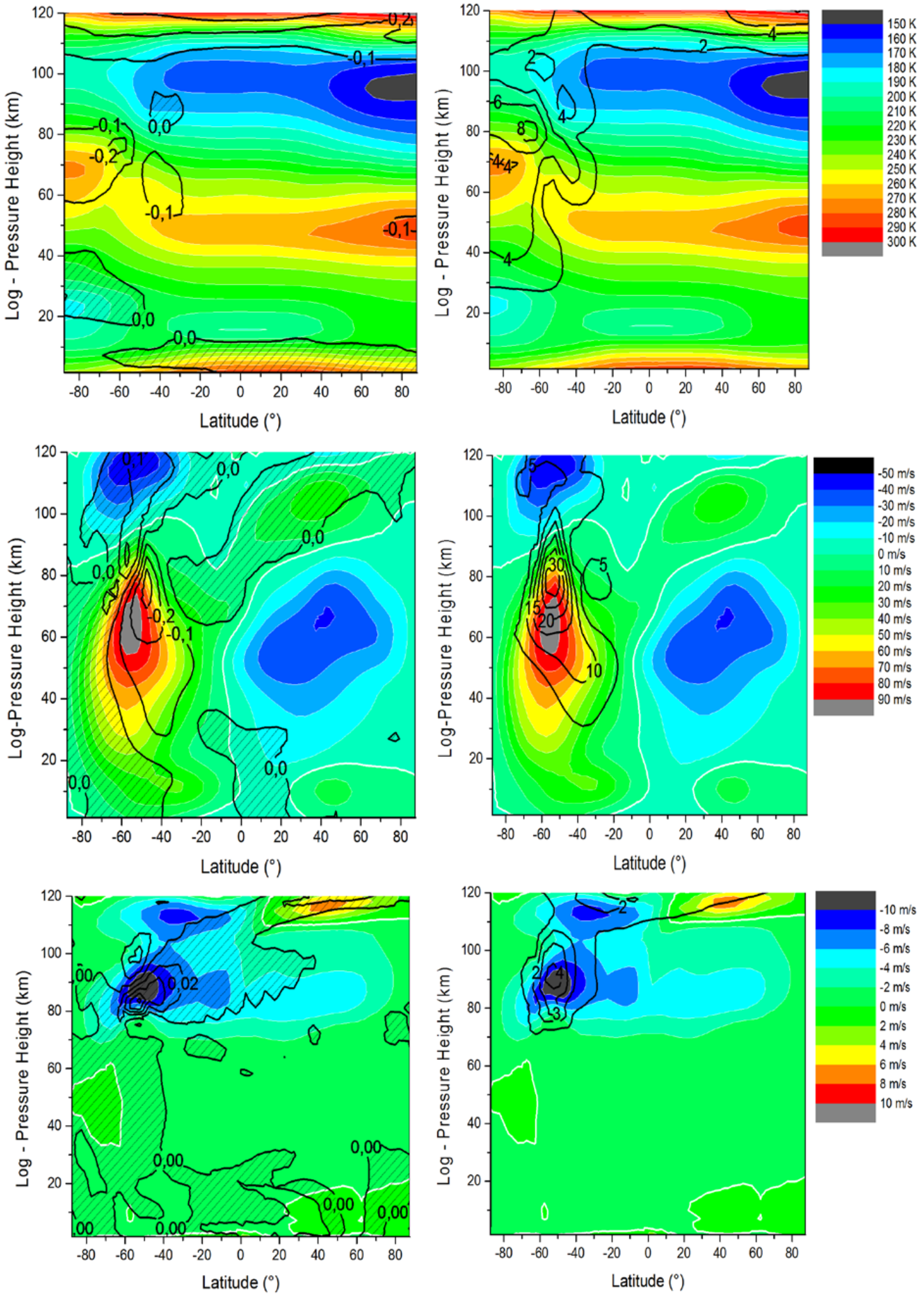

Fig. 4: Climatology of MUAM simulations from 1979 to 2015 for July (background) as zonal mean. Trends (left) as zonal mean per year and standard derivation (right) for temperature (top), zonal wind (mid) and meridional wind (bottom). Hatched for positive trends.

The upper right panel of Fig. 4 shows the standard deviation of the temperature. The highest values are in the range of the middle and high southern latitudes with a maximum in the mesosphere. High standard deviations can be observed in all latitudes above 100 km. The standard deviation of the temperature is therefore greatest in the middle and high latitudes on the winter hemisphere. On the upper left side of Fig. 4 one can see that positive trends occur only in the troposphere and at middle and high southern latitudes in the stratosphere (up to 0.1 K/y). Note that this is not modeled but due to ERA-Interim trend. Larger negative trends are found in the stratopause and mesosphere of middle southern latitudes and in both polar regions with -0.2 K/y. Note that the polar negative trend maximum is found at higher altitudes than in northern hemisphere summer. This must have consequences for the thermal wind, and should be connected with a negative (inserted of positive) trend of the zonal westerly wind jet (middle left panel of Fig. 3). Above 100 km exists a large temperature decrease for all latitudes (up to -0.3 K/y) as was already seen in January.
On the middle right panel of Fig. 4, a maximum of the standard derivation for the zonal wind can be seen in the area of and slightly above the westerly wind jet of the southern middle latitudes in the mesosphere with over 30 ms^{-1}. For the trends of zonal wind in July a decrease of the westerly wind jet (-0.3 ms^{-1}) in the mesosphere of midlatitude of southern hemisphere can be observed. The increase of the westerly wind in the middle and higher latitudes of the stratosphere (up to 0.1 ms^{-1}) and in the high latitudes of the mesosphere indicates a poleward shift of the westerly wind jet in the mesosphere on the southern hemisphere. In addition, a decrease of the westerly wind (up to 0.2 ms^{-1}) in the southern midlatitude mesosphere is found. For the northern hemisphere, a slight increase of the easterly wind jet (up to 0.1 ms^{-1}) in mesosphere of the midlatitudes occurs. In the area of the westerly wind jet in the mesopause of the middle latitudes of the northern hemisphere, there is an increase of the westerly wind (up to 0.1 ms^{-1}).
The bottom panels of Fig. 4 show the standard deviation on the right hand side and the trend for the meridional wind on the left side. High values of standard deviation can be seen in the low und middle latitudes of mesosphere and mesopause. A maximum is located in the north wind maximum in the midlatitudes of southern hemisphere with 4 ms^{-1}. A decrease of the northerly wind (0.08 ms^{-1}) can be observed in the middle latitudes of the mesosphere in the southern hemisphere. On the other hand, there is an increase in the southerly wind (0.02 ms^{-1}) in the mesopause and lower thermosphere in the northern hemisphere.

5. Discussion and Conclusion

The run showed a decrease of the temperature above the troposphere, which was more pronounced above 100 km. For the northern hemisphere in winter there was a positive trend in the troposphere and a negative trend in the high and middle latitudes of the stratosphere. The same can be seen in winter of the southern hemisphere. During summer in the southern hemisphere there was a weak negative trend in strato- and mesosphere and a weak positive trend in high latitudes of tropopause. In summer on the northern hemisphere there is a negative trend with maximum in the polar stratopause. This is in agreement with the general view known, e.g., from reviews by Lastovicka et al. (2008), Ramaswamy et al. (2001) and Qian et al. (2011). The CO_2 has the largest

proportion of the negative temperature trend (Akmaev et al., 2002; Lübken et al., 2013). Also it was found that the temperature decrease in the mesopause was less intense (Lastovicka et al., 2008; Lübken et al., 2013; Marsh et al., 2013). This is also confirmed by measurements by Bremer and Berger (2002) and agrees with reports by Beig et al. (2003). The increased temperature drop in the winter polar stratosphere is also confirmed by satellite measurements (Ramaswamy et al., 2001; Funatsu et al., 2016).
The model calculations showed a weakening of the jet in the mesosphere of the northern hemisphere winter hemisphere north of 50°N in January and a strengthening south if it (and actually in the center of the jet). The increase in the region south of 50°N was also seen by Jacobi et al. (2015b). As Jacobi et al. (2015b) showed by comparison of different measurements at about 80-100 km altitude, in the middle latitudes at about 50°N it first came I to a strengthening of the westerly wind in winter, from 2005 onwards this turned to a tendency for a drop. Hoffmann et al. (2011), however, could also see an increase of the westerly wind in winter until 2010. Jacobi et al. (2005) could still see a clear trend towards the increase in 2005. This also shows that a change in the trend in the westerly wind jet in winter in northern hemisphere is possible after 2005. An increase of the easterly wind of the southern hemisphere was only calculated at about 80 km altitude in January, also seen by Marsh et al. (2013), as well as a decrease of the westerly wind in the mesopause at 110 km altitude. In July, an increase of the westerly wind south of 80°S could be observed in the winter hemisphere, whereas a decline in wind speeds could be seen for large parts of the westerly wind jet. Also, there was a weakening of the easterly wind in the mesopause and lower thermosphere. The increase of the easterly wind in the mesosphere in the run on the northern hemisphere in July was confirmed by measurements in Juliusruh (Keuer et al., 2007; Hoffmann et al., 2011). Both also showed the increase of the westerly wind in the mesopause. It also became clear that the ozone and CO_2 induced trend is very low. The exception of the westerly wind jet of the southern hemisphere a clearly positive trend could be observed, which is contrary to the run. Another exception for the CO_2 is the area above 100 km altitude, where CO_2 have a large effect of the trend shown in the run. The largest effect is caused by the lower boundary conditions.
For the meridional wind, the run for January provided an intensification of the meridional wind jet, while in July a decline be observed, especially in the middle latitudes of the southern hemisphere. The influence of ozone and CO_2 on the trend of the meridional wind is generally low, at most in the southern hemisphere, in connection with the meridional wind jet, weak trends can be identified. The greatest effect is nevertheless caused by the lower boundary conditions. The evoked developments of ozone and CO_2 are contradictory. For January, Jacobi and Kürschner (2006) and Keuer et al. (2007) also showed an increase of the southerly wind in the meridional wind jet. In July, there was no trend or only a slight decrease of the northerly wind; this confirms result by Jacobi and Kürschner (2006).

Acknowledgements

ERA-Interim reanalyses have been provided by ECMWF through www.ecmwf.int/en/research/climate-reanalysis/era-interim, and have been used in MUAM for assimilation in the troposphere as lower boundary condition. Carbon dioxide data were provided by NOAA: www.esrl.noaa.gov/gmd/ccgg/trends/. Global ozone data

were calculated from MERRA provided by NOAA on disc.sci.gsfc.nasa.gov/daac-bin/FTPSubsreanalyses et.pl?LOOKUPID_List=MAIMCPASM.

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