Review 1

Review of: “Connection between the length of day and wind measurements in the mesosphere and lower thermosphere at mid and high latitudes.”
by Sven Wilhelm et al. [AnGeo 2018-15, rcvd June 2018]

Relation between zonal wind and length of day variations is a very ambitious topic.
The discussion is very interesting, but I can't find any proof that LOD affects the measured winds.

General reply: We thank the Referee for this constructive suggestions and comments that help to improve the paper.

Aim of this study is to show that, according to previous work by Stober et al. (2012), the mesospheric/lower thermospheric zonal wind is connected to changes in the neutral density. Due to a lack of global density observations these concern are hard to proof. Therefore we took the LOD for comparison to the zonal wind, because the LOD is related to changes in the global Earth rotation speed. These changes can be influenced by large scale atmospheric processes and we further state that within the MLT the atmospheric rotation speed is also affected by changes in the neutral density. We figured out that the connection occurs on annual or longer time scales, and further follows the influence of solar radiation (on 11-year solar cycle scale, as well as differences in the Earth-Sun-distance). On shorter time scales, only based on wind measurements, a connection between the LOD and MLT winds, with respect to the impact of the Sun are quite complicated to find. We will leave a true understanding of the effect, which implies exact velocity values, for future work.

There are a few points which should be addressed in the introduction.

1. If the earth-atmosphere system were rigid, and the atmosphere expands, the whole system would slow down (become less eastward or more westward) to maintain conservation of angular momentum, But it is not rigid, and since atmospheric drag is the proposed cause of the earth seasonal LOD change, it is important to estimate the time constant. If longer than a season, then maybe no effect on wind would be noticeable. Pg. 8 L 23 mentions the matter, but there is no estimate.

Reply: We agree that a calculation of a time constant is important to estimate a direct LOD effect on higher located winds, but only based on our available radar measurements we are not able to estimate the lag. We will mention this for future work. Nevertheless, we added the following part to the paper:

According to e.g., Dickey et al. (1994) a direct effect exists between the stratospheric and tropospheric zonal wind and the LOD on annual time scales due to long term geophysical effects, as e.g., QBO and El Nino. They found that the stratosphere cannot be neglected in the Earth’s angular momentum. Around 20 % of the LOD relative to the atmosphere below 100 mbar, belongs to the impact of the stratosphere. Furthermore, they mentioned a small lag (10 - 20 days) between the LOD and variations in the angular momentum, but the lag do not appear to be statistically significant.

Dickey, J., O., Marcus, S., L., Hide, R., Eubanks, T., M., and Boggs, D., H.: Angular momentum exchange among the solid Earth, atmosphere, and oceans: A case study of the 1982 - 1983 El Nino event., Journal of geophysical research, 99, 23, 921–23,937, 1994.

2. If the atmosphere is heated why would expansion be simple and not lead to a different climatology, including winds.

Reply: We assume that the expansion/shrinking of the atmosphere also influence the climatology, but the effect is relatively small compared to the atmospheric drivers, as gravity waves and chemistry. In a model simulation Marsh et al. (2007) showed for the whole atmosphere a response to changes in the 11-year solar cycle, with e.g., the result of temperature changes in the lower thermosphere by over 100 K at solar maximum relative to solar minimum. Further they showed the occurrence of tropospheric wind and temperature changes due to changes in the solar radiation. But they also mention that changes in the climatology due to solar radiation are too complex to lead to simplified results. Furthermore, there are other factors as e.g., the composition of chemical components and the occurrence and propagation of gravity waves which lead to the state of the climatology.

We added/reformulated some text in the manuscript to clarify the point of the study:

We have to note that beside many others factors, this is only one reason, and by far not the dominant factor, for the wind differences between both locations at theses altitudes. Other physical processes have also a strong effect on the hemispheric wind differences e.g., the topography, chemical composition of the atmosphere (Marsh (2007), Lee (2018)), and the occurrence and propagation of gravity waves. These waves are the main drivers of the atmospheric wind circulation and therefore also influence the local wind differences at both hemispheres. Furthermore gravity waves lead, compared to the annual mean, to a colder summer mesosphere and a warmer winter mesosphere e.g., Luebken (2014). These temperature differences also fit well to the atmospheric expansion/shrinking. Unfortunately, based only on wind measurements we are not able to estimate a precise value on how strong the connection is between zonal mean wind with the LOD. For a more detailed understanding of these phenomena global density observations would be required.

and

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Lübken, F.-J., Höffner, J., Kaifler, B., and Morris, R., J.: Winter/summer mesopause temperature transition at Davis (69°S) in 2011/2012, Geophys. Res. Lett., 41, 5233–5238, https://doi.org/10.1002/2014GL060777, 2014.

Marsh, D., R., Garcia, R., R., Kinnison, D., E., Boville, B., A., Sassi, F., Solomon, S., C., and Matthes, K.: Modeling the whole atmosphere response to solar cycle changes in radiative and geomagnetic forcing, Journal of geophysical research, 112, https://doi.org/doi:10.1029/2006JD008306, 2007.

Lee, J., N., Wu, D., L. R. A., and Fontenla, J.: Solar cycle variations in mesopheric carbon monoxide, Journal of atmospheric and solarterrestial physics, 170, 21–34, https://doi.org/https://doi.org/10.1016/j.jastp.2018.02.001, 2018.

3. The proposed LOD effect depends on heating: the solar cycle radiation variation is surely bigger than the earth-sun distance effect. Does zonal mean wind show a solar cycle variation?

Reply: Yes, the zonal mean wind shows a solar cycle variation. We added a Figure, where for the location of Andenes the zonal mean wind between 84 and 94 km is displayed together with the F10.7 solar cycle index. As result is shown that for a low F10.7 index an enhanced westward wind appears, while for stronger a F10.7 index the eastward directed wind gets enhanced. Further also a shift in the summer vertical wind shear occurs, which is also correlated to the solar cycle. There occurs a shift onto higher altitudes together with a decrease of the solar radiation, due to a change in the neutral density. This pattern can also be seen for the other locations.

We added the text:

To underline this statement, Figure 4 shows, for the location of Andenes, the zonal mean wind between 84 and 94 km together with the F10.7 11-year solar cycle index (black line). An enhancement of the eastward directed wind occurs together with a stronger F10.7 index and more clearly an increase of the westward directed wind together with a smaller F10.7. Furthermore a shift occurs in the summer vertical wind shear, which is also correlated with the solar cycle, whereby a shift to higher altitudes takes place together with a decrease of the solar radiation, due to a change in the neutral density.

Caption (Figure 4.. see attachment): Zonal mean wind for Andenes for the heights between 84 and 94 km, together with the F10.7 11 year solar cycle index in black.

4. It appears that heating to the winter atmosphere should be smaller, even with a closer sun-earth distance, else why is it winter. Why is not atmospheric expansion smaller than in summer?

Reply: Propagation of gravity waves which breaks in the mesosphere leads, compared to the annual mean/radiative equilibrium, to a cold mesosphere during the summer and a warm mesosphere during the winter. This temperature difference fits well with the atmospheric shrinking/expansion.

We added a comment in the text: (see point 2.)

Other physical processes have also a strong effect on the hemispheric wind differences e.g., the topography, chemical composition of the atmosphere (Marsh (2007), Lee (2018), and the occurrence and propagation of gravity waves. These waves are the main drivers of the atmospheric wind circulation and therefore also influence the local wind differences at both hemispheres. Furthermore gravity waves lead, compared to the annual mean, to a colder summer mesosphere and a warmer winter mesosphere e.g., Luebken (2014). These temperature differences also fit well to the atmospheric expansion/shrinking.

Marsh, D., R., Garcia, R., R., Kinnison, D., E., Boville, B., A., Sassi, F., Solomon, S., C., and Matthes, K.: Modeling the whole atmosphere response to solar cycle changes in radiative and geomagnetic forcing, Journal of geophysical research, 112, https://doi.org/doi:10.1029/2006JD008306, 2007.

Lee, J., N., Wu, D., L. R. A., and Fontenla, J.: Solar cycle variations in mesopheric carbon monoxide, Journal of atmospheric and solarterrestial physics, 170, 21–34, https://doi.org/https://doi.org/10.1016/j.jastp.2018.02.001, 2018.

Lübken, F.-J., J. Höffner, T. P. Viehl, B. Kaifler, and R. J. Morris (2014), Winter/ summer mesopause temperature transition at Davis (69◦S) in 2011/2012, Geophys. Res. Lett., 41, 5233–5238, doi:10.1002/2014GL060777.

Fig. 6,7 seem to be showing the full zonal wind vs. LOD. According to an earlier statement, 4 m/s is the estimated contribution from LOD (e.g. Fig. 4), both having annual variations. How does this figure show the LOD-only contribution?

Reply: A precise estimation of the impact of the LOD on the wind is difficult. Based on the wind observations only we are not able to estimate a correct value for the LOD contribution. According to the equations 1-4 estimations could be done, but due to a lack of density measurements we are not able to determine correct values. This point is added as an outlook for future work.

Fig. 8 The long term effect of tides and earth deformation are usually taken to be the cause of slowing the earth's rotation, not atmosphere. How does that physically create a trend in the zonal wind.

Reply: We added this text to the introduction:

On short time scales a change in the Earth rotation can lead to an uneven heating of the Earth’s surface, which results to temperature differences between the surface and the atmosphere above. This can further cause convection currents, which leads to pressure differences in the atmosphere and results in a different wind formation, which can influence the LOD. On longer time scale and especially on higher altitudes increases the importance of the solar influence. An increase of the solar radiation, which can be caused due to a slowing of the Earth’s rotation, leads to an expansion of the higher atmosphere, which further results, due to the conversation of angular momentum, in a slower rotation of the atmosphere. What further needs to be considered is e.g., the influence of volcanic eruptions, which influence the Earth’s rotation as well as the atmospheric chemistry/temperature (e.g., She et al. (2015)). Changes in these parameters can further lead to changes in the neutral density.

She, C., Krueger, D., A., and Yuan, T.: Long-term midlatitude mesopause region temperature trend deduced from quarter century (1990- 2014) NA lidar observations, Annales Geophysicae, 33, 363–369, https://doi.org/doi:10.5194/angeocom-33-363-2015, 2015.

Minor typos, grammatical, etc.

General Reply: Thanks for the advices. We will correct the mentioned points, and added here for some points few comments for the Referee.

Pg 1 L 10 siderial time
L 11 full rotation , "86400" to make it international.
But 86400s is a mean solar day, not a mean siderial day, and LOD was said to based on siderial time; the difference is ~ 4 minutes. Some text changes are necessary.

Reply : we added some text : Within the estimation of the LOD the sidereal time gets converted into solar time, by taking into account the Earth's position and motion with respect to the stars (Aoki, 1981).

Aoki, S., Guinot, B., Kaplan, G., Kinoshita, H., McCarthy, D., and Seidelmann, P.: The new Definition of Universal Time, Astronomy and Astrophysics, 105, 359–361, 1981.

L 13 deceleration ? – no, eastward directed wind (or westerly) leads to an acceleration of the Earth's rotation.

Pg 2 L 10 at solar minimum as well as decrease in the temperature ... ?

Reply: We reformulated the sentence and added some more references:

Previous studies as, e.g., Walterscheid (1989), Marsh et al (2007), Emmert (2015), and Lee et al. (2018) showed that solar cycle variations affects the atmospheric density, temperature, chemical composition and winds over the whole atmosphere, but in particular, in the MTI (Mesosphere-Thermosphere-Ionosphere) system.

Walterscheid, R., L.: Solar Cycle effects on the upper atmosphere: Implications for Satellite Drag, Journal of spacecraft and rockets, 26, 439–444, https://doi.org/DOI: 10.2514/3.26089, 1989.

Marsh, D., R., Garcia, R., R., Kinnison, D., E., Boville, B., A., Sassi, F., Solomon, S., C., and Matthes, K.: Modeling the whole atmosphere response to solar cycle changes in radiative and geomagnetic forcing, Journal of geophysical research, 112, https://doi.org/doi:10.1029/2006JD008306, 2007.

Emmert, J. T.: Altitude and solar activity dependence of 1967-2005 thermospheric density trends derived from obrital drag, Journal of geophysical research: space physics, 120, 2940–2950, https://doi.org/doi:10.1002/2015JA021047., 2015.

Lee, J., N., Wu, D., L. R. A., and Fontenla, J.: Solar cycle variations in mesopheric carbon monoxide, Journal of atmospheric and solar terrestial physics, 170, 21–34, https://doi.org/https://doi.org/10.1016/j.jastp.2018.02.001, 2018.

Pg 3 L 22 its? –corrected-

Pg 4 L 4 ``... atmosphere were vertically ..." –corrected-
L 19 1960s and 70s –corrected-
L 23 60s –corrected-
L 24 What is "d" ? We changed d to D, which is the angular velocity of the Earth. To avoid misunderstandings we didn't choose ω, because it is already used in the equations 1,5 and 6 as angular velocity for an altitude defined atmospheric layer.

Pg 5 L 6 describe –corrected-
L 8 `` ... under the assumption of equal density ..." –corrected-
L 30 The Aura MLS GPH at 0.001 hPa is virtually always ~90 km

Reply: We converted the geopotential height into geometric height, as e.g., done in Matthias et al (2013). We added some text to clarify this.

Added text:
The geometric heights are approximately estimated from pressure levels as described in Matthias (2013): $h = -7 \ln(9/1000)$, where h is the altitude in km and p the pressure in hPa. Furthermore, we are aware about a difference between the geometric and geopotential heights, which increase especially above 80 km. Therefore, we focus in this work on the height range between 60 to 80 km…

Matthias, V., Hoffmann, P., Manson, A., Meek, C., Stober, G., Brown, P., and Rapp, M.: The impact of planetary waves on the latitudinal displacement of sudden stratospheric warmings, Ann. Geophys., 31, 1397-1415, https://doi.org/10.5194/angeo-31-1397-2013, 2013.

L 32 `` density-dependent " ? –see above

Pg 6 L 1 ``height and temperature ..", ``horizontal grids which are ..." –corrected-
L 23 ~ 90 km again –corrected-
L 24 ``... in qualitatively good agreement ..." –corrected-

Pg 7 L 2 Geopotential? or is geometric calculated from geopotential ? – we added some more words to clarify this.

L 9,12 `` Gaussian" –corrected-

L 13 `` these results agree with the observations ..." ?
Only based on wind measurements we are not able to extract a specific value.

L 15 misplaced ``(`` -corrected-
L 31 these , this phenomenon or these phenomena –corrected-

Pg 8 L 8 explicitly –corrected-
L 22 relatively –corrected-
L 34 "solar cycle variation " (there is only one cycle here) –corrected-

Pg 9 L 14-20 need to be re-written.
Reply: we reformulated the part:

In the Figures 10 and 11 are shown long term changes of annual LOD (black) and annual zonal mean winds (red) for Collm and for Davis. At this point, we have to mention that a tendency over a long time series is not linear in time. Parameter which influence the tendency of the wind and the LOD also vary over time and therefore be observed in long time series should be limited within a specific period. Such changes are often be approximated by a piecewise linear trend model (e.g., Tomé and Miranda (2004), Merzlyakov et al. (2009) and Jacobi et al. (2011)), where different linear fit tendencies are estimated for different time periods. Nevertheless, due to the length of the available data series we decide to use no piecewise linear trend model. The wind values exclude seasonal and solar cycle variations and the LOD excludes the seasonal variations. Exemplary for the locations of Collm (Figure 10) the altitudes between 80 and 96 km are displayed. The errorbars corresponds to the annual variance for each height and the dotted lines show the long term tendency for each parameter. The result is that a long term increase of the LOD occurs together with a long term decrease of the zonal wind. Above 94 km the tendency reverses for the mid latitude locations into a slightly positive wind. This reversal can be explain by the stronger influence due to gravity wave filtering, which has to be considered and cannot be excluded by filtering the data. The tendencies of an increased value for the LOD and a decreased value for the zonal mean wind can be seen for all mid latitude locations and also for Davis (see Figure 11). Andenes shows for all altitudes increase tendency in the zonal wind. The results indicates that the connection between the LOD and the wind are more pronounced at lower latitudes, which simply explainable by the rotation velocity, which is higher at the middle latitude stations than at the polar latitudes like Andenes and Davis. The results of an increase of the LOD and a decrease of zonal wind fits to the relation between fluctuations in the neutral density and the zonal wind, as shown Stober et al. (2012).

Tomé, A., R. and Miranda, P., M. A.: Piecewise linear fitting and trend changing points of climate parameters, Geophys. Res. Lett., 31, https://doi.org/doi:10.1029/2003GL019100, 2004.

Merzlyakov, E., G., Jacobi, C., Portnyagin, Yu., I., and Solovjova, T., V.: Structural changes in trend parameters of the MLT winds based on wind measurements at Obninsk (55°N, 37°E) and Collm (52°N, 15°E), Journal of atmospheric and solar-terrestial physics, 71, 1547–1557, https://doi.org/doi:10.1016/j.jastp.2009.05.013, 2009.

Jacobi, C., Hoffmann, P., Liu, R., Q., Merzlyakov, E., G., Portnyagin, Yu., I., Manson, A., H., and Meek, C., E.: Long-term trends, their changes, and interannual variability of Northern Hemisphere midlatitude MLT winds, Journal of Atmospheric and Solar-Terrestrial Physics, 75-76, 81–91, https://doi.org/doi:10.1016/j.jastp.2011.03.016, 2011.

L 21 "an overall ..." –corrected-
L 22 " is more ..." –corrected-

L 33 "stations" –corrected-

Pg 10 L 10 "can not be figured ..." –corrected-
L 16 "... at these altitudes. " –corrected-

Pg 11 L35 "using" –corrected-
Caption Figure 2, 3: "positive" –corrected-

Reviewer 2

Review of “Connection between the length of day and wind measurements in the mesosphere and lower thermosphere at mid and high latitudes”
General comments

A topic of this manuscript, study of correlation between a length of a day and zonal mean winds, is very interesting. However, I concern about three points.

General reply: We thank the Referee for this constructive suggestions and comments that help to improve the paper.

Although data analysis results are presented in 6 figures in the manuscript, all of them are about mean zonal winds from meteor radars. Among them, only 3 figures overplot lengths of a day. Trends of lengths of a day and zonal mean winds look somehow correlated in the figures, but correlations are not presented numerically. Because mean winds are presented in terms of seasonal and interannual variations. I would like to have seen them for lengths of a day, too.

Reply: We added numerical correlation values between the parameters for different heights and different locations, whereby we want to mention that these values corresponds to the whole data set and not for short time series (below one/half year). With our current methods we do not find a connection between the LOD and the zonal MLT wind on time scales less than a year.

We added to the text:

Additionally, we show in Table 1 correlation coefficients for the 4 locations for the altitudes between 80 and 98 km. Positive correlation values correspond to the occurrence of an eastward directed wind together with an increased LOD. The values of the NH follow a similar pattern, with positive coefficients below the vertical transition height and negative above. Davis shows a different pattern, with overall negative correlation coefficients. This relies in the opposite zonal wind pattern compared to the NH. Theoretical, a time shift of ~ half a year would lead to a similar correlation pattern as the NH.

According to Abarca-del Rio et al. (2003) an accurate estimation of the impact of the solar radiation is quite complicated, due to the point that internal oscillations in the climate system show variations within the same frequency as the 11 year solar cycle. Further, Gray et al. (2010) supports this statement and mention that the problem is further caused due to the small influence of the solar forcing on the climate. Nevertheless, Chapanov and Gambis (2008) showed that based on a decomposition of the LOD, the solar activity (10.47 years) is included.

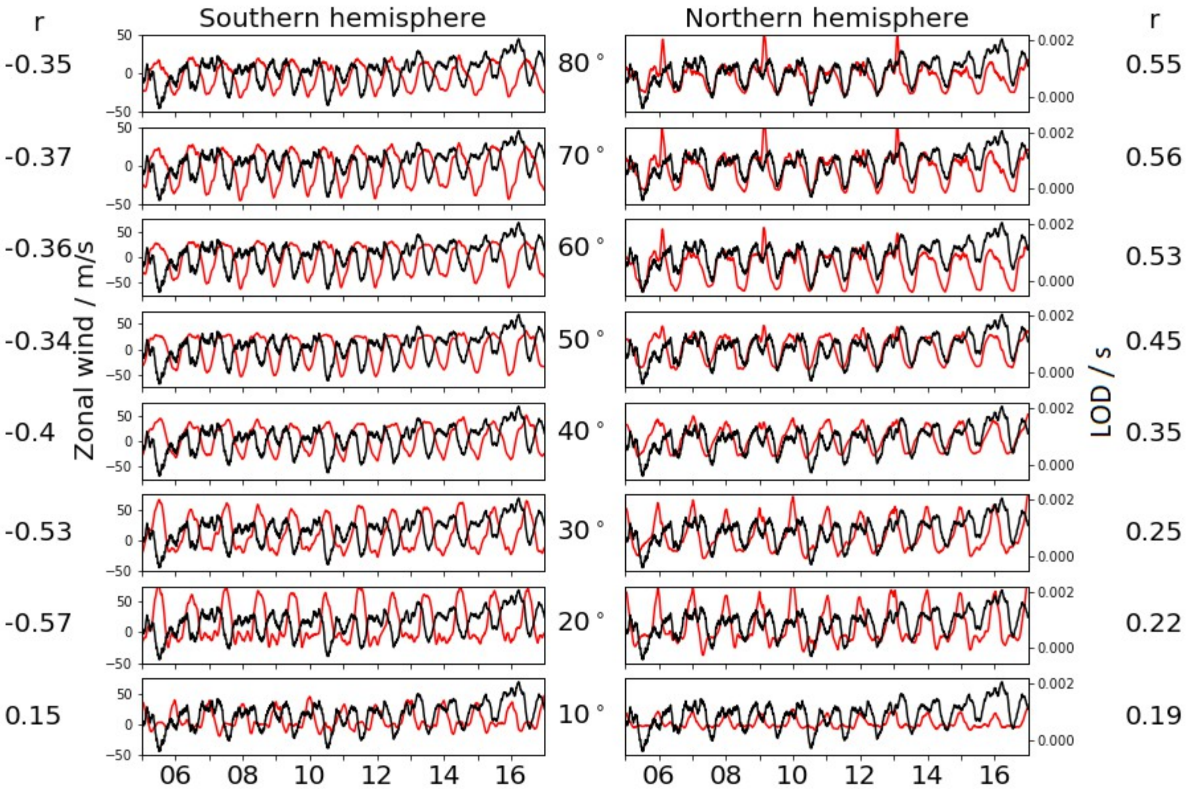
Abarca-del Rio, R., Gambis, D., Salstein, D., Nelson, P., and Dai, A.: Solar activity and earth rotation variability, Journal of geodynamics, 36, 423–443, https://doi.org/doi:10.1016/S0264-3707(03)00060-7, 2003.

Gray, L. J., Beer, J., Geller, M., Haigh, J. D., Lockwood, M., Matthes, K., Cubasch, U., Fleitmann, D., Harrison, G., Hood, L., Luterbacher, J., Meehl, G. A., Shindell, D., van Geel, B., and White, W.: Solar influence on climate, Reviews of Geophysics, 48, https://doi.org/10.1029/2009RG000282, http://dx.doi.org/10.1029/2009RG000282, 2010.

Chapanov, Y. and Gambis, D.: Correlation between the solar activity cycles and the Earth rotation, Proc. Journées 2007 “Systèmes de référence Spatio-Temporels”, edited by: Capitaine, N., Obs. de Paris, 206–207, 2008.

Zonal mean winds are presented using meteor radar measurements at 3 sites in the northern hemisphere and the high latitude southern hemisphere, and Aura/MLS. I expected that Aura/MLS data results are compared with radar results for a validation and then would present any global variations. However, Aura/MLS results are used only for comparisons of radar results in the northern hemisphere. Because authors conclude zonal mean winds agree between MLS/Aura and radar measurements, I do not understand motivation of presenting trends of lengths of a day and zonal mean winds from both meteor radars (Figure 6) and Aura/MLS (Figure 7).

Reply: Based on MLS data we added a Figure where is shown the zonal mean winds at ~80 km geometric height together with the LOD at the fixed longitude 0°-20°E between northern high latitudes and southern high latitudes. With this Figure we show the development of the global variations between both parameters. As result can be seen that the correlation between the LOD and the mean zonal wind increase towards the northern high latitude. The same would be seen if half a time shift of ~ half a year would be added to the time series.



Caption Figure9 : Zonal MLS wind (red) and LOD (black) at ~80km geometric height for 0°-20°E. The left part show the values for the southern hemisphere, the right for the northern hemisphere, for every 10° latitude.

Further we added some text:

Figure 9 shows, based on MLS data, the zonal mean wind at ~80 km geometric height and the LOD. These zonal mean winds include wind values within the longitude grid between 0°E and 20°E, which is comparable to the NH stations. The Figure is divided in 10° latitude steps from 80° to 10°S/N. Each latitude grid includes values for +/- 6°. For the MLS observations the comparison between the wind and the LOD are similar to the 80 km meteor results at the respective latitudes. Further can be seen the occurrence of half a year time shift, between both high hemispheres. A 180° phase shift would lead to the wind-LOD pattern of the opposite hemisphere. Furthermore, the strongest correlation can be seen between both parameters at northern polar latitudes. Due to an increase in the difference between the geometric and geopotential heights, we do not show comparison for higher altitudes. Further we added correlation coefficient between the zonal mean wind and the LOD for each latitude. As result occurs a correlation increase towards the northern high latitude. The same could be seen if a 180° phase shift is added to the time series.

Lastly, authors compare zonal mean winds using Andenes and Davis in the northern and southern hemisphere in a same season and conclude that a difference is caused **only** by lengths of a day between northern hemisphere summer and winter. However, I believe that mean winds from ground measurement only one site include zonal mean wind and stationary planetary waves and difference of stationary planetary wave amplitudes largely results to a difference of mean winds of ground measurements. I also believe that main reason of interhemispheric differences in atmospheric dynamics is a difference of topography. It makes a difference of atmospheric waves with interact with mean winds. The difference of topography makes an interhemispheric difference of chemical composition in the atmosphere, such as water vapour, ozone, and carbon dioxide, which makes an interhemispheric difference of viscosity and then winds.

Reply: We totally agree with that point. Our aim is not to state that the differences in the mesospheric zonal mean winds are **only** a result of the LOD. As we already wrote, we only want to point out, that beside other factors, which have a way stronger influence on the differences of the wind, the LOD has an influence on the winds on both hemispheres. As example for other influencing factors can be called the topography, chemical components and the occurrence and propagation of gravity waves. These waves are the main drivers of the atmospheric wind circulation and therefore also influences the local wind differences at both hemispheres. Unfortunately based only on wind measurements we are not able to estimate a precise value on how strong the connection is between zonal mean wind the LOD.

We added/reformulated some text in the manuscript to clarify the point in the manuscript.

We have to note that beside many others factors, this is only one reason, and by far not the dominant factor, for the wind differences between both locations at theses altitudes. Other physical processes have also a strong effect on the hemispheric wind differences e.g., the topography, chemical composition of the (Marsh (2007), Lee (2018)), and the occurrence and propagation of gravity waves. These waves are the main drivers of the atmospheric wind circulation and therefore also influence the local wind differences at both hemispheres. Furthermore gravity waves lead, compared to the annual mean, to a colder summer mesosphere and a warmer winter mesosphere e.g., Luebken (2014). These temperature differences also fit well to the atmospheric expansion/shrinking. Unfortunately, based only on wind measurements we are not able to estimate a precise value on how strong the connection is between zonal mean wind with the LOD. For a more detailed understanding of these phenomena global density observations would be required.

Lübken, F.-J., Höffner, J., Kaifler, B., and Morris, R., J.: Winter/summer mesopause temperature transition at Davis (69°S) in 2011/2012, Geophys. Res. Lett., 41, 5233–5238, https://doi.org/10.1002/2014GL060777, 2014.

Marsh, D., R., Garcia, R., R., Kinnison, D., E., Boville, B., A., Sassi, F., Solomon, S., C., and Matthes, K.: Modeling the whole atmosphere response to solar cycle changes in radiative and geomagnetic forcing, Journal of geophysical research, 112, https://doi.org/doi:10.1029/2006JD008306, 2007.

Lee, J., N., Wu, D., L. R. A., and Fontenla, J.: Solar cycle variations in mesopheric carbon monoxide, Journal of atmospheric and solarterrestial physics, 170, 21–34, https://doi.org/https://doi.org/10.1016/j.jastp.2018.02.001, 2018.

I report that this manuscript needs further consideration and discussion.

Specific comments

Line 24 on page 4: What is *d*? Because equation (7) shows *d(t)*, it must be a variable parameter depending on time (I expect that *t* stands for time). Can authors change "*d*" to another symbol or acronym because it is very confusing with integral and differential symbols?

Reply: d which we changed now to D is the angular velocity of the Earth. To avoid misunderstandings we didn't choose ω, because it is already used in the equations 1, 5 and 6 as angular velocity for an altitude defined atmospheric layer.

Lines 21 to 24 on page 5: I am suspicious if you can estimate winds at 78 (or below ~85 km) and 100 km by meteor radars. What is an altitude resolution, and every how much in km did authors determine hourly mean winds? Is there any threshold for a determination, such as elevation angle, range, minimum and maximum radial velocities, and minimum number of sampling meteor echoes? Although authors mention uncertainties as "between 2 and 6 m/s", weightings of uncertainties are very different between 50 m/s wind with 6 m/s uncertainty and 5 m/s with 6 m/s uncertainty.

Reply: Some literature to show results for the wind estimation based on specular meteor trails:

Hall, C., Aso, T., Tsutsumi, M., Nozawa, S., Meek, C., and Manson, A.: Comparison of meteor and medium frequency radar kilometer scale MLT dynamics at 70_ N, J. Atmos. Sol.-Terr. Phys., 68, 309–316, https://doi.org/10.1016/j.jastp.2005.03.025, 2006.

Hocking, W. K., Fuller, B., and Vandepeer, B.: Realtime determination of meteor-related parameters utilizing modern digital technology, J. Atmos. Sol.-Terr. Phys., 69, 155–169, https://doi.org/10.1016/S1364-6826(00)00138-3, 2001a.

Jacobi, C., Arras, C., Kürschner, D., Singer, W., Hoffmann, P., and Keuer, D.: Comparison of mesopause region meteor radar winds, medium frequency radar winds and low frequency drifts over Germany, Adv. Space Res., 43, 247–252, https://doi.org/10.1016/j.asr.2008.05.009, 2009.

McCormack, J., Hoppel, K., Kuhl, D., de Wit, R., Stober, G., Espy, P., Baker, N., Brown, P., Fritts, D., Jacobi, C., Janches, D., Mitchell, N., Ruston, B., Swadley, S., Viner, K., Whitcomb, T., and Hibbins, R.: Comparison of mesospheric winds from a high-altitude meteorological analysis system and meteor radar observations during the boreal winters of 2009/2010 and 2012/2013, J. Atmos. Sol.-Terr. Phy., https://doi.org/10.1016/j.jastp.2016.12.007, 2016.

Stober, G., Matthias, V., Jacobi, C., Wilhelm, S., Höffner, J., and Chau, J. L.: Exceptionally strong summer-like zonal wind reversal in the upper mesosphere during winter 2015/16, Ann. Geophys., 35, 711–720, https://doi.org/10.5194/angeo-35-711-2017, 2017.

Wilhelm, S., Stober, G., and Chau, J. L.: A comparison of 11-year mesospheric and lower thermospheric winds determined by meteor and MF radar at 69_ N, Annales Geophysicae, 35, 893–906, https://doi.org/10.5194/angeo-35-893-2017, https://www.ann-geophys.net/35/893/2017/, 2017.

The monostatic meteor radars cover an altitude range between 75 and 110 km and the obtained winds have an hourly temporal resolution and a vertical altitude resolution of 2 km in the applied analysis. Within these altitudes, we are able to detect meteors whereby qualitative good wind measurements are reached between 78 and 100 km. Below 75 km we are limited due atmospheric conditions and above 110 km due to technical limitations.

In these time and height window each meteor is weighted by its statistical uncertainty and by its temporal distance from the centre of the window by using a Gaussian kernel. Further regularization is implemented in the wind estimation, which allows estimating the wind within the windows by having at least 3 meteors. As example in December 2015 we detected ~90.000 meteors between 78 and 100 km for the location of Andenes. These meteors follow a Gaussian height distribution, which leads to detections of ~300 meteors at 90+/-1 km altitude window per hour. At 90 km these meteors are detected within an observational diameter of 425 km and all detected meteors within the diameter are taken for the wind analysis. Of course there are thresholds for the determination, as e.g. elevation angle of zenith < 65°. Further details can be found in then mentioned literature.

Depending on the amount of available detected meteors within the window, the statistical uncertainties of the meteor wind measurements vary between 2 and 6 m/s, whereby values larger than 4 m/s nearly only be reached at the edges of the observation range. In Wilhelm et al. (2017) is shown in Figure 1 an altitude/time distribution of the uncertainties. There its shown that based on the meteor altitude distribution, which includes daily as well as seasonal variations, the statistical uncertainties vary between 2 and 4 m/s between 84 and 94 km.

We don't want to describe the complete wind analysis within this manuscript, therefore we linked to Stober et al. (2017) as well as to Hocking et al. (1999) where the analysis are described in detail.

Line 31 on page 5: Please check a vertical resolution. In my knowledge, Aura/MLS data are every 1.3 km up to 50 km, 2.7 km up to 62 km and 5.4 km above.

Reply: The vertical resolution which we use in this study is ~4 km in the stratosphere and ~14 km in the mesosphere. We added a reference.

Livesey, N.J., Read, W.G., Lambert, A., Cofield, R.E., Cuddy, D.T., Froidevaux, L., Fuller, R.A., Jarnot, R.F., Jiang, J.H., Jiang, Y.B., Knosp, B.W., Kovalenko, L.J., Pickett, H.M., Pumphrey, H.C., Santee, M.L. , Schwartz, M.J., Stek, P.C., Wagner, P.A., Waters, J.W., Wu, D.L., 2007. EOS MLS Version 2.2 Level 2 Data Quality and Description Document. Technical Report, Version 2.2 D-33509, Jet Propulsion Lab., California Institute of Technology, Pasadena, California 91198-8099.

Matthias, V., Hoffmann, P., Rapp, M., and Baumgarten, G.: Composite analysis of the temporal development of waves in the polar {MLT} region during stratospheric warmings, J. Atmos. Sol.-Terr. Phy., 90–91, 86–96, https://doi.org/10.1016/j.jastp.2012.04.004, 2012.

Line 18 on page 6: Juliusruh and Collm are at nearly same location in a global sense. What causes a difference of reversal altitudes by 3 km? Are they systematic difference?

Reply: Even if, on a global sense, Collm and Juliusruh are nearly located on the same latitude, small changes at mid and especially lower latitudes can show strong differences in the transition height. Even if it is not included in this paper, we further compared the mid latitude data with meteor radar data from a Canadian location (43.3 °N), with the result of an even deeper (80 km and blow) vertical wind shear.

Lines 9 to 10 on page 8: How was "the fluctuation in the LOD" obtained? Was it by equation (7)? If so, what is *d(t)*, as asked above? Was *d(t)* obtained from measurements or some simulation models?

Reply: The LOD data are the result from a combination of several intra-technique services, each associated with a given space geodetic technique. One of them is the VLBI technique, which is able to determine the celestial pole and the Earth rotation angle and therefore observes changes in the day lengths. Measurements derived by VLBI consist of simultaneous observations of extra-galactic radio sources by two or more radio telescopes. During a standard VLBI observation of 24 hours, three to eight globally distributed telescopes observe up to 60 extra-galactic radio sources. These sources are located in a distance of 2-12 billion light-years and emit broadband microwave signals which can be assumed as a plane wave front when they arrive at the Earth. These radio sources are e.g., quasars which are active galactic nucliis of very high brightness, and which are so far away that no proper motion of them has ever been observed. Therefore they serve as best available fixed position to a fixed reference. Any change in the Earth's spinning or in the Earth orientation, measured by extra-galactic signals can be determined within a fraction of a millisecond of arc. The use of interferometry between several stations leads to the fundamental geodetic VLBI information. Therefore the LOD can be defined by equation (7).

Thomas, J.: An Analysis of Long Baseline Interferometry. DSN Progress Report, JPL Techniqcal Report, 8, 32–1526, 1972.

Campbell, J.: Very long baseline interferometry., pp. 67–87, Berlin Springer Verlag, ttps://doi.org/doi:10.1007/BFb0010105, 1987.

Boeckmann, S.: Robust determination of station positions and Earth orientation parameters by VLBI intra-technique combination, Ph.D. thesis, Friedrich-Wilhelms-University, http://hss.ulb.uni-bonn.de/diss_online, 2010.

Line 22 on page 8: What is "the F10.7 solar cycle"? Is it the 11-year cycle, the 27-day cycle, or both cycles?

Reply: The F10.7 solar cycle is the 11 –year solar cycle. We further tried to estimate the 27-day-cycle within the zonal winds, but didn't found any correlation. We changed in the manuscript F10.7 solar cycle to F10.7 11-year solar cycle.

Line 29 on page 8: LOD (either length of a day or fluctuation in a length of a day) must have unit of time (probably second from Figures 6 to 8). Why is an LOD unit ms (millisecond or meter times second)?

Reply: ms = milliseconds, we added this in the text.

Line 33 on page 8: Again, please make sure what "the solar cycle" is, 11 year, 27 day, both, or some other cycle? Also, how much does "the solar cycle" influence on a fluctuation of a length of a day? It means how much important to remove a solar cycle influence.

Reply: We added some text to clarify this part: (see 1st point)
According to Abarca-del Rio et al. (2003) an accurate estimation of the impact of the solar radiation is quite complicated, due to the point that internal oscillations in the climate system show variations within the same frequency as the 11 year solar cycle. Further, Gray et al. (2010) supports this statement and mention that the problem is further caused due to the small influence of the solar forcing on the climate. Nevertheless, Chapanov and Gambis (2008) showed that based on a decomposition of the LOD, the solar activity (10.47 years) is included.

Abarca del Rio, R., Gambis, D., Salstein, D., Nelson, P., and Dai, A.: Solar activity and earth rotation variability, J. Geodyn., 36, 423–443, 2003.

Gray, L. J., Beer, J., Geller, M., Haigh, J. D., Lockwood, M.,Matthes, K., Cubasch, U., Fleitmann, D., Harrison, G., Hood, L., Luterbacher, J., Meehl, G. A., Shindell, D., van Geel, B., and White, W.: Solar influences on climate, Rev. Geophys., 48, RG4001, doi:10.1029/2009RG000282, 2010.

Chapanov, Y. and Gambis, D.: Correlation between the solar activity cycles and the Earth rotation, Proc. Journées 2007 "Systèmes de Référence Spatio-Temporels", edited by: Capitaine, N., Obs. De Paris, 206–207, 2008. (https://syrte.obspm.fr/jsr/journees2007/pdf/s4_18_Chapanov.pdf)

Line 12 on page 9: What is "the size range"?

Reply: we corrected the sentence.

Line 25 on page 9: I do not see that the authors showed effects on mesospheric winds by expansion/shrinking of the upper atmosphere in this work.

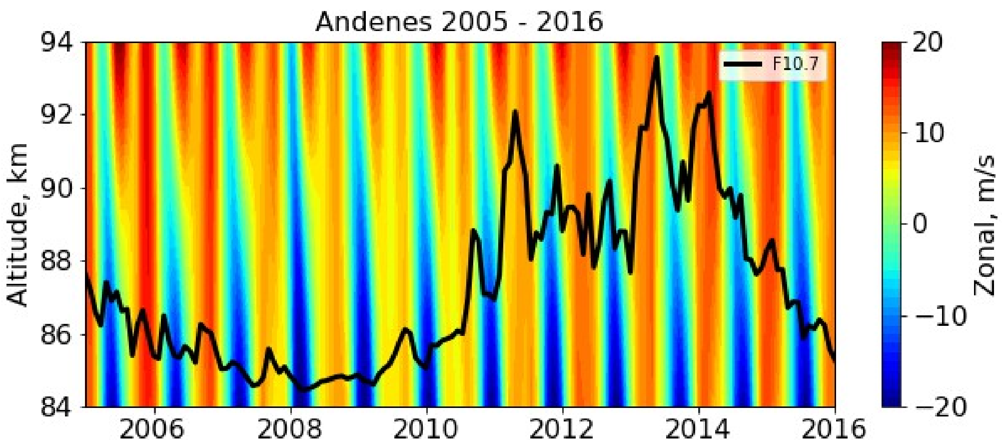
I saw that the authors showed correlations between zonal winds in the mesosphere and fluctuations in a length of a day. Stober et al. inferred that fluctuations in a length of a day are correlated with a variation of a thickness of the upper atmosphere. It is possible to expect that zonal winds in the mesosphere are related to a thickness of the upper atmosphere. Please revise it.

Reply: We added Figure 4 to show a direct connection between fluctuation in the solar radiation and the zonal wind. Based on this and on the results of Emmert et al.

(2004) and Stober et al. (2012) we show the relation between the thickness of the upper atmosphere and the prevailing zonal wind.

We added the text:

To underline this statement, Figure 4 shows, for the location of Andenes, the zonal mean wind between 84 and 94 km together with the F10.7 11-year solar cycle index (black line). An enhancement of the eastward directed wind occurs together with a stronger F10.7 index and more clearly an increase of the westward directed wind together with a smaller F10.7. Furthermore a shift occurs in the summer vertical wind shear, which is also correlated with the solar cycle, whereby a shift to higher altitudes takes place together with a decrease of the solar radiation, due to a change in the neutral density.



Caption Figure4: Zonal mean wind for Andenes for the heights between 84 and 94 km, together with the F10.7 11 year solar cycle index in black.

Emmert, J., T., Picone, J., M., Lean, J., L., and Knowles, S., H.: Global change in the thermosphere: Compelling evidence of a secular decrease in density, Journal of geophysical research, 109, doi:doi:10.1029/2003JA010176, 2004.

Stober, G., Jacobi, C., Matthias, V., Hoffmann, P., and Gerding, M.: Neutral air density variations during strong planetary wave activity in the mesopause region derived from meteor radar observations, Journal of Atmospheric and Solar-Terrestrial Physics, 74, 55–63, doi:10.1016/j.jastp.2011.10.007, 2012.

Figure 2 and 3: Why do they exclude Davis in Figure 2 and southern hemisphere?
Reply: We will add Davis, as well as the southern hemisphere (MLS) in Figure 2 / 3. Further we will add for both locations a description in the text.

Figure 2 and 3 captions: Correct to “positive”.
Reply: corrected

Figure 6: Please describe what black and blue dashed lines are in a caption.
Reply: description is added in the caption.

Technical corrections

General Reply: We thank the referee for the advices. We will correct the mentioned points, and added here for some points few comments for the Referee.

Line 10 on page 1: Do authors use LOD as “length of a day” or “fluctuations in a length of a day” in this manuscript? Line 24 on page 4 says “length of day (LOD)”. However, “LOD” is used in a subsection 3.2 and a caption of Figure 6 although most of them must imply “fluctuation of LOD”, except for lines from 9 to 10 on page 8 say “fluctuation in the LOD”. Please make it consistent.

Reply: LOD is the acronym for the “fluctuation in a length of a day”, which is also used as this in the area of geodesy. We added and corrected parts to make this more clear.

Lines 9 to 10 on page 2: “shrinking of the middle atmosphere between solar minimum and solar maximum” is very confusing. Does the middle atmosphere shrink at the solar minimum, the solar maximum, or both at the solar minimum and maximum?

Reply: We reformulated the sentence and added some more references:

Previous studies as, e.g., Walterscheid (1989), Marsh et al (2007), Emmert (2015), and Lee et al. (2018) showed that solar cycle variations affects the atmospheric density, temperature, chemical composition and winds over the whole atmosphere, but in particular, in the MTI (Mesosphere-Thermosphere-Ionosphere) system.

Later on we wrote that Emmert et al. (2010) showed compared to an average over some solar cycles a decrease in the neutral density during a solar minimum.

Walterscheid, R., L.: Solar Cycle effects on the upper atmosphere: Implications for Satellite Drag, Journal of spacecraft and rockets, 26, 439–444, https://doi.org/DOI: 10.2514/3.26089, 1989.

Marsh, D., R., Garcia, R., R., Kinnison, D., E., Boville, B., A., Sassi, F., Solomon, S., C., and Matthes, K.: Modeling the whole atmosphere response to solar cycle changes in radiative and geomagnetic forcing, Journal of geophysical research, 112, https://doi.org/doi:10.1029/2006JD008306, 2007.

Emmert, J. T.: Altitude and solar activity dependence of 1967-2005 thermospheric density trends derived from obrital drag, Journal of geophysical research: space physics, 120, 2940–2950, https://doi.org/doi:10.1002/2015JA021047., 2015.

Lee, J., N., Wu, D., L. R. A., and Fontenla, J.: Solar cycle variations in mesopheric carbon monoxide, Journal of atmospheric and solar terrestial physics, 170, 21–34, https://doi.org/https://doi.org/10.1016/j.jastp.2018.02.001, 2018.

Line 19 on page 2: Does “conversation” mean “conservation”? yes, it does. -corrected-

Line 8 on page 5: What does “on an in average” mean? – we modified the sentence -

Line 4 on page 6: I feel that “combined 04 data from the international Earth Rotation and Reference System Service (IERS)” is more appropriate. –corrected-, Thanks for the advice.

Line 24 on page 6: “qualitatively”? – corrected -

Lines 24 to 25 on page 6: I do not understand the sentence and suggest revision. – **Reply**: we deleted the sentence, because it causes confusion and were not needed.

Line 30 on page 6: Are MLS data shown in a geopotential height? If so, why "above 90 km" is suddenly described in geometric height?

Reply: The geometric altitudes are approximately estimated from the pressure levels as described in Matthias et al. (2013): h = -7 * ln(p/1000), where h is the altitude in km and p the pressure in hPa. We are aware that there is difference between the geometric and the geopotential heights especially in the MLT. Furthermore, we neglect altitudes above 85 km geometric height for closer investigations, because the obtained winds show larger discrepancies to the local radar measurements. We only used the upper heights for a general validation based on composites to show similarities.

Matthias, V., Hoffmann, P., Manson, A., Meek, C., Stober, G., Brown, P., and Rapp, M.: The impact of planetary waves on the latitudinal displacement of sudden stratospheric warmings, Ann. Geophys., 31, 1397-1415, https://doi.org/10.5194/angeo-31-1397-2013, 2013.

Added text: The geometric heights are approximately estimated from pressure levels as described in Matthias (2013): h = -7* ln(9/1000), where h is the altitude in km and p the pressure in hPa. Furthermore, we are aware about a difference between the geometric and geopotential heights, which increase especially above 80 km. Therefore, we focus in this work on the height range between 60 and 80 km …

Lines 6 to 7 on page 7: It is very ambiguous. Does a density increase occur in summer OR winter, and at the solar minimum OR maximum?

Reply: Figure 4 is a theoretical approach to show changes in the rotation speed, for a defined atmospheric layer, based on changes in the density. For this approach it doesn't matter when the density increase/decrease occurs, it only show the results based on the theoretical change.
Nevertheless, according to Emmert (2010) occurs a density decrease during the time of a solar minimum and a density increase during a solar maximum, respectively.

We reformulated the text:
The density increase takes place for longer time scales during a solar maximum (e.g., Emmert et all, 2010) and on annual time scales during the winter, when the Earth-Sun distance is smaller. Both cases influence the temperature within this atmospheric layer as well as their expansion compared to the annual mean. Overall the density variation during an 11-year solar cycle are stronger than the variation causes due to Earth-Sun distance.

Emmert, J. T., Lean, J. L., and Picone, J. M.: Record-low thermospheric density during the 2008 solar minimum, Geophysical Research Letters, 37, n/a–n/a, https://doi.org/10.1029/2010GL043671, http://dx.doi.org/10.1029/2010GL043671, l12102, 2010.

Line 16 on page 7: Change "the northern and the southern hemisphere" to "the northern and southern hemispheres". –corrected-

Line 16 on page 7: Remove comma between "opposite" and "fluctuations". –corrected-

Lines 20 to 21 on page 7: What is "between two locations on the same latitude"? Does it mean "at the same latitude in the northern and southern hemispheres"?

Reply: we reformulated the sentence: Therefore the prevailing wind within the MLT region should be similar in magnitude between Andenes and Davis, which are located at the same latitude in the northern and southern hemispheres.

Line 21 on page 8: It should be “additionally”. –corrected-

Line 22 on page 8: It should be “relatively”. –corrected-

Line 29 on page 8: Please make sure if “seasonal fluctuation” means “seasonal variation of a fluctuation”, “seasonal means of fluctuation”, or something else. –corrected, Thanks for the advice-

Line 33 on page 8: What does “as result as” mean? –corrected-

Line 19 on page 9: “This reversal can be explain can be explain” must be “This reversal can be explained”. –corrected-

Lines 20 to 21 on page 9: First, “station” on line 21 must be “stations”? What are “the polar and the second midlatitude stations”? “the polar stations” include both Andenes and Davis? Is “the second milatitude station (I think not “stations” in this case)” Juliusruh or Collm? Did the authors define “first” and “second” stations previously?

Reply: We reformulated the part according comments of Ref #1:
In the Figures 10 and 11 are shown long term changes of annual LOD (black) and annual zonal mean winds (red) for Collm and for Davis. At this point, we have to mention that a tendency over a long time series is not linear in time. Parameter which influence the tendency of the wind and the LOD also vary over time and therefore be observed in long time series should be limited within a specific period. Such changes are often be approximated by a piecewise linear trend model (e.g., Tomé and Miranda (2004), Merzlyakov et al. (2009) and Jacobi et al. (2011)), where different linear fit tendencies are estimated for different time periods. Nevertheless, due to the length of the available data series we decide to use no piecewise linear trend model. The wind values exclude seasonal and solar cycle variations and the LOD excludes the seasonal variations. Exemplary for the locations of Collm (Figure 10) the altitudes between 80 and 96 km are displayed. The errorbars corresponds to the annual variance for each height and the dotted lines show the long term tendency for each parameter. The result is that a long term increase of the LOD occurs together with a long term decrease of the zonal wind. Above 94 km the tendency reverses for the mid latitude locations into a slightly positive wind. This reversal can be explain by the stronger influence due to gravity wave filtering, which has to be considered and cannot be excluded by filtering the data. The tendencies of an increased value for the LOD and a decreased value for the zonal mean wind can be seen for all mid latitude locations and also for Davis (see Figure 11). Andenes shows for all altitudes increase tendency in the zonal wind. The results indicates that the connection between the LOD and the wind are more pronounced at lower latitudes, which simply explainable by the rotation velocity, which is higher at the middle latitude stations than at the polar latitudes like Andenes and Davis. The results of an increase of the LOD and a decrease of zonal wind fits to the relation between fluctuations in the neutral density and the zonal wind, as shown Stober et al. (2012).

Tomé, A., R. and Miranda, P., M. A.: Piecewise linear fitting and trend changing points of climate parameters, Geophys. Res. Lett., 31, https://doi.org/doi:10.1029/2003GL019100, 2004.

Merzlyakov, E., G., Jacobi, C., Portnyagin, Yu., I., and Solovjova, T., V.: Structural changes in trend parameters of the MLT winds based on wind measurements at Obninsk (55°N, 37°E) and Collm (52°N, 15°E), Journal of atmospheric and solar-terrestial physics, 71, 1547–1557, https://doi.org/doi:10.1016/j.jastp.2009.05.013, 2009.

Jacobi, C., Hoffmann, P., Liu, R., Q., Merzlyakov, E., G., Portnyagin, Yu., I., Manson, A., H., and Meek, C., E.: Long-term trends, their changes, and interannual variability of Northern Hemisphere midlatitude MLT winds, Journal of Atmospheric and Solar-Terrestrial Physics, 75-76, 81–91, https://doi.org/doi:10.1016/j.jastp.2011.03.016, 2011.

Line 1 on page 10: “hemisphere” must be “hemispheres”. –corrected-

Lines 6 to 7 on page 10: Why do authors specify “the middle latitude stations” as Collm and Juliusruh? Is “the polar station” only Andenes? How about Davis? **Reply:** We added to location of Davis, and corrected the sentence if needed

Line 10 on page 10: “not figured out” must be “not be figured out”. –corrected-

Line 13 to 14: I do not understand this sentence. Please revise it.
Reply: For a better understanding we partly reformulated the conclusion.

Line 1 on page 11: “ssignal” must be “signal”. –corrected-

Line 20 on page 11: “datadata” must be “data”. –corrected-

Connection between the length of day and wind measurements in the mesosphere and lower thermosphere at mid and high latitudes.

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Abstract.

This work presents a connection between the density variation within the mesosphere and lower thermosphere (MLT) and changes in the intensity of the solar radiation. On a seasonal time scale, these changes take place due to the revolution of the Earth around the Sun. While the Earth, during the northern hemispheric winter, is closer to the Sun, the upper mesosphere expands due to an increased radiation intensity, which results in changes in density at these heights. ~~Theses~~ These density variations, i.e. a vertical redistribution of atmospheric mass, have an effect on the rotation rate of Earth's upper atmosphere owing to angular momentum conservation. In order to test this effect we applied a theoretical model, which shows a decrease of the atmospheric rotation speed of about ∼4 m/s in the case of a density change of 1% between 70 and 100 km. To support this statement, we compare the wind variability obtained from meteor radar (MR) and MLS satellite observations with fluctuations in the length of a day (LOD). ~~The LOD is defined as the difference between the astronomical determined time the Earth needs for a full turnaround and a standard day length of 86.400 seconds.~~ Changes in the LOD on time scales of a year and less are primarily driven by tropospheric large scale geophysical processes and their impact on the Earth's rotation. A global increase of lower atmospheric eastward directed winds leads, due to friction with the Earth's surface, to an acceleration of the Earth's rotation by up to a few milliseconds per rotation. The LOD shows an increase during northern winter and decrease during summer, which corresponds to changes in the MLT density due to the Earth - Sun movement. Within the MLT the zonal mean wind show similar fluctuations as the LOD, on annual scales as well longer time series, which is connected to the seasonal wind regime as well as to density changes excited by variations in the solar radiation. Further, we show that, even after removing the seasonal and 11-year solar cycle variations, the zonal mean wind and the LOD are connected, by analyzing ~~trends~~ long term tendencies for the years 2005 - 2016.

1 Introduction

According to the first Kepler's law the Earth travels, in a good approximation, on an elliptic trajectory around the Sun. Within a year the distance between both celestial bodies changes. During the northern hemispheric (NH) winter the range is approximately 3.29% shorter than in the ~~northern hemispheric~~ NH summer. Due to the inverse square law, where the intensity ~~I~~ I of the radiation is inverse proportional to the Earth-Sun distance squared ~~. This~~ this shorter distance between the Sun and the Earth during boreal winter leads to an increased heating of the mesosphere and lower thermosphere (MLT) resulting in an expansion of the MLT and thermosphere, compared to the annual mean. Another effect on the expansion/shrinking of the MLT is given by the variability of solar radiation due to the 11-year solar cycle effect. Figure ~~??~~ 1 shows a scheme of the Earth Sun constellation and the resulting effects, which will be explained in the following. ~~Keckhut et al. (1995) showed the occurrence of a pronounced shrinking of the middle atmospherebetween solar minimum and solar maximum as well as~~ Previous studies as, e.g., Walterscheid (1989), Marsh et al. (2007), Emmert (2015), and Lee et al. (2018) showed that solar cycle variations affects the atmospheric density, temperature, chemical composition and winds over the whole atmosphere, but in particular, in the MTI (Mesosphere-Thermosphere-Ionosphere) system. In a model simulation Marsh et al. (2007) showed, for the whole atmosphere, response to changes in the 11-year solar cycle, with e.g., the result of temperature changes in the lower thermosphere by over 100 K at solar maximum relative to solar minimum. Further they showed the occurrence of tropospheric wind and temperature changes due to changes in the solar radiation. But they also mention that changes in the ~~temperature by 2 K~~climatology due to solar radiation are too complex to be explained by simplified methods. Stober et al. (2014) showed that a solar cycle effect between 2002 and 2013 led to changes in the neutral density within the MLT region by up to 2.5%. Furthermore, satellite measurements showed on global scales a neutral density decrease by up to ∼30% between solar maximum and solar minimum at about 400 km (Emmert et al., 2010). For the winter season 2009/2010 Stober et al. (2012) showed a connection between the neutral density and the expansion/shrinking of the atmosphere by using meteor radar (MR) winds, Lidar and Microwave Limb Sounder (MLS) satellite ~~wind and~~ temperature measurements. Further, they show a strong anti-correlation of neutral air density and prevailing zonal ~~wind~~winds. This indicates that an increase/decrease of the neutral density occurs almost simultaneously with a decrease/increase in zonal wind speed, respectively.

Changes in the thickness of the atmosphere, resulting from differences in the distance between Earth and Sun as well as from solar cycle effects, go along with changes of the Earth~~'~~'s rotation speed. Based on the ~~conversation~~ conservation of angular momentum L, the angular velocity ω for an altitude defined atmospheric layer a, with the thickness $a_o - a_i$, can be estimated by:

$$L = J\omega = \frac{2}{5}\, m\, \frac{{a_o}^5 - {a_i}^5}{{a_o}^3 - {a_i}^3}\, \omega, \tag{1}$$

where J is the moment of inertia for a spherical shell, which rotates about an axis through the center, $a_{o,i}$ are the inner and outer radius of the spherical shell, and m is the atmospheric mass. On this occasion the atmospheric mass is calculated according Trenberth and Guillemot (1994) by

$$m = \int_{r_0}^{\infty} \int_{0}^{2\pi} \int_{-\pi/2}^{\pi/2} \rho r^2 cos\phi \, d\phi \, d\lambda \, dr, \qquad (2)$$

where $\rho = \rho(\lambda, \phi, r)$ is the density of air at longitude λ and latitude ϕ, and r is the distance from the Earth's center, while $r = r_0$ at the surface of the Earth. In a good approximation the Earth's surface can be described as an ellipsoid $r_0^2 = a^2(1 - 2\alpha sin^2\phi)$, where a is the equatorial radius, $\alpha = (a^2 - b^2)/2a^2$ is related to the flattening and b is the polar radius. With respect to the height above the surface z, this results in $r^2 = (a+z)^2(1 - 2\alpha sin^2\phi)$ and $dr = (1 - 2\alpha sin^2\phi)^{\frac{1}{2}} dz$. Further, under the assumption that $\rho = \rho_1(r)\rho_2(\lambda, \phi)$, the atmospheric mass can be derived by

$$m = \int_{0}^{2\pi} \int_{-\pi/2}^{\pi/2} \left[\int_{0}^{\infty} \rho_1(z)(a+z)^2 dz \right] \rho_2(\lambda, \phi)(1 - 2\alpha sin^2\phi)^{\frac{3}{2}} cos\phi \, d\phi \, d\lambda \quad . \qquad (3)$$

The integral with respect to z and the relation to the measurements of the surface pressure p_s can be estimated by solving

$$p_s = \int_{0}^{\infty} \rho_1(z) g(z) \, dr, \qquad (4)$$

where g is the acceleration due to gravity. Considering that ~~g~~ g is a function of height and latitude the total atmospheric mass can be written in numerical terms as $m = 5.22371$ x 10^{15} $\bar{p}_s$, where m is given in kilograms, and $\bar{p}_s$ is given in ~~hectopascal~~hectoPascal, for standard gravity at 45° latitude. More detailed information about the estimation of the total mass of the atmosphere can be found in Trenberth and Guillemot (1994). According to Trenberth and Smith (2004) the total mean mass of the atmosphere is 5.148 $\times 10^{18}$ kg and varies slightly on annual scales mainly due to the amount of available water vapor.

A method to measure variations in the rotation speed of the solid Earth is estimating the time the Earth needs for a full rotation. In the following we define the crust, mantle and core of the Earth as solid Earth. To estimate the percentage of the atmospheric rotation velocity from the solid Earth rotation velocity, their rotation ~~speed~~ rate and their variations are necessary. The time the Earth needs for a full rotation is not constant. The rate of rotation and the orientation of the Earth's axis varies in time and space. Perturbations in the Earth's rotation rate are caused either by external forces, as e.g., the influence of celestial bodies, or by internal torques, which are, e.g., large scale geophysical processes (Brzezinski et al., 2001). These internal torques are a combination of relative movements and mass reallocation of Earth's core, mantle, crust, oceans tides, and the atmosphere. Geographical differences in wind pattern and oceans cause shifts in the air and in the water masses. Earthquakes displacing the Earth's mantle might also influence the Earth's rotation on longer time scales (Carter and Robertson, 1986).

On time scales less than a year the dominant geophysical process to influence the duration of the Earth's rotation is the atmosphere (Volland, 1988). Every large scale momentum exchange of the Earth's atmosphere on the Earth's surface increases or decreases their rotation, due to the law of conservation of total angular momentum within ~~a~~ its system. The total angular momentum of the Earth's atmosphere M can be approximately written as

$$M = \int_v \rho_{apc} L_{apc}\, dV = \int_v \rho_{apc} r \times (u_{rel} + \omega \times r)\, dV, \tag{5}$$

where L_{apc} is the angular momentum of an air parcel of unit mass, ρ_{apc} the density of the air parcel, u_{rel} the relative velocity, and $\omega \times r$ is the velocity due to the rotation of the Earth (Madden and Speth, 1995).

The total angular momentum and the velocities can be split into two parts. The mass part M_ω represents the value the angular momentum would take if the atmosphere ~~would be~~ were vertically and horizontally stationary relative to the ground, and the relative part M_r describes the part of the atmosphere angular momentum that is due to the motion of the atmosphere relative to the Earth's rotation. Following Madden and Speth (1995), Egger et al. (2007), and Driscoll (2010) these parts of angular momentum can be written as

$$M = M_\omega + M_r = \frac{r^4\omega}{g} \int_0^{2\pi} \int_{-\pi/2}^{\pi/2} p_{sfc} cos^3\theta\, d\theta\, d\lambda + \frac{r^3}{g} \int_0^{1000} \int_0^{2\pi} \int_{-\pi/2}^{\pi/2} u_{rel} cos^2\theta\, d\theta\, d\lambda\, dp. \tag{6}$$

Thus, changes in the atmospheric angular momentum depend on the sum of different torques $dM/dt = T_F + T_M + others$. Here T_F is the friction torque, T_M is the mountain torque, and others torques include for example, the gravity wave torque~~. However, the gravity wave torque~~ , which is small compared to the other two mentioned. The friction torque is exerted on the Earth's surface mainly due to frictional forces between the wind and the surface. If eastward directed surface winds are prevailing on a global scale, this torque leads to an increase of the rotation rate due to angular momentum transfer from the atmosphere to the Earth's surface. The mountain torque is based on the surface pressure and orography, and it is the torque which is exerted on the Earth's surface due to a difference of pressure on two sides of a mountain. Both torques vary according to their global location and reach values in the range of 10^{19} Nm ~~(Egger et al. (2007), Driscoll (2010),de Viron and Dickey (2014))~~(Egger et al., 2007; Driscoll, 2010; de Viron and Dickey, 2014). The dominant exchange of the angular momentum between atmosphere and Earth takes place in the atmospheric boundary layer, which, depending on the orography and latitude, has a typical thickness of about 1 km at mid-latitudes (Volland, 1988).

Already in the ~~1960's and 70's~~ 1960s and 70s scientists showed that fluctuations in the orientation of the Earth's rotation axis, on seasonal time scales, are associated with changes in the east-west tropospheric wind on a global scale and therefore accompanied with a transfer of angular momentum between the Earth's crust and the atmosphere (Munk and MacDonald (1961), Lambeck (1978)). Changes in the speed of the Earth's rotation axis can be seen in fluctuations in the duration of a day. These fluctuations have been measured since the 60's 60s using the Very Long Baseline Interferometry (VLBI) technique. They are connected with the length of day (LOD), which The fluctuations in the day length is the difference between the astronomical determined duration of a full day $2\pi/d$ $2\pi/D$ and the standard 86400 SI seconds(Aoki et al. , 1981), whereby D is the angular velocity (Aoki et al., 1981). Henceforth, we use the acronym LOD for the fluctuations in the length of day. The LOD can be written as

$$LOD(t) = \frac{2\pi}{d(t)}\frac{2\pi}{D} - 86400s. \quad (7)$$

Within the estimation of the LOD the sidereal time gets converted into solar time, by taking into account the Earth's position and motion with respect to the stars (Aoki et al., 1981).
Carter and Robertson (1986) studied the influence of geophysical processes of the atmosphere on the duration of a day. They showed that when the globally averaged mean winds from east to west increase, the rotation rate of the Earth decreases and the day gets longer. Rosen and Salstein (1991) showed that the effect of the wind on the LOD decreases with heights, by showing that winds in the atmospheric layer between 1000 and 10 mbar hPa contributes 0.5 ms, from 10 to 1 mbar hPa contributes 0.03 ms, and winds above 1 mbar hPa contributes less than 4 μs to the inter-annual LOD budget. The impact of large scale geophysical processes like, e.g., El Niño (e.g., Dickey et al., 1994) and the stratospheric quasi-biennial oscillation (QBO) can also be seen in the LOD (e.g., Volland (1988), Eubanks et al. (1988)).
On short time scales a change in the Earth rotation can lead to an uneven heating of the Earth's surface, which results to temperature differences between the surface and the atmosphere above. This can further cause convection currents, which leads to pressure differences in the atmosphere and results in a different wind formation, which can influence the day length. On longer time scale and especially on higher altitudes increases the importance of the solar influence. An increase of the solar radiation, which can be caused due to a slowing of the Earth's rotation, leads to an expansion of the higher atmosphere, which further results, due to the conversation of angular momentum, in a slower rotation of the atmosphere. What further needs to be considered is e.g., the influence of volcanic eruptions, which influence the Earth's rotation as well as the atmospheric chemistry/temperature (e.g., She et al., 2015). Changes in these parameters can further lead to changes in the neutral density.

Within this study we focus 5 on heights between 60 and 100 km. These heights are sensitive enough to density changes due to the changes in the intensity of the solar radiation. After we described describe the data we used in this study in Section 2, we show results and discuss the theoretical change of the rotation speed due to an expanding/shrinking atmosphere in Section 3. We will show that due to the expansion/shrinking effect even under the assumption on an in average, of equal density distribution between the northern and southern hemisphere (SH), differences in the prevailing wind occur. Furthermore, we will show a connection between the LOD and the prevailing wind by showing correlations in the MLT region by using MR and MLS data for one polar and two mid latitude locations. We use the LOD data to show~~how deep is~~ , how deep the influence of the solar radiation ~~on the atmospheric rotation speed~~penetrates into the atmosphere. The conclusions are found in ~~section~~ Section 4.

2 Data

The wind data we use in this study are derived from MR and MLS satellite measurements. The MRs are located at the northern high latitude station Andenes (32.5 MHz, 69.3°N, ~~16~~16.0°E, Norway), the ~~northern mid latitude~~ mid-latitude stations Juliusruh (32.5 MHz, 54.6°N, 13.4°E, Germany), and Collm (36.2 MHz, 51.3°N, ~~13~~13.0°E, Germany) on the northern hemisphere and the southern high latitude station Davis (33.2 MHz, 68.6°S, ~~78~~78.0°E, Antarctic). The radars cover an altitude range between 75 and 110 km and the obtained winds have an hourly temporal resolution, and a vertical altitude resolution of 2 km in the applied analysis. At 90 km altitude the observed volume of each radar has a diameter of approximately ∼400 km, and the mean wind above each station is a weighted average over this volume. In the case of the Andenes, Davis and Collm MR data are available ~~since~~ between 2005 and 2016 and for Juliusruh since 2008. We focus on an altitude range between 78 and 100 km where we obtain continuous measurements. The statistical uncertainties of winds are obtained from a fitting procedure by taking into account the number of detected meteors per ~~bin into account~~altitude and time bin, as well as a full non-linear error propagation of the radial wind errors. Therefore the resulting uncertainties for the hourly winds vary in a range between 2 and 6 m/s with larger errors at the edges of the meteor ~~layer~~observations. More information about the all-sky meteor radars and the used wind estimation method can be found in Hocking et al. (2001), Holdsworth et al. (2004) and Stober et al. (2017). For this research, we focus primarily on the zonal wind component, because a connection between winds and changes in ~~LOD~~ day length will be mainly seen in the main rotation direction of the Earth.

In addition to local radar observations, we use satellite data from the Microwave Limb Sounder (MLS) to extend the vertical coverage. MLS onboard the Aura satellite (Waters et al. (2006), Livesey et al. (2015)) has a global coverage from 82°N to 82°S and an useful height range from approximately 11 to ~~97~~ 90 km (261 to 0.001 hPa). The vertical resolution varies between ∼4 km in the stratosphere and ∼14 km at the mesopause ~~. In this work we focus~~ (Livesey et al., 2007). The geometric heights are approximately estimated from pressure levels as described in Matthias et al. (2013): $h = -7 \cdot ln(p/1000)$, where h is the altitude in km and p the pressure in hPa. Furthermore, we are aware about a difference between the geometric and geopotential heights, which increase especially above 80 km. Therefore, we focus in this work on the height range between 60 ~~and~~ to 80 km (if not otherwise specified) to investigate a connection between the LOD and the density depending zonal wind within ~~the northern MLT~~these heights. Daily quasi geostrophic winds for the years between 2005 and 2016 are derived from MLS geopotential height observations. For this study we use ~~two~~ three different horizontal grids ~~cells,~~ which are located around Andenes (~~67-71~~70°N and ~~0-30~~0-20°E) and around Juliusruh/Collm (~~49-53~~50-60°N, ~~0-30~~0-20°E), which are further referred to as northern high and mid latitude station, respectively. For the SH we use a horizontal grid around Davis(70°S, 60-80°E).

Further we use in this study ~~Combined 04 data (IERS) from the International~~ combined data from the international Earth Rotation and Reference ~~Systems Service~~ System Service (IERS). The use of interferometry between several stations, which observe radio sources, leads to fundamental geodetic information as changes in the Earth's spinning or in the Earth orientation (Rothacher (2002), Altamimi et al. (2007), Boeckmann (2010)). Based on these information the mean rotation rate and the astronomical duration of the day were computed ~~(?)~~according to equation 6 (Aoki et al., 1981). The IERS provides uncertainties for the ~~LOD~~ day length measurements which most of the time vary in a range of ∼5~~%~~%. More information about the ~~LOD~~ data provided by IERS and their algorithm to estimate the ~~LOD~~ duration of a day can be found in Bizouard et al. (2017).

3 Results and Discussion

3.1 LOD and neutral air density at the MLT

~~Figure ??~~ Figure 2 shows composites of zonal winds from MR measurements at Andenes, Juliusruh, ~~and Collm~~Collm, and Davis. These data are estimated by using a mean wind adaptive spectral filter (Stober et al., 2017)~~, which~~ . It uses a 1 day sliding window, which mainly ~~suppresses~~ removes the impact of short-term variations, as atmospheric tides and gravity waves. All three ~~stations show~~ NH stations show almost similar wind patterns, with typical mesospheric eastward directed winds during the winter, with mean values of up to 10 m/s, and a wind reversal during spring. The spring wind reversal occurs earlier at mid latitudes than at polar latitudes. During the summer ~~a~~ considerable vertical wind shear is present with westward directed winds below 90 km for Andenes, below 88 km for Juliusruh, and below 85 km for Collm. Above these heights a strong eastward jet occurs. The westward and the eastward jets reach wind values of up to 40 m/s at all three locations. These annual wind climatologies are consistent with previous studies e.g., Manson et al. (2004), Hoffmann et al. (2010), and Jacobi (2012). Compared to Andenes a nearly opposite wind pattern can be seen for Davis. A dominant eastward directed wind occurs between March and September for the complete observation range. Between September and March occurs a vertical wind shear, which reaches around October heights above 100 km. Compared to the NH stations the summer vertical wind shear remains more below 90 km.

Besides the radar data we additionally use MLS data within this study to extend the vertical coverage down to 60 km. In Figure ~~??~~ 3 the zonal wind is shown for the high latitude location of Andenes~~and~~ , for middle latitudes at Collm ~~. In both cases the~~ and for the southern latitude location Davis. The altitude ranges between ∼60 and ∼~~97 km geopotential heights~~90 km geopotential height. A comparison of the MLS composite winds with MR composite winds results ~~, below 90 km, in a qualitativ good agreement of~~ in a qualitatively good agreement for the seasonal amplitudes and phases. ~~Above that height differences occur, which are based on the use of the geopotential height, as well as on the higher resolution of the meteor radar. Nevertheless, both Figures~~ Both NH locations show eastward directed ~~wind~~ winds between September and April for nearly all altitudes, with values of up to 40 m/s for the high latitude area and up to 60 m/s for the midlatitudes. During summer westward directed wind dominates below 95 km and reaches values of up to 30 m/s for the high latitudes. For the middle latitude, below 90 km, the wind reaches values of up to 50 m/s. A similar pattern of an eastward directed wind occurs in both cases during summer above 90 km geometric height. The SH location also shows similar wind pattern as the observed MR data. In the following discussion we will focus on the MLS altitude range 60-80 km and use the MR data for the altitudes between 80 and 100 km.

According to previous studies as e.g., by Emmert et al. (2004) and Stober et al. (2012), a connection exists between the thickness of an atmospheric layer and the density fluctuation within that layer. Stober et al. (2012) explained the occurrence of this connection by showing variations in the neutral density, based on MLS and MR observations, together with changes in the MLT geometric height. Furthermore they showed a strong anti-correlation between the simultaneous occurrence of the zonal wind and the density change within the mesosphere. ~~Therefore within the~~ To underline this statement, Figure 4 shows, for the location of Andenes, the zonal mean wind between 84 and 94 km together with the F10.7 solar radio index (black line). An enhancement of the eastward directed wind occurs together with a stronger F10.7 index and more clearly an increase of the westward directed wind together with a smaller F10.7. Furthermore a shift occurs in the summer vertical wind shear, which is also correlated with the solar cycle, whereby a shift to higher altitudes takes place together with a decrease of the solar radiation, due to a change in the neutral density. In the following part we investigate a potential connection between the expanding MLT and the atmospheric rotation speed. Figure ~~??~~ 5 shows, as an example, the theoretical variation in the atmospheric rotation velocity with height due to a density increase up to 1% between 70 and 100 km. The calculation is done in 2 km height layers. The density increase ~~in the MLT should correspond to the impact of fluctuations in the solar intensity between summer and winter, or between a solar minimum and solar maximum, which~~ takes place for longer time scales during a solar maximum (e.g., Emmert et al., 2010) and on annual time scales during the winter, when the Earth-Sun distance is smaller. Both cases influences the temperature within this atmospheric layer as well as their expansion compared to the annual mean. Overall the density variation during an 11-year solar cycle are stronger than the variation causes by the changes of the Earth-Sun distance. According to equations ~~1~~ 1 - ~~4~~4, we estimated for three different cases (linear (red), exponential (green) and a ~~gaussian~~ Gaussian shape (blue) density increase) the resulting theoretical change in the rotation speed within these heights, with the solid Earth rotation speed (black) as background flow. Based on the conserved quantity of the angular momentum within a narrow atmospheric layer (2 km vertical) this sums up, according to each case, to a decrease of the rotation speed by up to ∼2-4 m/s, with the strongest variation within the ~~gaussian shape~~ Gaussian shaped curve. These results fit to the observations ~~from~~ by Stober et al. (2012) and show the dependence of the rotation speed within an atmospheric layer due to changes in the neutral density.

However, only based on wind measurements we are not able to extract a specific wind value.

Based on ERA40 data, Trenberth and Smith (2004) showed that the global mean of the surface pressure is nearly constant, and surface pressure anomalies at the northern and the southern ~~hemisphere~~ hemispheres are nearly identical, but ~~opposite, fluctuations~~ the fluctuations are opposite in sign. These anomalies are mainly ~~derived~~ due to the changing amount of available water vapor in the atmosphere. Under the assumption of opposite surface pressure anomalies within both hemispheres and therefore by neglecting other factors as e.g., different gravity wave forcing between the hemispheres, we assume, on annual scales, similar pressure values within the MLT region. Therefore the prevailing wind within the MLT region should be similar in magnitude between ~~two locations on~~ Andenes and Davis, which are located at the same latitude in the northern and southern hemispheres. To underline the influence of the intensity of the solar radiation on the density and also on the amplitude of the zonal wind, we compare the temporal development of the seasonal mean wind measurements from the ~~northern hemispheric~~ NH station Andenes (69.3°N) and ~~southern hemispheric~~ SH station Davis (68.3°S). Figure ~~?? shows~~6 shows, for both stations, the winter and summer mean wind for the altitudes at 88 and 96 km. The northern winter includes the mean of the months December, January and February, and the southern winter the months June, July and August. The northern winter period comes along with the perihelion, which is the point where the Earth comes nearest to the Sun. At the perihelion the intensity of the solar radiation on the upper atmosphere is higher as during the aphelion. While during the winter season the wind values are higher ~~in~~ over Davis for both altitudes, they are higher ~~in Andenes during~~ over Andenes during the summer season, especially at 96 km, with values of up to 10 - 20 m/s. Both seasonal wind differences are consistent with the change in the average density within the upper mesosphere, resulting from the different distance between Earth and Sun and leading to the variation of the averaged zonal wind, as shown in Stober et al. (2012). We have to note that beside many others factors, this is only one reason, and by far not the dominant factor, for the wind differences between both locations at theses altitudes. ~~For a closer understanding of this phenomena global density observations are required and therefore we can not say~~ Other physical processes have also a strong effect on the hemispheric wind differences e.g., the topography, chemical composition of the atmosphere (Marsh et al. (2007), Lee et al. (2018)), and the occurrence and propagation of gravity waves. These waves are the main drivers of the atmospheric wind circulation and therefore also influence the local wind differences at both hemispheres. Furthermore, gravity waves lead, compared to the annual mean, to a colder summer mesosphere and a warmer winter mesosphere (e.g., Lübken et al., 2014) . These temperature differences also fit well to the atmospheric expansion/shrinking. Unfortunately, based only on wind measurements we are not able to estimate a precise value on how strong the ~~effect is .~~

connection is between zonal mean wind with the LOD. For a more detailed understanding of these phenomena global density observations would be required.

3.2 Correlation of mean winds and LOD

In the following we want to show that the LOD (fluctuations in the length of a day) correlates with the prevailing wind from the ~~three northern hemispheric~~ four stations. If the Earth's rotation is constant the LOD should be zero, however, small wobbles of the Earth's rotation between the days ~~causes tiny deviation~~ cause tiny fluctuations in the day length. These have to be compensated by a momentum transfer between the different parts of the Earth ~~to~~ including the atmosphere. As the atmosphere is slaved to the Earth crust, because the atmospheric momentum and mass are much smaller than of the Earth core, the atmosphere has to respond to changes in the rotation velocity and at least the troposphere can trigger an own feedback on the LOD. So far we use the LOD ~~just~~ explicitly as reference for the changes in the rotation speed, which can be seen in the zonal wind, as well as to verify up to which height the solar driven density effect is dominant. Therefore the next two Figures ~~?? and ??~~ 7 and 8 show wind values for Andenes~~and Collm~~, Collm, and Davis at different altitudes and the ~~fluctuation in the~~ LOD by using the same ~~smoothing~~ filtering method as done for the winds. Two different altitudes in the MLT are considered from the MR winds for all locations: (1) 80 km, where within a year a change between eastward and westward directed wind occurs, and (2) 96 km~~for both locations~~, the altitude where the wind, during ~~the~~ each hemispheric summer shows the opposite direction as at 80 km (see Figure ~~??~~2). Positive wind values ~~corresponds~~ correspond to eastward directed winds and positive

LOD values ~~corresponds~~ correspond to a longer duration of the day. If not explicit mentioned, the results of the two ~~mid latitude~~ mid-latitude stations are nearly identical. Therefore we only show the results for the location around Collm.

~~At the altitude of~~

At 80 km (Figure ~~??~~7) the oscillation pattern of the smoothed zonal wind (blue) and the smoothed LOD (black) are similar for Andenes. According to previous studies the LOD consists of superpositions of ~~serval~~ several periods, as 0.5 years, 1 year (see also Vondrák and Burša, 1977), 2-3 years (Buffet, 1996), 5.9 years (Abraca del Rio et al., 1999) and ~~other~~ others (e.g., Munk and MacDonald (1961), Holme and de Viron (2013)). ~~Although, the~~ According to Abarca-del Rio et al. (2003) an accurate estimation of the impact of the solar radiation is quite complicated, due to the fact that internal oscillations in the climate system show variations with the same frequency as the 11 year solar cycle. Further, Gray et al. (2010) support this statement and mention that the problem is further complicated due to the small influence of the solar forcing on the climate. Nevertheless, Chapanov and Gambis (2008) showed that based on a decomposition of the LOD, the solar activity (10.47 years) is included. Also the zonal wind includes a superposition of several periods as the solar cycle, diurnal, and semidiurnal tides and more (e.g., Emmert et al. (2010), Hoffmann et al. (2010)). Therefore, we ~~additional~~ additionally show with the red line a smoothed zonal wind after removing variations due to the ~~F10.7~~ 11-year solar cycle. The influence of the solar cycle on the daily zonal wind is ~~relativ~~ relatively small, therefore the smoothness of the red line is ~~stronger for the~~ enhanced for better visualization. Changes in the LOD are sluggish compared to variations in the wind, due to the amount of momentum which is needed to influence the Earth's rotation speed. According to e.g., Dickey et al. (1994), a direct effect between the stratospheric and tropospheric zonal wind and the day length exists, on annual time scales due to long term geophysical effects, as e.g., QBO and El Niño. They found that the stratosphere cannot be neglected in the Earth's angular momentum. Around 20% of the LOD relative to the atmosphere below 100 hPa, belongs to the impact of the stratosphere. Furthermore, they mentioned a small lag (10 - 20 days) between the LOD and variations in the angular momentum, but the lag does not appear to be statistically significant. Therefore only comparisons on seasonal and longer time scales are useful to be considered. All parameters which are displayed in Figure ~~??~~ 7 show a seasonal pattern~~, with~~ . First we describe the results for the NH stations. For the NH the zonal wind and the LOD shows decreasing values during summer and increasing values during winter. Beside the striking seasonality, short time fluctuations within a year are observable during the winter in the zonal wind for some years. During the winter of 2010 and 2011, and on even shorter time scales as few months during the winter 2006, 2014 and 2015, decreases in the LOD together with decreases in the zonal wind are visible. The LOD varies between -1 and 4 ~~ms~~milliseconds. The LOD oscillation shows seasonal ~~fluctuations~~ variations of a fluctuation with shorter day lengths during NH summer and longer day lengths during winter, which fits to the density increase and decrease of the MLT as described above. For the ~~mid latitude~~ midlatitude station the oscillation pattern in the LOD and the wind are qualitatively similar, but shifted in time. The wind peaks occur earlier in the year than the LOD peaks, which goes along with the earlier wind transition at ~~the mid latitude~~midlatitudes, which can be seen in Figure ~~??. Removing variations of the solar cycle shows a similar pattern as result as with the impact of the solar cycle. For the MLS observations the comparison between the~~ 2. For Davis a time shift of approximately half a year occurs between the zonal wind and the LOD~~are similar to the 80 km meteor results. Beside the dominant seasonal cycle in the wind regime as well as in the LOD, also short time fluctuations occur at both locations (not shown here), but with lower heights the influence~~

of the density variation , due to the solar radiation is decreasing.opposite seasonal wind pattern.

In the summer wind transition altitude , which is in the case of Andenes roughly at 88 km, for Juliusruh at 86 km and for Collm at 84 km (see Figure ??) a time shift occurs between both parameters. The altitude of the wind transition in these cases is defined as the height between the above located eastward and the below located westward wind during summer. At these heights the wind and the LOD seems almost not to be correlatedare almost uncorrelated. Above the summer wind transition altitude the oscillation pattern between the LOD and the winds are quite the opposite than for 80 km altitude, with a 180° shift between both parameters, which can be seen in Figure ??8. The phase shift, which is pronounced during the summer, obviously results from the opposite wind regime compared to the 80 km altitude. Nevertheless, above the transition height, changes in the density, due to the intensity of the solar radiation, are more sensitive pronounced than at lower heights. Therefore the existing seasonal wind pattern fits well to the atmospheric density increase and decrease at these layers.

According to Figure ??, we showed that already a density change of 1 % results in wind changes in the size range of a few m

Additionally, we show in Table 1 correlation coefficients for the 4 locations for the altitudes between 80 and 98 km. Positive correlation values correspond to the occurrence of an eastward directed wind together with an increased LOD. The values of the NH follow a similar pattern, with positive coefficients below the vertical transition height and negative above. Davis shows a different pattern, with overall negative correlation coefficients. This is owing to the opposite zonal wind pattern compared to the NH. Theoretical, a time shift of ∼ half a year would lead to a similar correlation pattern as in the NH.

Figure 9 shows, the mean zonal wind at ∼80 km geometric height, based on MLS data, and the LOD. These mean zonal winds include wind values within the longitude grid between 0°E and 20°E, which is comparable to the NH stations. The Figure is divided in 10° latitude steps centered at latitudes from 80° to 10°S/s. Though to prove this, it is necessary to distinguish between further natural factors and density variations and we are also not able to estimate the influence of N. Each latitude grid includes values for +/- 6°. For the MLS observations the comparison between the wind and the LOD are similar to the 80 km meteor results at the respective latitudes. Furthermore, the occurrence of half a year time shift between both high hemispheres can be seen. A 180° phase shift would lead to the wind-LOD pattern of the opposite hemisphere. Furthermore, the radius on the velocity due to lack of global density measurements. Nevertheless, we show in Figure ?? the development of the LOD, and therefore indirect of the density, together with the zonal wind. We show here for Collm, annual mean values for the zonal wind strongest correlation between both parameters can be seen at northern polar latitudes. Due to an increase in the difference between the geometric and geopotential heights, we do not show comparisons for higher altitudes. Further, we added correlation coefficients between the zonal mean wind and the LOD for each latitude. A correlation increase towards the northern high latitudes is visible. The same would be seen if a 180° phase shift is added to the time series.

In the Figures 10 and 11 are shown long term changes of annual LOD (black) and annual zonal mean winds (red) and the LOD (black), after removing the for Collm and for Davis. At this point, we have to mention that the tendency over a long time series is not linear in time. Parameter which influence the tendency of the wind and the LOD also vary over time. Such changes are often be approximated by a piecewise linear trend model (e.g., Tomé and Miranda (2004), Merzlyakov et al. (2009) and Jacobi et al. (2011)), where different linear fit tendencies are estimated for different time periods. Nevertheless, due to the length of the available data series we decided not to use a piecewise linear trend model. The wind values exclude seasonal and solar cycle variations ~~, for the heights~~ and the LOD excludes the seasonal variations. Exemplary for the locations of Collm (Figure 10) the altitudes between 80 and 96 km are displayed. The error bars correspond to the annual variance for each height and the dotted lines show the long term tendency for each parameter. Figure 10 shows that a long term increase of the LOD occurs together with a long term decrease of the zonal wind. ~~Further we added tendency lines , which show for the LOD an increase between the years 2005 and 2015, while the wind trend shows up to 94 km a decrease.~~ Above 94 km the ~~trend turns~~ tendency reverses into a slightly positive wind~~incline~~. This reversal can be explain ~~can be explain by~~ by the stronger influence due to gravity wave filtering, which ~~we can not exclude this consideration. Furthermore, the same effect~~ has to be considered and cannot be excluded by filtering the data. The tendencies of an increased value for the LOD and a decreased value for the zonal mean wind can be seen ~~at the polar and the second midlatitude station for all observed altitudes, with the result of and overall negative wind trend for~~ for all ~~altitudes~~mid latitude locations, and also for Davis (see Figure 11). Andenes shows for all altitudes increase tendency in the zonal wind (not shown). The results ~~show~~ indicate that the connection between the LOD and the wind are more pronounced at lower latitudes, which ~~can be explained by the influence of the radius on the~~ is simply explainable by the rotation velocity, which is ~~much~~ higher at the middle latitude stations than at ~~Andenes.~~ the polar latitudes like at Andenes and Davis. The results of an increase of the LOD and a decrease of zonal wind fits to the relation between fluctuations in the neutral density and the zonal wind, as shown in Stober et al. (2012).

4 Conclusion

Within this work we show that the mesospheric winds are affected by an expansion/shrinking of the upper atmosphere that takes place due to changes in the intensity of the solar radiation, which effects the density within the atmosphere. A reason, besides the solar cycle effect, is the annual movement of the Earth around the Sun, which leads to a smaller distance between both celestial bodies during the ~~northern hemispheric~~ NH winter, and a longer distance during summer. This leads to a shrinking/expansion of the atmosphere during the ~~northern hemispheric~~ NH summer/winter. This shrinking effect takes mainly place in the upper ~~at mosphere~~atmosphere, where the amount of mass is small enough to be sensitive ~~enough~~ to changes to the intensity of solar radiation, as well as temperature changes. ~~We~~ According to Stober et al. (2012) an increase of the neutral density together with a decrease of the zonal wind in the MLT region occurs. Based on these findings we showed that a theoretical density increase by 1% between 70 and 100 km leads to a decrease in the atmospheric rotation speed, within a defined layer, by up to 4 m/s. The influence of the Earth-Sun distance on the wind speed was further investigated using winds from ~~in total four station~~four stations in total, whereby two stations are located at similar high latitudes for the northern and southern ~~hemisphere.~~ hemispheres. The other two locations are located at the northern midlatitudes. Based on summer and winter mean wind, we found that during the perihelion, where the MLT expands, a decrease in the zonal wind speed for the respective location occurs together with an increase in the LOD. During the opposite aphelion, an increase in the zonal wind occurs beside ~~an~~ a decrease in the day length.

Further

Further, we showed that even after removing the seasonal and the solar cycle (F10.7) variations these parameters 11 year solar cycle variations the zonal wind and the LOD (fluctuations in the length of a day) are connected. We showed the annual tendency development over the whole time period, with the result of an increasing LOD trend together with and more pronounced westward directed wind tendency for the middle latitude stations. This effect weakens at the polar station, which is on the one hand due to a smaller radius, which effects the rotation speed of the atmospheric layer. On the other hand, there are further natural factors, as e.g., the gravity wave drag, who strongly influence these tendencies. Further, we were only able to investigate the connection between theses parameters on time scales which are at least one year. On shorter time scales a connection between the LOD and the winds can not be figured out, the LOD consists of oscillations with at least half a year period and with the current available data we are not able to fully resolve the superpositions of both parameters. Future work remains necessary to fully understand these effects when global density data measurements are available. Additional, in future work the estimation of a time lag between the LOD and the winds needs to be considered.

Additionally, we do not want to state that the tropospheric wind LOD drives the mesospheric zonal wind, neither that the wind drives the LOD . We want to mention that based on our findings a connection between both parameters occursthe zonal wind and the LOD exists, which we explain by the variation of the available atmospheric density. Further on the one side we only compare on the one side global LOD data with local measurements, and on the other side there are way stronger geophysical effects which drives the wind regime in theses at these altitudes. Within this work we only want to point on this effect, and for closer investigations we need global longtime density data.

Data availability.

The Andenes/Juliusruh radar data are available upon request from Gunter Stober (stober@iap-kborn.de).

The Collm radar data are available upon request from Christoph Jacobi (jacobi@rz.uni-leipzig.de)

The Davis radar data are available upon request from Damian Murphy (Damian.Murphy@aad.gov.au)

Authors contributions.

Sven Wilhelm wrote the manuscript with input from all authors. Gunter Stober provided thigh resolution meteor wind data for all stations and ensured the operation of the Andenes and Juliusruh meteor radar. Christoph Jacobi ensured the operation of the Collm meteor radar and Damian Murphy the Davis meteor radar. Vivien Matthias provided the used mircowave limb sounder data. Furthermore contributed all co-authors with the data interpretation.

Competing interests.

The authors declare that they have no conflict of interest. C. Jacobi is one of the Editors-in-Chief of Annales Geophysicae.

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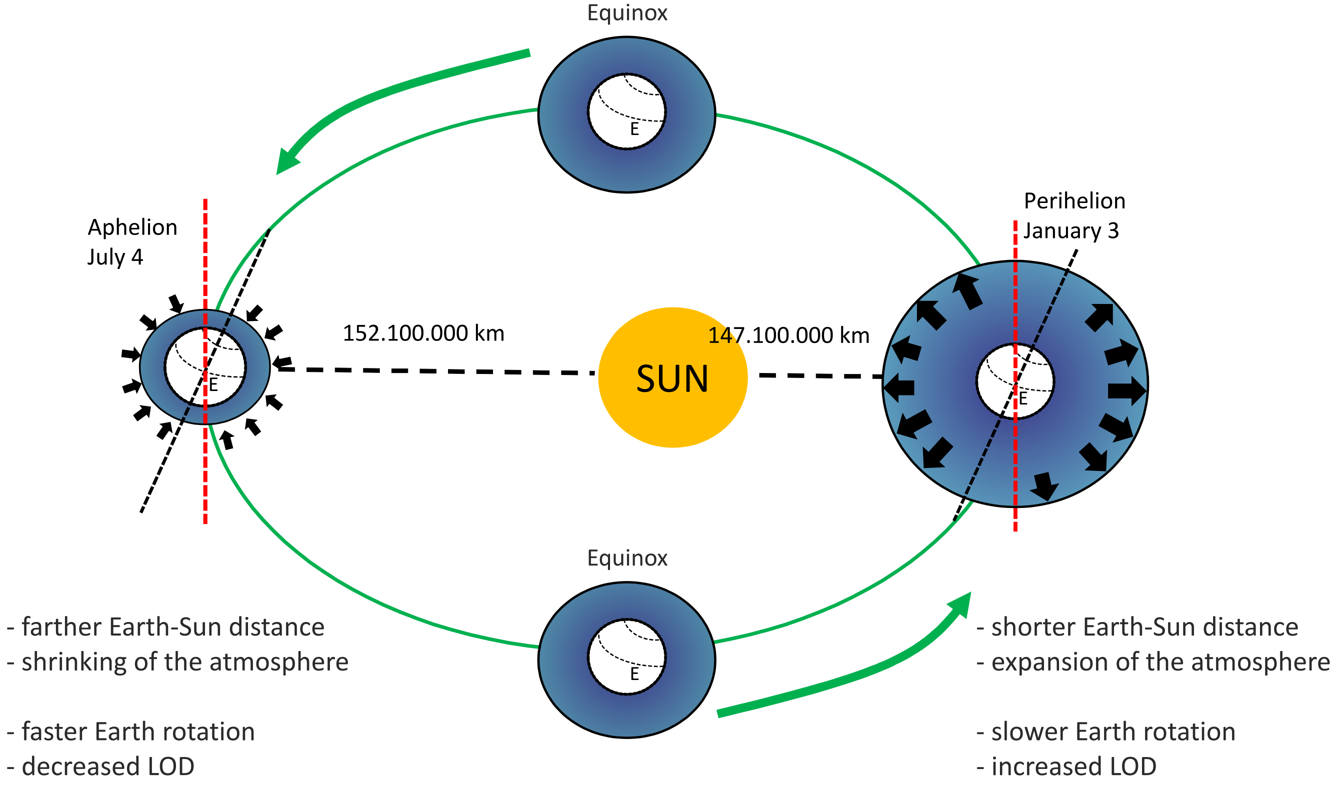

Figure 1. Schema of Earth and Sun correlation and the resulting effects on the thickness of the atmosphere and the Earth's rotation velocity.

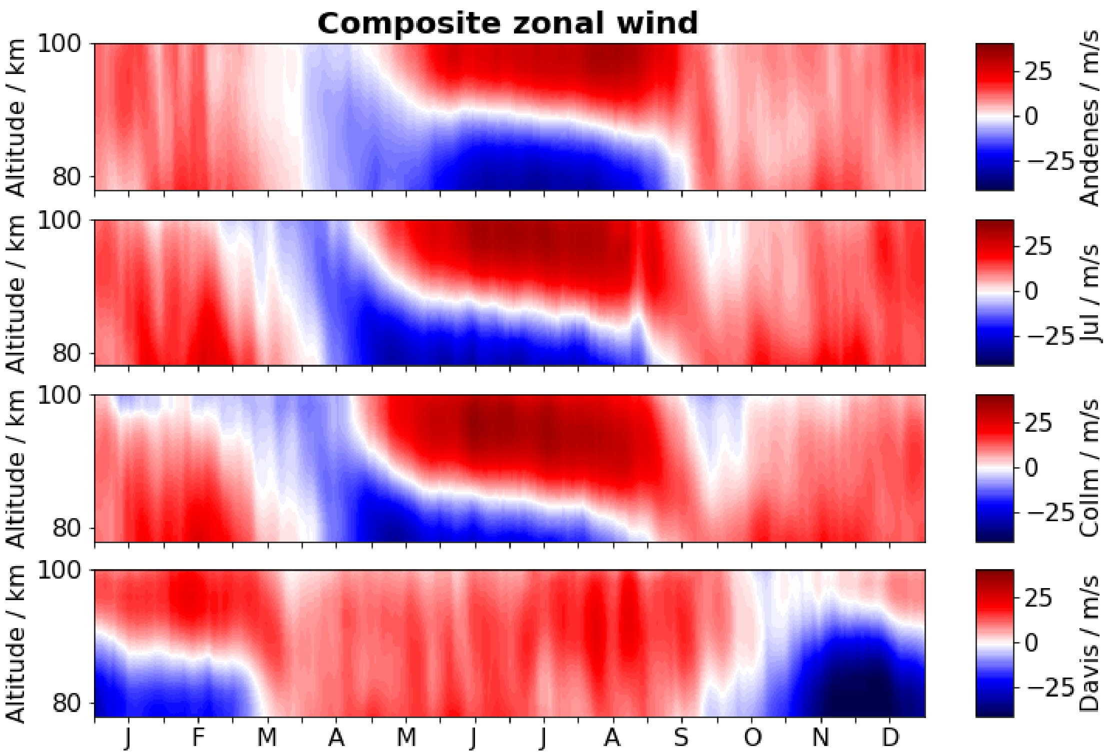

Figure 2. Composites of zonal wind for the northern hemisphere stations Andenes (top), Juliusruh (~~mid~~2nd row), and Collm (~~bottom~~3th row). At the bottom is shown the southern hemispheric station of Davis. The composite for Andenes~~and~~ , Collm, and Davis include 12 years of meteor radar data and that of Juliusruh 9 years. ~~Positiv~~ Positive values correspond to eastward directed winds and negative to westward directed winds.

km	80	82	84	86	88	90	92	94	96	98
Andenes	0.57	0.56	0.52	0.42	0.21	-0.13	-0.45	-0.61	-0.67	-0.69
Juliusruh	0.43	0.36	0.23	0.04	-0.23	-0.48	-0.62	-0.67	-0.68	-0.68
Collm	0.3	0.19	-0.01	-0.3	-0.54	-0.65	-0.68	-0.68	-0.66	-0.64
Davis	-0.37	-0.37	-0.38	-0.39	-0.41	-0.42	-0.41	-0.38	-0.35	-0.32

Table 1. Correlation coefficients between the zonal wind and the LOD. Positive values corresponds to the occurrence of e.g., an eastward directed zonal mean wind together with a positive fluctuation in the LOD.

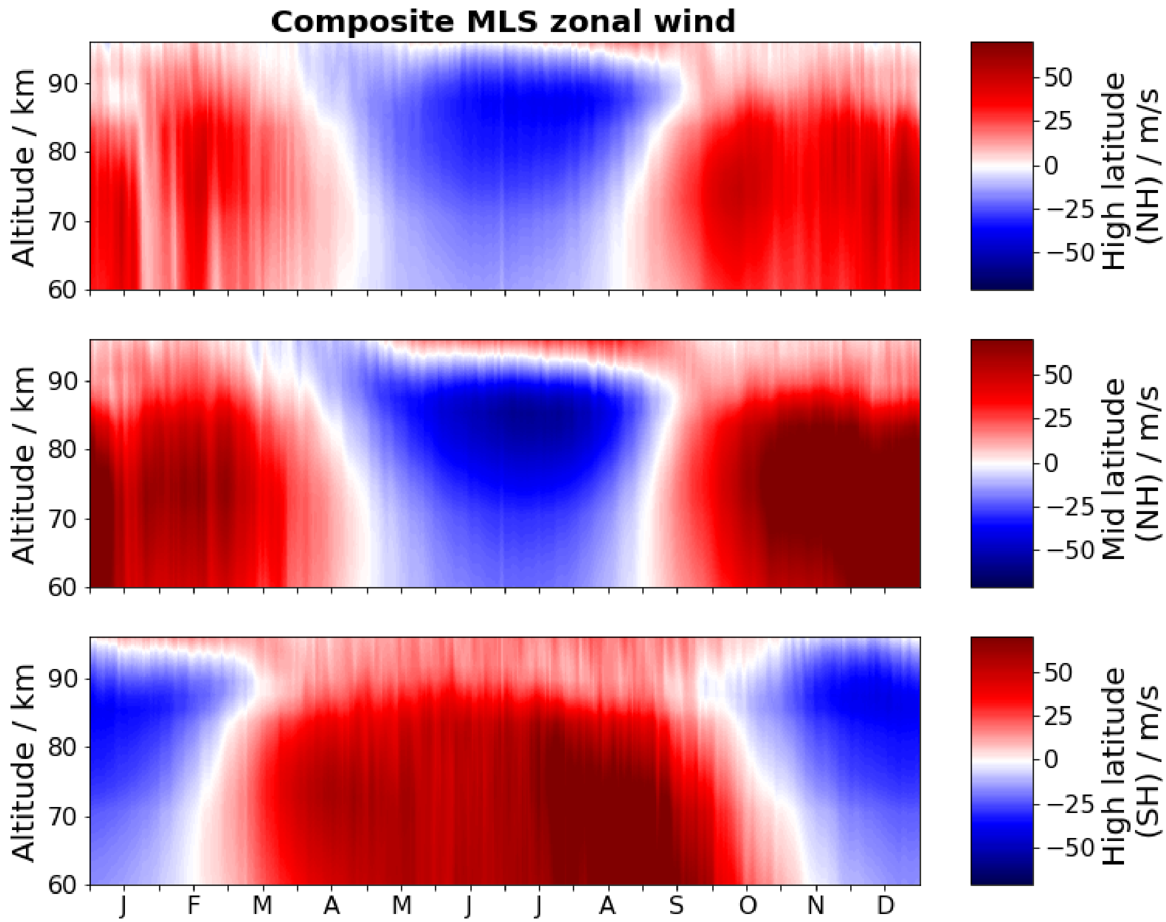

Figure 3. Composite of zonal wind for high latitude location (top), and mid latitude location (bottom). The composite of both figures includes 12 years of data wind data derived from MLS geopotential height data. ~~Positiv~~ Positive values corresponds to eastward directed winds and negative to westward directed winds. The altitude is given in geopotential height.

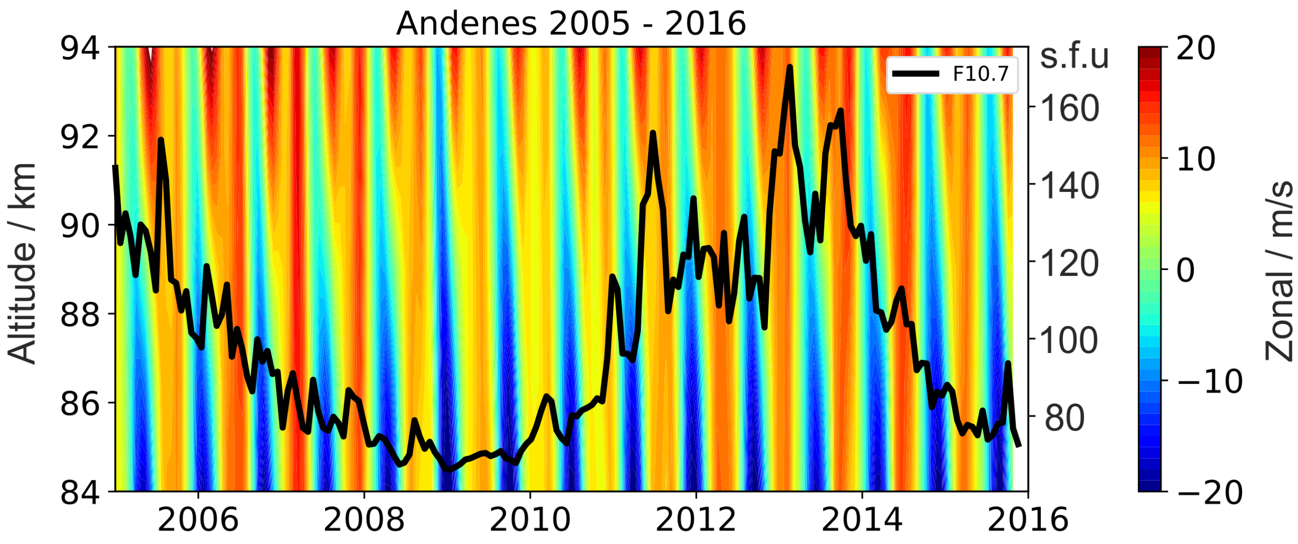

Figure 4. Zonal mean wind for Andenes for the heights between 84 and 94 km, together with the F10.7 solar radio index in solar flux units in black.

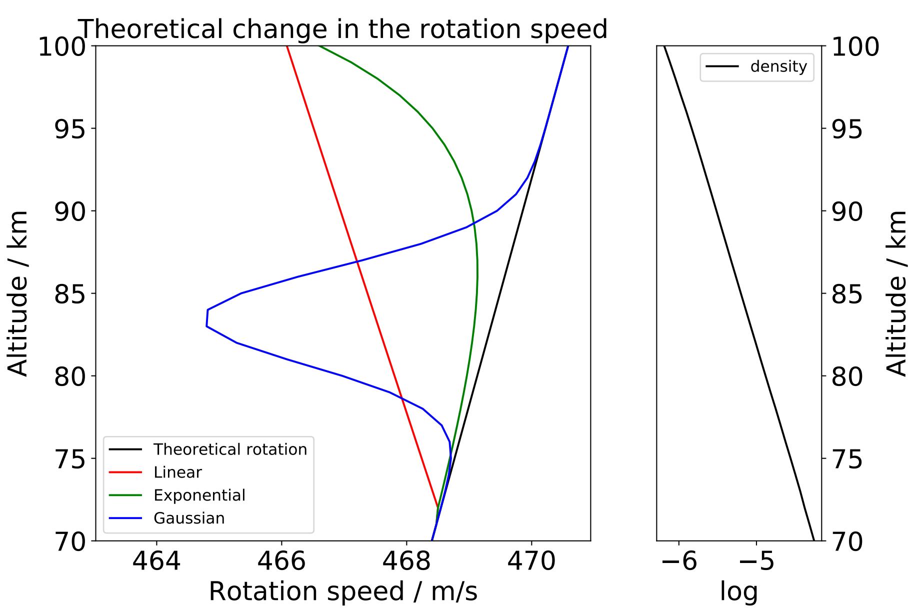

Figure 5. Theoretical change of the rotation speed (left side) for a rigid atmospheric layer. In black the theoretical rotation speed of the Earth's atmosphere and in colors the change due to density increase of 1% according the legend. On the right side the density progress is shown for specific altitudes.

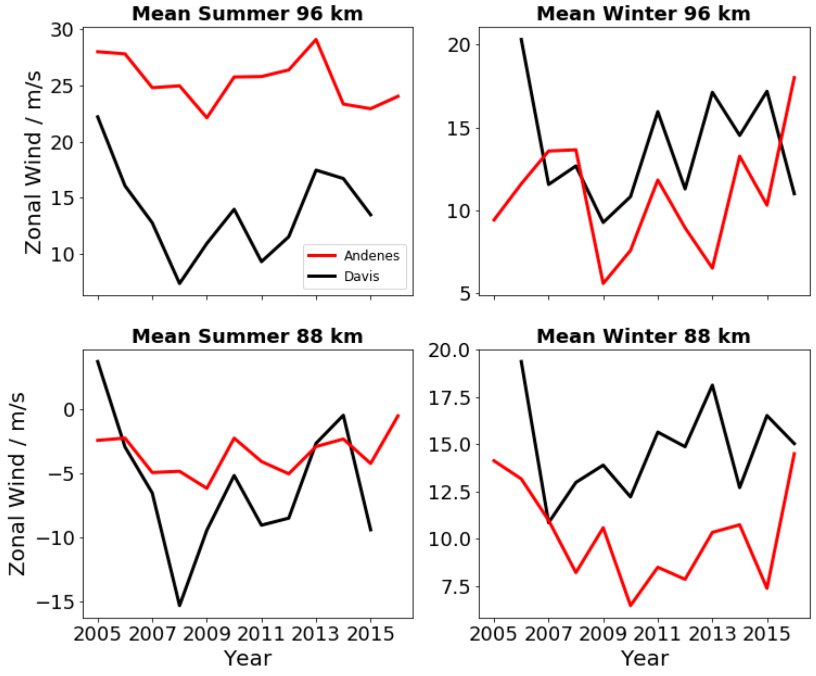

Figure 6. Zonal wind amplitudes for winter and summer season at 96 km and 88 km for Andenes and Davis.

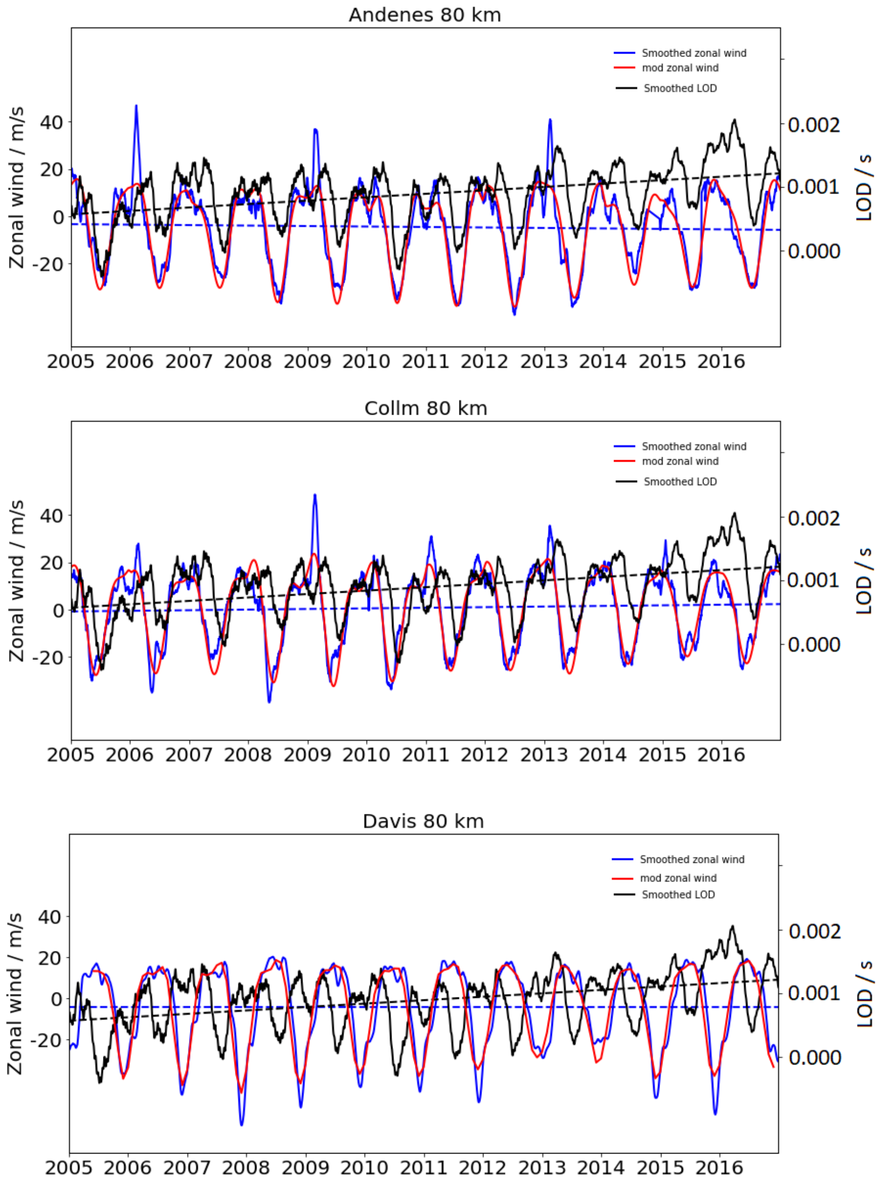

Figure 7. Smoothed zonal wind (blue) values based on meteor radar wind data at 80 km and smoothed LOD (black) values. The modulation of the smoothed zonal wind is displayed in red after removing the impact of the solar cycle, whereby the smoothing is stronger as in blue. All curves are done by a smooth over several days, without removing the day-to-day variations, to show the seasonal pattern of the parameters. The dashed lines corresponds to the tendency of the wind/LOD based on linear regression.

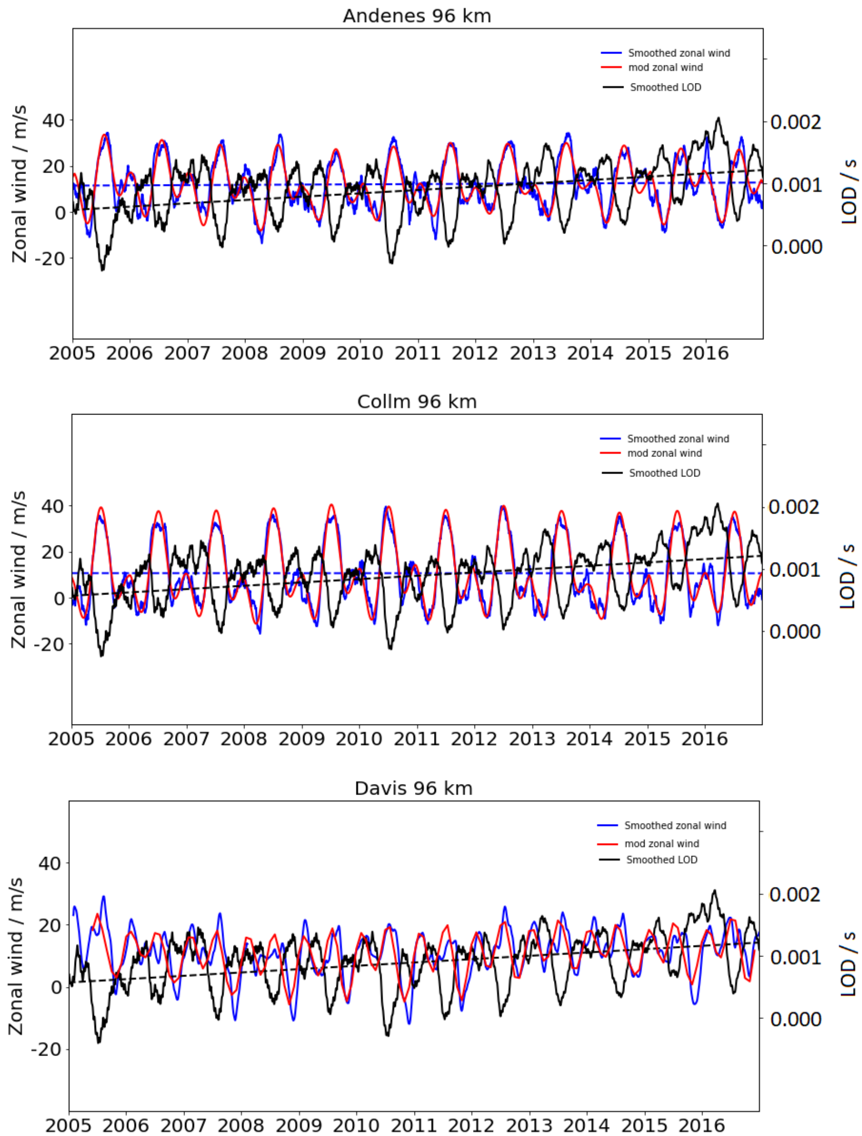

Figure 8. Same as Figure ??7, but for 96 km.

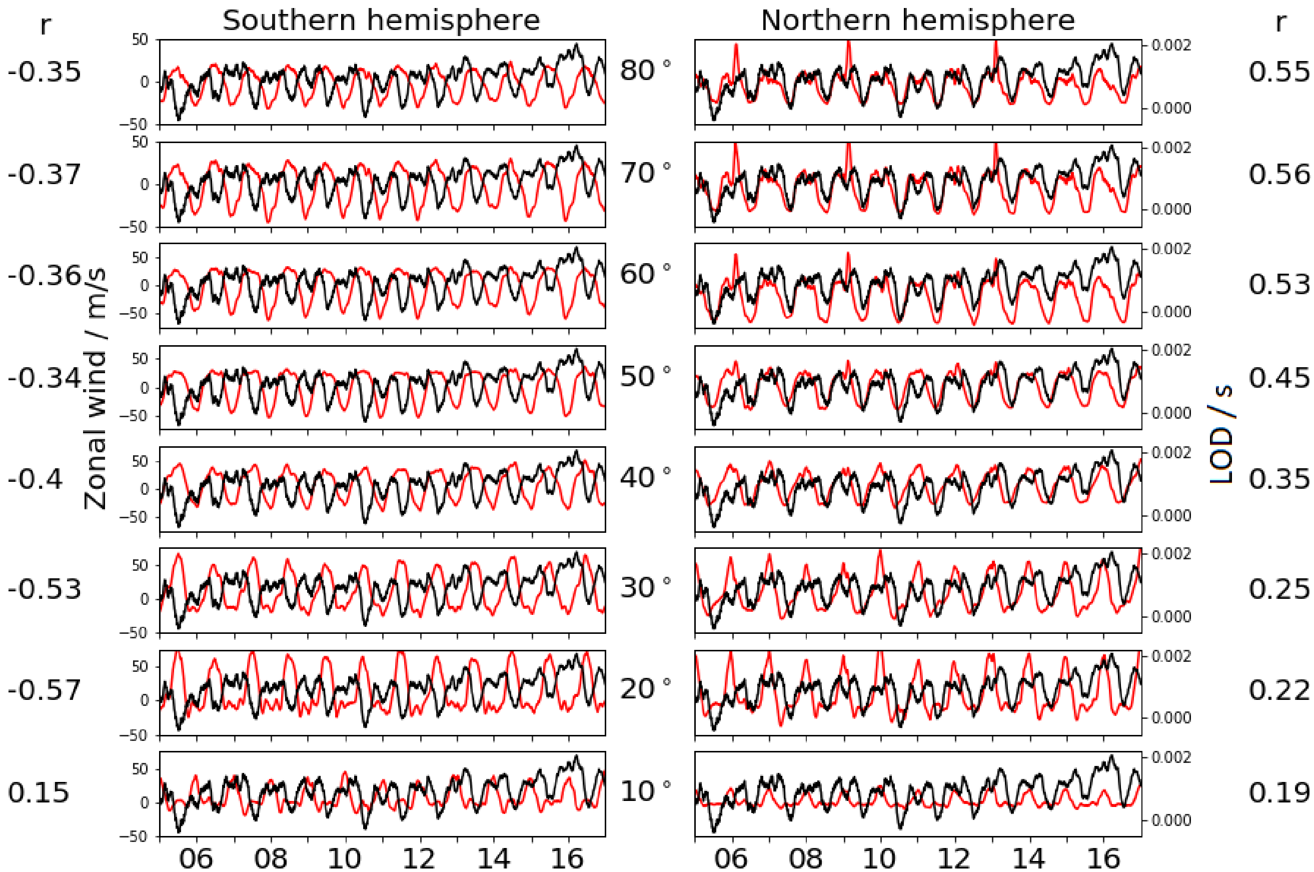

Figure 9. ~~Annual mean values for the LOD~~ Zonal MLS wind (~~black~~red) and ~~the zonal wind~~ LOD (~~red~~black) ~~,~~ at ~80 km geometric height for 0°-20°E. The left part show the ~~station Collm~~values for the southern hemisphere, ~~after removing seasonal variations and~~ the ~~solar cycle~~ right for the ~~altitudes between 80 and 100 km~~northern hemisphere, for every 10° latitude.~~The dashed lines represents the trend over the years 2005 – 2016.~~

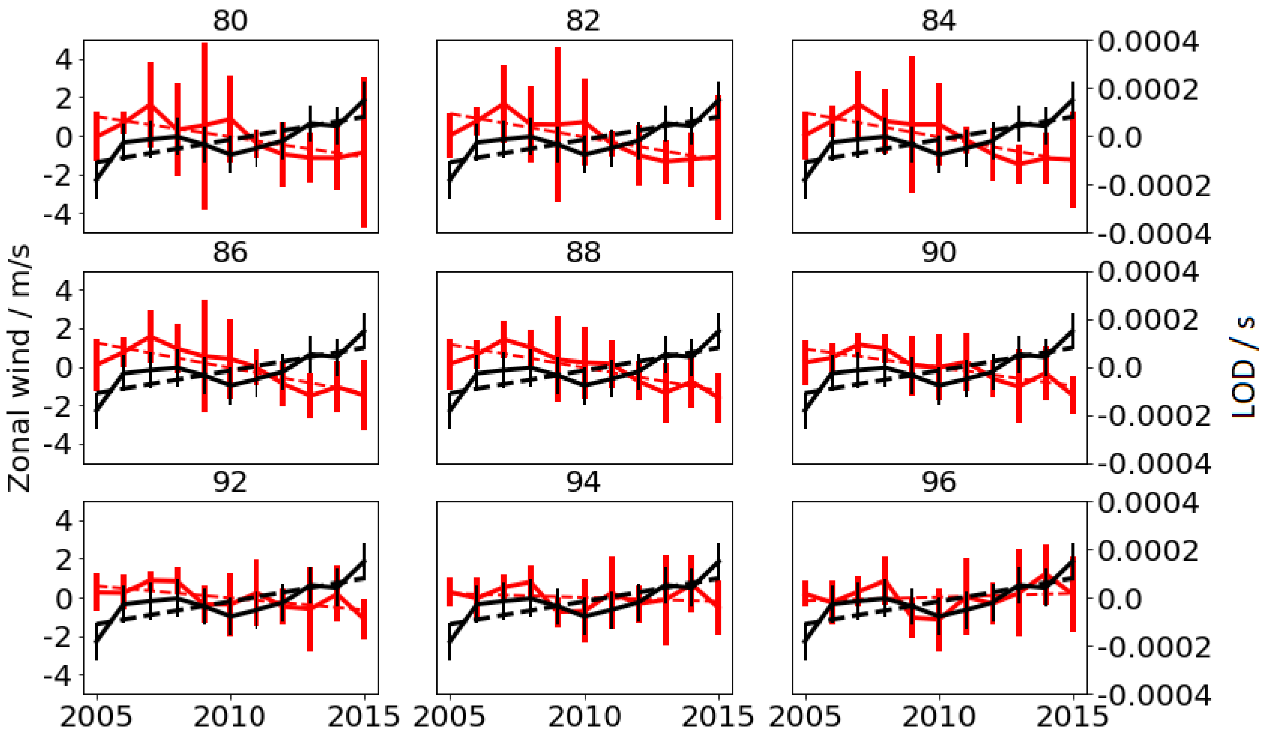

Figure 10. Annual mean values for the LOD (black) and the zonal wind (red), for the station Collm, after removing seasonal variations and the solar cycle for the altitudes between 80 and 100 km. The errorbars corresponds to the standard deviation. The dashed lines represents the tendency.

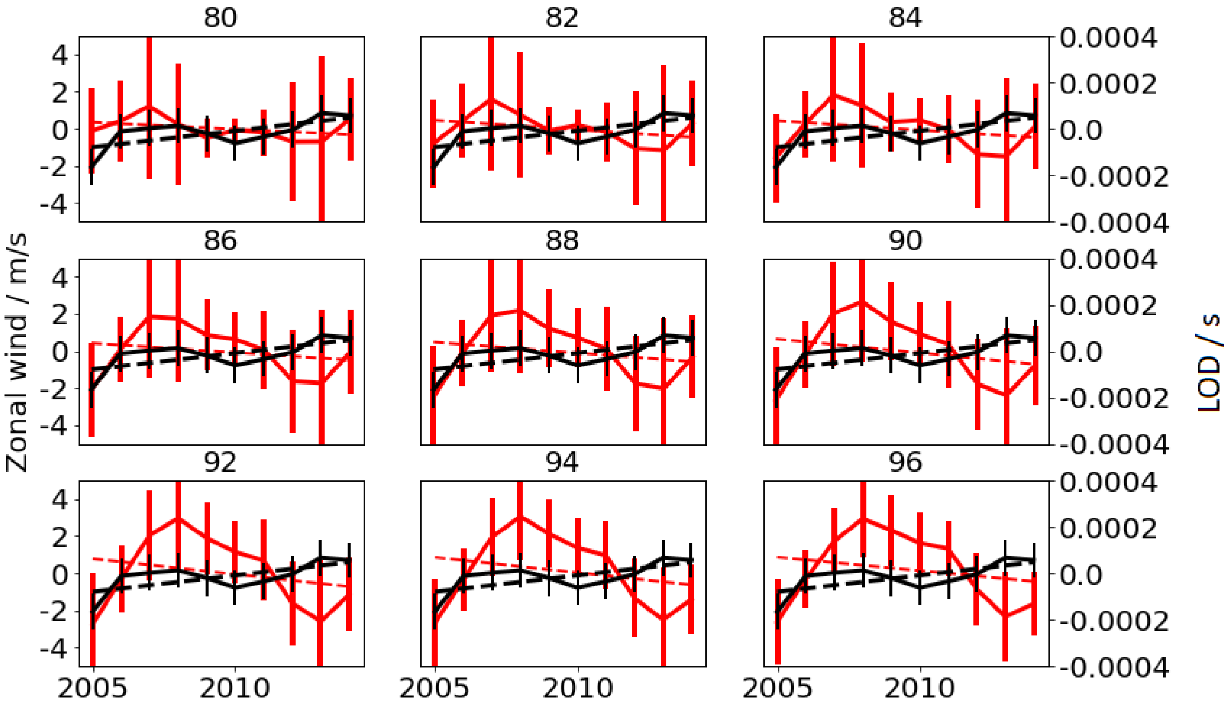

Figure 11. Same as Figure 10, but for Davis.