Review #1

Review of revised angeo-2018-51, “Connection between the length of day and wind measurements in the mesosphere and lower thermosphere and mid and high latitudes”

General comments

The manuscript is revised very well. My main concern in the original one was it might impress that the authors concluded that fluctuations in the length of a day (LOD) caused interhemispheric variations of mean zonal winds. Because the topic is not conclusive, rather introducing a new insight, it needs to be very careful that the LOD may be one of possible sources of interhemispheric variations.

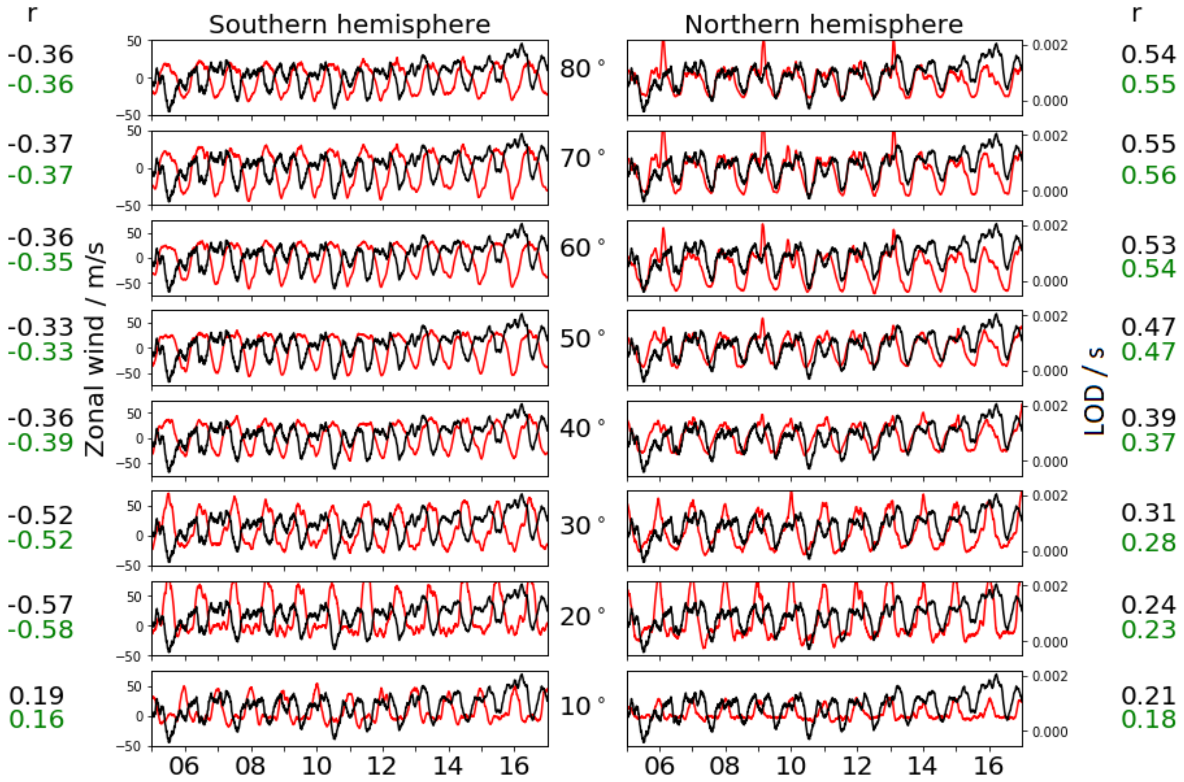
This interesting topic in the manuscript addresses further curious questions to readers, correlations of the LOD with mean meridional winds and tidal amplitudes while it may be very difficult to analyze correlations with tidal phases and periods due to very small values if they exist. I expect that the authors have already had them for future work.

General reply:
We appreciate the work which was done by the referee to increase the quality of the manuscript.

1. Adding correlations of the LOD with global mean zonal winds from MLS satellite observations presents very interesting, why the correlations are not consistent globally and it is probably because the LOD is not the only source for interannual variations. My only one concern is that mean winds from a radar at one site is a superposition of zonal mean and stationary planetary wave winds. Using satellite data at nearby longitudes is fine for comparisons with radars. But we would like authors to present global correlations by averaging data at all longitudes, so that correlations with zonal mean zonal winds are seen by cancelling stationary planetary waves.

Reply: We added global correlations by averaging zonal mean wind data over all longitude in the Figure (green numbers), as well as, in some comments the text. The shape of the curves between the global average and the previous average between 0-20°E are nearly equal, therefore we didn’t add them in the Figure.

Added /modified text : We added correlation coefficients (black) between the mean zonal 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. Additionally, we present global correlations (green) by averaging mean zonal wind data over all longitudes, whereby possible stationary planetary waves are filtered. The global correlation coefficients are nearly similar to the values for previous average winds between 0-20°E. The shape of the curves between the global average winds are also are nearly equal, therefore we didn’t add them in the Figure.



Caption: Zonal MLS wind (red) and LOD (black) at ~80 km 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. The black correlation coefficients (r) are estimated for the mean between 0°-20°E, and the green coefficients corresponds to global average over all longitudes.

Specific comments

Page 1, Line 8: Does a value "~4 m/s" a critical value regardless locations (latitude and latitude) and time (season)? If not, please specify conditions for this value.

Reply: The above mentioned value was estimated for latitude of 45°. Different latitudes lead to slightly different values for gravity (g). Furthermore, the theoretical estimation of the rotation speed is independent of the longitude and time (season).

We added in section 3.1. additional notes: The calculation is done in 2 km height layers and for the latitude of 45°. Different latitudes lead to slightly different values of g, which is used in equation 4.

We appreciated and corrected the hints regarding the following typos.

Page 1, Line 14: "show" must be "shows".
Page 1, Line 17: "zonal mean wind" must be "mean zonal wind".
Page 2, Line 3: "inverse" must be "inversely".
Page 2, Line 10: "affects" must be "affect".
Page 2, Line 12: Add "by" between "simulation" and "Marsh".
Page 2, Line20: "show" must be "showed".
Page 3, Line 3: Add "to" between "according" and "Trenberth".

Page 5, Line 1: Replace “of” by “around”.
Page 5, Line 2: “fluctuations in the day length” can be replaced by “LOD”.
Page 5, Line 29: “hemisphere” must be “hemispheres”.
Page 6, Line 27: “station” must be “stations”.
Page 6, Line 28: Add space between “Davis” and “(”.
Page 8, Line 7: “influences” must be “influence”.
Page 8, Line 8: “are” must be “is”.
Page 8, Line 9: “causes” must be “caused”.
Page 8, Line 32: What does “this is only one reason”?
Page 10, Line 20: Remove “the” between “quite” and “opposite”?
Page 11, Lines 2, 5 and 16: “zonal mean wind” must be “mean zonal wind”.
Page 11, Line 7: Remove “be”.
Page 11, Line 11: “locations” must be “locations”.
Page 11, Line 14: “explain” must be “explained”.
Page 11, Line 18: “are” must be “is”
Page 11, Line 20: “fits” must be “fit”.
Page 11, Line 25: Does “smaller” mean “shorter”?
Page 12, Line 9: “theses” must be “these”.
Page 12, Line 13: “Additional” must be “Additionally”.
Page 12, Line 17: Remove “way”.
Page 12, Line 18: “point on” is “point out”?

Review #2

Re-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 rev., rcvd Oct. 2018]

My previous comments on the original version criticisms have well answered - but there have been interesting new items added. So I have a few more comments.

General reply:
We appreciate the work which was done by the referee to increase the quality of the manuscript.

1. According to the theory here, the expansion and contraction of the atmosphere based on the distance from the sun should influence the seasonal changes in the LOD. So the LOD should lag the heating - that is heating causes expansion, the atmosphere slows down (maintaining conservation of angular momentum) and since the earth is turning eastward, that means there will be a westward perturbation in the atmospheric wind. The correlations presented in Table 1 appear to present an ideal way to test this lag. Is there a lag, and if so, is it in the expected sense? There are 10 years of data available; if the theory is correct, some effect of lag on correlation should be seen.

Reply:
The fluctuations within a year are too weak to be seen in the wind measurements and we are also not able to separate them from the general wind pattern. The influence of the atmospheric waves and large scale geophysical events dominate the wind regime. Furthermore, the solar maximum during the last 24th solar cycle was quite weak compared to the previous ones. Under the assumption of a stronger next solar cycle it could be possible to see differences and also a time lag in the wind and also in the LOD during the solar minimum and the solar maximum.

2. Pg 5 lines 3-8 and equation 7: This is not clear. I take “astronomically determined" to mean D is “sidereal" angular velocity, which results in ~4 min. per day rotation time (_86164 sec.) less than \mean solar day" (defined as 86400 sec.). In this case the “LOD" as defined by equation 7 will always be negative.
Alternately, if D refers to \solar day" - then there is another daily/seasonal non-rotational factor related to the changing speed of the Earth in its slightly elliptical orbit.

Reply:
For the paper we added the following text:
Within the estimation of the LOD the sidereal time gets converted into solar time, by taking into account the Earth's position, nutation, precession and motion with respect to the stars. Detailed information about the transformation from sidereal time into solar time can be found in e.g., Aoki (1981) and Schnell (2006).

For the referee:

Within this study we don't want explicit explain the transformation from sidereal time into solar time, because it could cause additional questions. Nevertheless, we added additional information, which are mostly cited according the work of Schnell (2006).

Within the estimation of the LOD the sidereal time gets converted into solar time. To explain this we need to go back a step and first need to define the notation of the earth orientation parameters (according IAU1980). The earth orientation parameters (EOP) describe the rotary position of the solid earth relative to a space fixed non-rotation reference system. Here, the EOP is the sum of several consecutive rotations transforming the celestial into the terrestrial system by using according Schnell (2006) and the included references:

$x_{TRS} = W(t) * S(t) * N(t) * P(t) * x_{CRS}$

with W(t) = transformation due to polar motion, S(t) = diurnal earth rotation, N(t) = nutation of the earth, P(t) = Precession. TRS and CRS correspond to the terrestrial and celestial reference system, respectively. In detail S(t) is expressed by

$S(t) = R(GAST)$

With R for a 3-dimentional rotation matrix, and the argument GAST as acronym for the Greenwich Apparent Sidereal Time. This argument corresponds to the current hour angle of the Greenwich meridian relative to the direction of the true spring equinox. The spring equinox varies in time relative to the fixed space coordinates, which is based on P(t) and N(t) and the difference between the true and the mean spring equinox is referred as Equation of Equinoxes (EqE), and the hour angle with respect to the mean equinox is called Greenwich Mean Sidereal Time (GMST). The relation between the mean sidereal time then is

$GAST = GMST + EqE.$

The EqE depends on the current nutation in longitude dp and on the mean obliquity e0:

$EqE = dp * \cos(e0)$

While GMST is referred to the mean spring equinox, the epoch of the solar time UT1 is given by the hour angle relative to the direction of the mean sun. The solar time therefore depends on the diurnal rotation of the earth and additionally on the revolution of the earth around the sun. The true sun is hereby replaced by a mean sun because the motion of the earth is not uniform as a result of the 2nd Kepler's Law. The difference between the true and the mean sun is referred as Equation of Time (EqT).

The Greenwich Mean Sidereal Time can be expressed using the solar Universal time as :

$GMST = a_{mSu} – 12h + UT1$

with a_{mSu} as the right ascension of the mean sun. The 12h subtraction are because 0 hr UT1 is defined to be midnight.

From GAST, the solar Universal Time UT1 can be calculated as:

UT1 $= \text{GMST} – a_{mSu} + 12h$
$= \text{GAST} – dp * \cos(e0) – a_{mSu} +12h$

Using the ratio C between the length of a sidereal and a solar time interval:

$C = d(\text{GMST}) / d\ \text{UT1} = (\text{GMST} – \text{GMST}\ (\text{UT1} = 0hr)) / \text{UT1}$

the relationship between GMST and UT1 can be expressed by:

$\text{UT1} = (1 / C) * (\text{GAST} – \text{EqE} – \text{GMST}(0hr\ \text{UT1}))$.

On this way the sidereal duration of a day, which is ~1/365 shorter than a mean solar day, gets converted by taking into account the Earth's positon, nutation and precession into the duration of a solar day.

Schnell, D.: Quality aspects of short duration VLBI observations for UT1 determinations, Ph.D. thesis, Rheinische Friedrich-Wilhelms- Universität zu Bonn, http://hss.ulb.uni-bonn.de/2006/0918/0918.htm, 2006.

3. Pg. 7 line 32-34: The statement says an enhanced eastward directed wind is linked to an increased F10.7 index. But presumably increased F10.7 means an expanded atmosphere which means slower atmospheric rotation, i.e. reduced eastward?

Reply: That is correct. We appreciate the comment.
The increase of the F10.7 leads to an expanded atmosphere, which further results in a slower atmospheric rotation, and so in e.g., a reduced eastward wind. We removed Figure 4 and the corresponding text, because it was misleading. A changing F10.7 does not have such a strong influence on the density/wind in the shown heights.

4. Much argument is expended in this paper to show that seasonal changes in LOD and zonal wind are expected due to the effect of changes in Sun-Earth distance on the atmosphere. In the abstract it should be stated clearly, as it is in the conclusion (Pg. 12, line 10,11) that these seasonal changes were not found in the wind and LOD data probably because of competing effects, such as ... (that is, unless lagged correlation show anything interesting.)

Reply: We added the following text to the abstract:

A direct correlation between the local measured winds and the LOD on shorter time scales cannot clearly be identified, due to stronger influences of other natural oscillations on the wind.

Minor typos etc.:

We appreciated and corrected the hints regarding the following typos.

Pg. 8 line 5: “... is higher than during ... "
Pg. 9 line 20: “explicitly"
Pg. 11 line 20: .”... zonal wind agrees with the relation ..." ?
Pg. 12 line 9: “.... between these ..."
Pg. 12 Line 14: “Additionally, ... "
Pg. 12 line 16: “Further we only compare ..."
Pg. 12 line 17: “... effects which drive ..."

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. 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 $\sim$4 m/s at a latitude of 45° 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). 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~~ decreases during summer, which corresponds to changes in the MLT density due to the ~~Earth - Sun~~ Earth-Sun movement. Within the MLT the ~~zonal mean wind show~~ mean zonal wind shows similar fluctuations as the LOD, on annual scales as well longer time series, which ~~is~~ are connected to the seasonal wind regime, as well as, to density changes excited by variations in the solar radiation. A direct correlation between the local measured winds and the LOD on shorter time scales cannot clearly be identified, due to stronger influences of other natural oscillations on the wind. Further, we show that, even after removing the seasonal and 11-year solar

cycle variations, the ~~zonal mean~~ mean zonal wind and the LOD are connected, by analyzing ~~long term~~ 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 NH summer. Due to the inverse square law, where the intensity I of the radiation is ~~inverse~~ inversely proportional to the Earth-Sun distance squared 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 **??** shows a scheme of the ~~Earth Sun~~ Earth-Sun constellation and the resulting effects, which will be explained in the following. Previous studies as, e.g., **?**, **?**, **?**, and **?** showed that solar cycle variations ~~affects~~ affect 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 **?**~~ A model simulation by (**?**) 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 climatology due to solar radiation are too complex to be explained by simplified methods. **?** 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 (**?**). For the winter season 2009/2010 **?** 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 temperature measurements. Further, they ~~show~~ showed a strong anti-correlation of neutral air density and prevailing zonal 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 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 to **?** by

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

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

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

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

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

where g is the acceleration due to gravity. Considering that 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, for standard gravity at 45° latitude. More detailed information about the estimation of the total mass of the atmosphere can be found in **?**. According to **?** 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 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 (**?**). 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 (**?**).

On time scales less than a year the dominant geophysical process to influence the duration of the Earth's rotation is the atmosphere (**?**). 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 its system. The total angular momentum of the Earth's atmosphere M can be approximately written as

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

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 (**?**).

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 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 **?**, **?**, and **?** these parts of angular momentum can be written as

$$M = M_\omega + M_r = \frac{r^4\omega}{g} \int\limits_{0}^{2\pi} \int\limits_{-\pi/2}^{\pi/2} p_{sfc} cos^3\theta\, d\theta\, d\lambda + \frac{r^3}{g} \int\limits_{0}^{1000} \int\limits_{0}^{2\pi} \int\limits_{-\pi/2}^{\pi/2} u_{rel} cos^2\theta\, d\theta\, d\lambda\, dp. \tag{6}$$

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, 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 (**???**). 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 (**?**).

Already in the 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 (**?**, **?**). Changes in the speed of the Earth's rotation axis can be seen in fluctuations in the duration ~~of~~ around a day. These fluctuations have been measured since the 60s using the

Very Long Baseline Interferometry (VLBI) technique. The ~~fluctuations~~ fluctuation in the day length is the difference between the ~~astronomical~~ astronomically determined duration of a full day $2\pi/D$ and the standard 86400 SI seconds, whereby D is the angular velocity (**?**). Henceforth, we use the acronym LOD for the fluctuations in the length of day. The LOD can be written as

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

Within the estimation of the LOD the sidereal time gets converted into solar time, by taking into account the Earth's position, nutation, precession and motion with respect to the stars~~(?).~~. Detailed information about the transformation from sidereal time into solar time can be found in (e.g., **??**).

? 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. **?** 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 hPa contributes 0.5 ms, from 10 to 1 hPa ~~contributes~~ contribute 0.03 ms, and winds above 1 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., **?**) and the stratospheric quasi-biennial oscillation (QBO) can also be seen in the LOD (e.g., **?**, **?**).
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 a 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., **?**). Changes in these parameters can further lead to changes in the neutral density.

Within this study, we focus 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 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 of equal density distribution between the northern and southern ~~hemisphere~~ hemispheres (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~~ mid-latitude locations. We use the LOD data to show, how deep the influence of ~~the~~ solar radiation penetrates into the atmosphere. The conclusions are found in 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, 16.0°E, Norway), the mid-latitude stations Juliusruh (32.5 MHz, 54.6°N, 13.4°E, Germany), and Collm (36.2 MHz, 51.3°N, 13.0°E, Germany) on the northern hemisphere and the southern high latitude station Davis (33.2 MHz, 68.6°S, 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 $\sim$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 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 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~~ upper/lower part the of the meteor ~~observations~~layer. More information about the all-sky meteor radars and the used wind estimation method can be found in Hocking et al. (2001a), **?** and Stober et al. (2017). For this research, we focus primarily on the zonal wind component, because a connection between winds and changes in 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 (**?**, **?**) has a global coverage from 82°N to 82°S and an useful height range from approximately 11 to 90 km (261 to 0.001 hPa). The vertical resolution varies between $\sim$4 km in the stratosphere and $\sim$14 km at the mesopause (**?**). The geometric heights are approximately estimated from pressure levels as described in **?**: $h = -7 \cdot ln(p/1000)$, 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 to 80 km (if not otherwise specified) to investigate a connection between the LOD and the density depending zonal wind within 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 three different horizontal grids which are located around Andenes (70°N and 0-20°E) and around Juliusruh/Collm (50-60°N, 0-20°E), which are further referred to as northern high and mid latitude ~~station~~stations, respectively. For the SH we use a horizontal grid around Davis (70°S, 60-80°E).

Further we use in this study combined data from the international Earth Rotation and Reference System Service (**?**). 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 (**?**, **?**, **?**). Based on these information the mean rotation rate and the astronomical duration of the day were computed according to equation **??** (**?**). The IERS provides uncertainties for the day length measurements which most of the time vary in a range of $\sim$5%. More information about the data provided by IERS and their algorithm to estimate the duration of a day can be found in **?**.

3 Results and Discussion

3.1 LOD and neutral air density at the MLT

Figure 3 shows composites of zonal winds from MR measurements at Andenes, Juliusruh, Collm, and Davis. These data are estimated by using a mean wind adaptive spectral filter (Stober et al., 2017). It uses a 1 day sliding window, which mainly removes the impact of short-term variations, as atmospheric tides and gravity waves. All three 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 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 **?**. 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 **??** the zonal wind is shown for the high latitude location of Andenes, for middle latitudes at Collm and for the southern latitude location Davis. The altitude ranges between ∼60 and ∼90 km geopotential height. A comparison of the MLS composite winds with MR composite winds results in a qualitatively good agreement for the seasonal amplitudes and phases. Both NH locations show eastward directed 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 **?** and **?**, a connection exists between the thickness of an atmospheric layer and the density fluctuation within that layer. **?** 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.

To underline this statement, ~~Figure **??** 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~~ we show in the following part the connection between the expanding MLT and the atmospheric rotation speed. Figure **??** 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 ~~.~~ and for the latitude of 45°. Different latitudes lead to slightly different values of g, which is used in equation **??**. The density increase takes place for longer time scales during a solar maximum (e.g., **?**) and on annual time scales during the winter, when the Earth-Sun distance is smaller. Both cases ~~influences~~ 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~~ is stronger than the variation ~~causes~~ caused by the changes of the Earth-Sun distance. According to equations **??** - **??**, we estimated for three different cases (linear (red), exponential (green) and a 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 shaped curve. These results fit to the observations by **?** 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, **?** showed that the global mean of the surface pressure is nearly constant, and surface pressure anomalies at the northern and the southern hemispheres are nearly identical, but the fluctuations are opposite in sign. These anomalies are mainly 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 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~~ evolution of the seasonal mean wind measurements from the NH station Andenes (69.3°N) and SH station Davis (68.3°S). Figure **??** 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 over Davis for both altitudes, they are higher 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 **?**. We have to note that ~~beside many others factors , this is only one reason, and by far not the dominant factor,~~ others factors exists, which are more dominant 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 (**?**, **?**), 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., **?**). 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~~ mean zonal 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 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 cause tiny fluctuations in the day length. These have to be compensated by a momentum transfer between the different parts of the Earth including the atmosphere. As the atmosphere is slaved to the Earth crust, because the atmospheric momentum and mass are much smaller than that 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 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 **??** show wind values for Andenes, Collm, and Davis at different altitudes and the LOD by using the same 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, the altitude where the wind, during each hemispheric summer shows the opposite direction as at 80 km (see Figure 3). Positive wind values correspond to eastward directed winds and positive LOD values correspond to a longer duration of the day. If not ~~explicit~~ explicitly mentioned, the results of the two mid-latitude stations are nearly identical. Therefore we only show the results for the location around Collm.

At 80 km (Figure **??**) 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 several periods, as 0.5 years, 1 year (see also **?**), 2-3 years (**?**), 5.9 years (**?**) and others (e.g., **?**, **?**). According to **?** 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, **?** support this statement and mention that the problem is further complicated due to the small influence of the solar forcing on the climate. Nevertheless, **?** 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., **?**, Hoffmann et al. (2010)). Therefore, we additionally show with the red line a smoothed zonal wind after removing variations due to the 11-year solar cycle. The influence of the solar cycle on the daily zonal wind is relatively small, therefore the smoothness of the red line is 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., **?**, 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 **??** show a seasonal pattern. 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 milliseconds. The LOD oscillation shows seasonal 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 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 midlatitudes, which can be seen in Figure 3. For Davis a time shift of approximately half a year occurs between the zonal wind and the LOD, due to the opposite seasonal wind pattern.

In the summer wind transition altitude 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 are 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 **??**. 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 pronounced than at lower heights. Therefore the existing seasonal wind pattern fits well to the atmospheric density increase and decrease at these layers.

Additionally, we show in Table **??** 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 **??** 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/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~~ polar hemispheres can be seen. A 180° phase shift would lead to the wind-LOD pattern of the opposite hemisphere. Furthermore, the 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~~ We added correlation coefficients ~~between the zonal mean~~ (black) between the mean zonal 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. Additionally, we present global correlations (green) by averaging mean zonal wind data over all longitudes, whereby possible stationary planetary waves are filtered. The global correlation coefficients are nearly similar to the values for previous average winds between 0-20°E. The shape of the curves between the global average winds are also nearly equal, therefore we didn't add them in the Figure.

In ~~the~~ Figures **??** and **??** ~~are shown~~ long term changes of annual LOD (black) and annual ~~zonal mean~~ mean zonal winds (red) are shown 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., **?**, **?** and **?**), 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 and the LOD excludes the seasonal variations. Exemplary for the ~~locations~~ location of Collm (Figure **??**) 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 **??** shows 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 into a slightly positive wind. This reversal can be ~~explain~~ explained 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~~ mean zonal wind can be seen for all mid latitude locations, and also for Davis (see Figure **??**). Andenes shows for all altitudes increase tendency in the zonal wind (not shown). The results indicate that the connection between the LOD and the wind ~~are~~ is more pronounced at lower latitudes, which is simply explainable by the rotation velocity, which is higher at the middle latitude stations than at the polar latitudes like at Andenes and Davis. The results of an increase of the LOD and a decrease of zonal wind ~~fits to~~ agrees with the relation between fluctuations in the neutral density and the zonal wind, as shown in **?**.

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~~ shorter distance between both celestial bodies during the NH winter, and a longer distance during summer. This leads to a shrinking/expansion of the atmosphere during the NH summer/winter. This shrinking effect takes mainly place in the upper 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. According to **?** 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 four stations in total, whereby two stations are located at similar high latitudes for the northern and southern hemispheres. The other two ~~locations~~ meteor radar systems 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 a decrease in the day length.

Further, we showed that even after removing the seasonal and the 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~~ evolution 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~~ these parameters on time scales which are at least one year. On shorter ~~time scales~~ timescales a connection between the LOD and the winds ~~can not~~ cannot be figured out, the LOD consists of oscillations with at least half a year period and with the ~~current~~ currently 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~~Additionally, in future work the estimation of a time lag between the LOD and the winds needs to be considered.

We want to mention that based on our findings a connection between the zonal wind and the LOD exists, which we explain by the variation of the available atmospheric density. ~~Further on the one side~~ Furthermore, we only compare ~~on the one side~~ global LOD data with local measurements, and ~~on the other side there are way~~ within the MLT exists stronger geophysical effects which drives the wind regime at these altitudes. Within this work we only want to point ~~on~~ out 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).
The Microwave limb sounder data are available at https://mls.jpl.nasa.gov/.

Authors contributions.

Sven Wilhelm wrote the manuscript with input from all authors. Furthermore, all co-authors contributed to the data interpretation. Gunter Stober provided ~~thigh~~ the high resolution meteor wind data analysis for all stations and ensured the operation of the Andenes and Juliusruh meteor radar. Vivien Matthias provided the used wind analysis for the mircowave limb sounder data. 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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~~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.~~

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 zonal wind together with a positive fluctuation in the LOD.

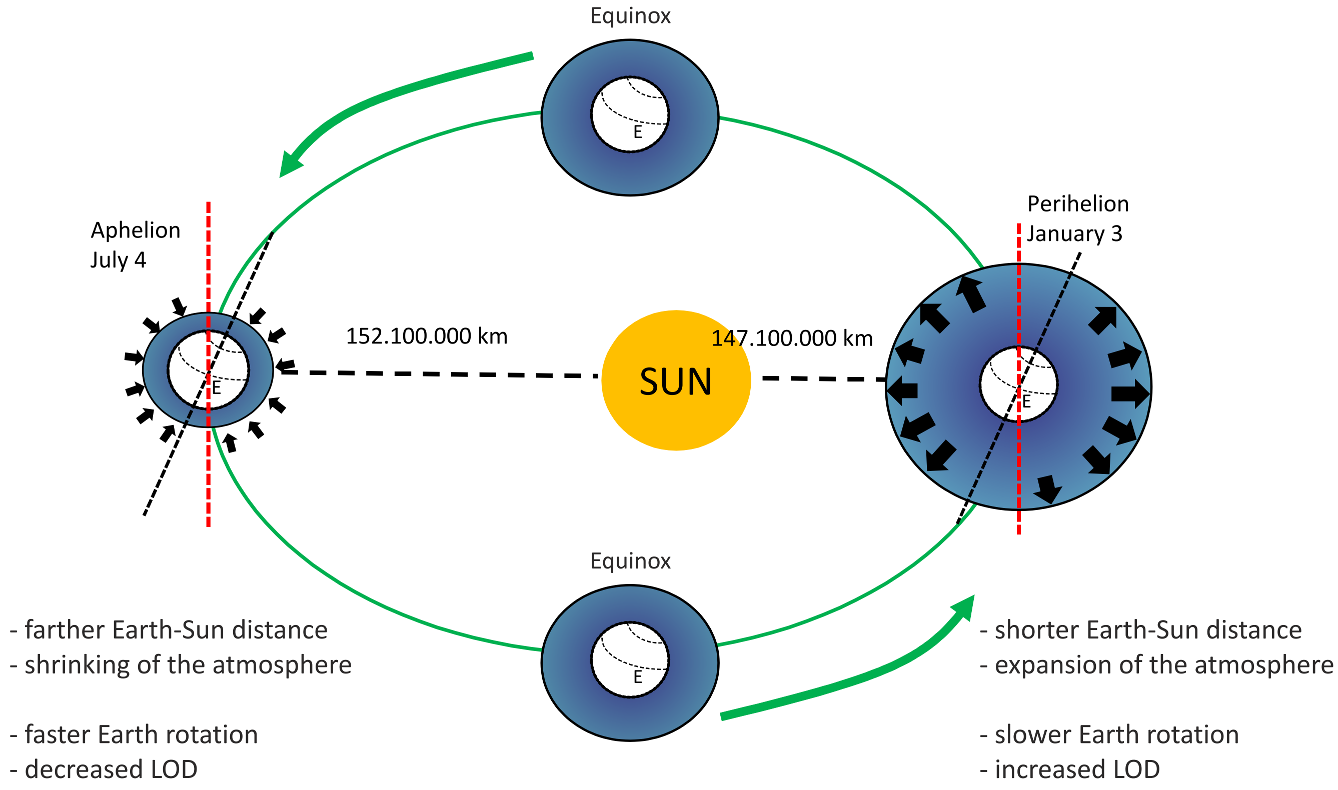

Figure 1. Schema of Earth and Sun correlation and the resulting effects on the thickness of the atmosphere and the Earth's rotation velocity.

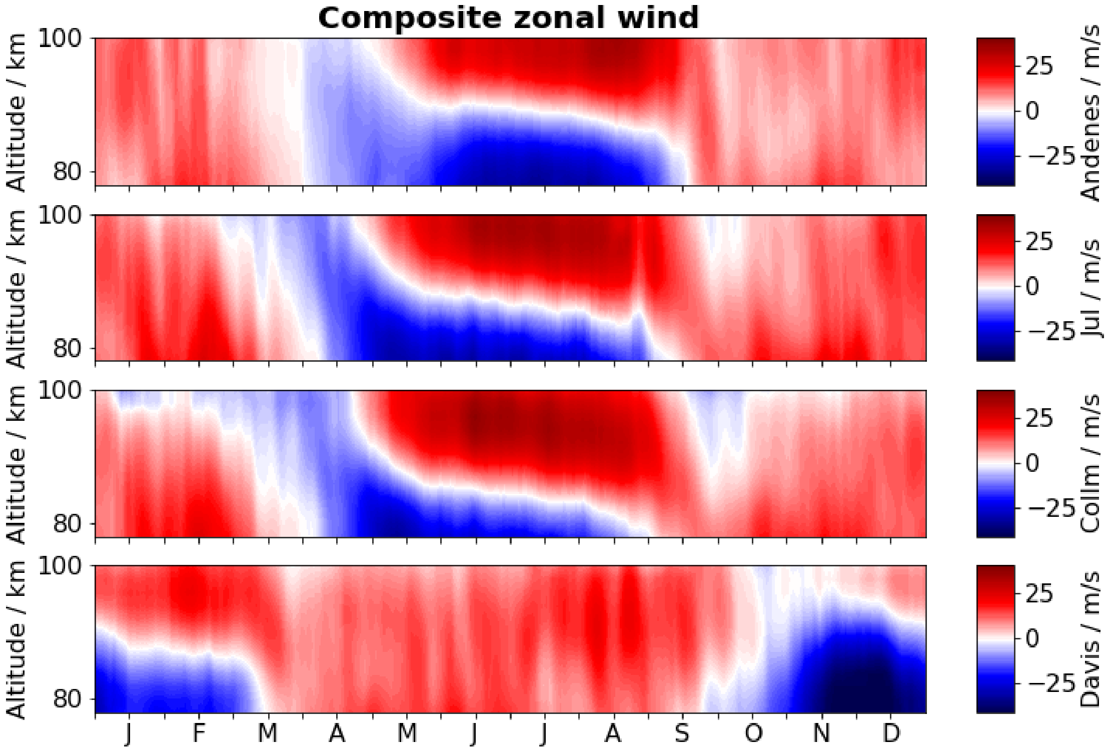

Figure 2. Composites of zonal wind for the northern hemisphere stations Andenes (top), Juliusruh (2nd row), and Collm (3th row). At the bottom is shown the southern hemispheric station of Davis. The composite for Andenes, Collm, and Davis include 12 years of meteor radar data and that of Juliusruh 9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

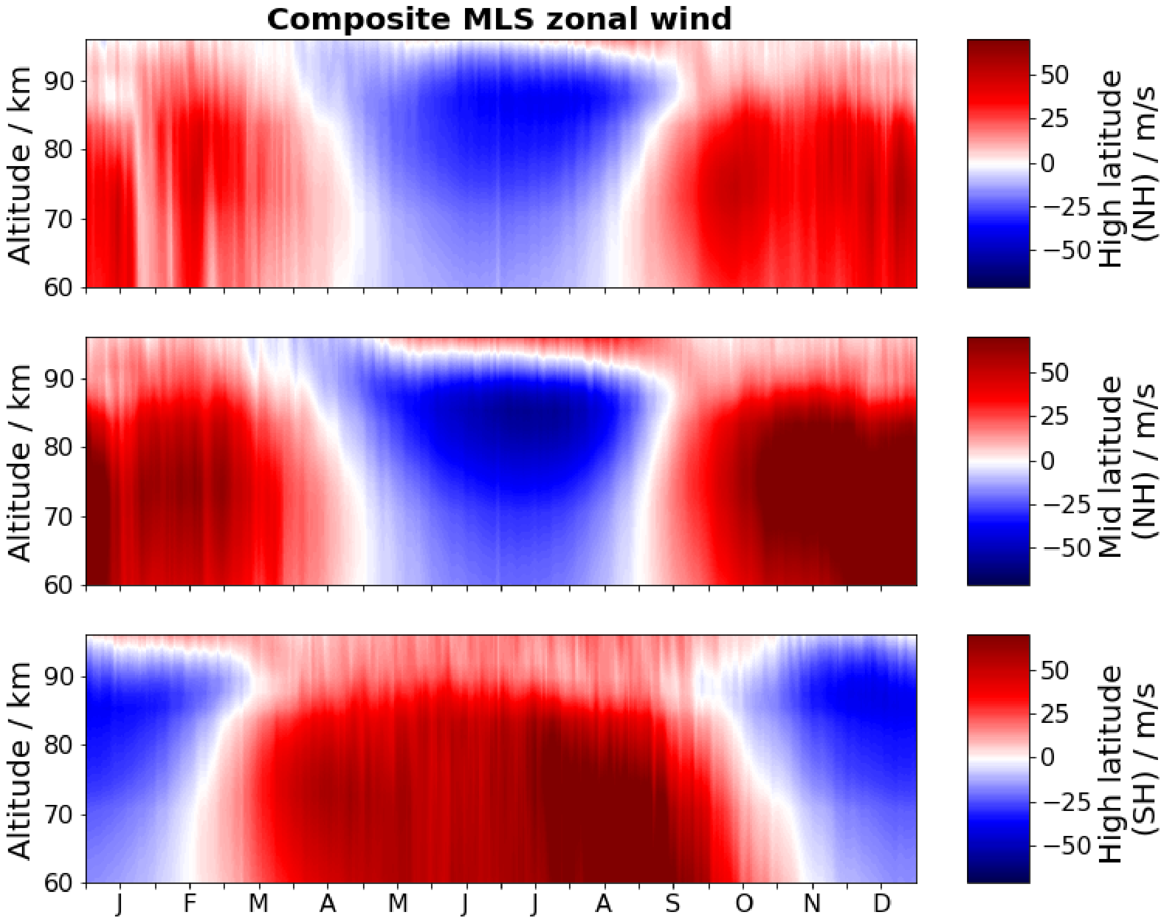

Figure 3. Composite of zonal wind for high latitude location (top), and mid latitude location (bottom). The composite of both figures includes 12 years of data wind data derived from MLS geopotential height data. Positive values corresponds to eastward directed winds and negative to westward directed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

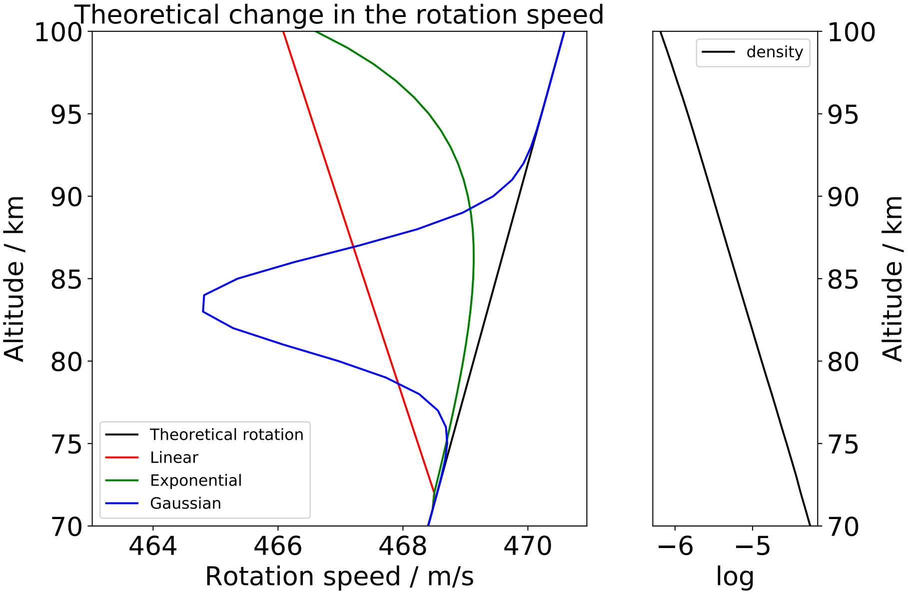

Figure 4. Theoretical change of the rotation speed (left side) for a rigid atmospheric layer. In black the theoretical rotation speed of the Earth's atmosphere and in colors the change due to density increase of 1% according the legend. On the right side the density progress is shown for specific altitudes.

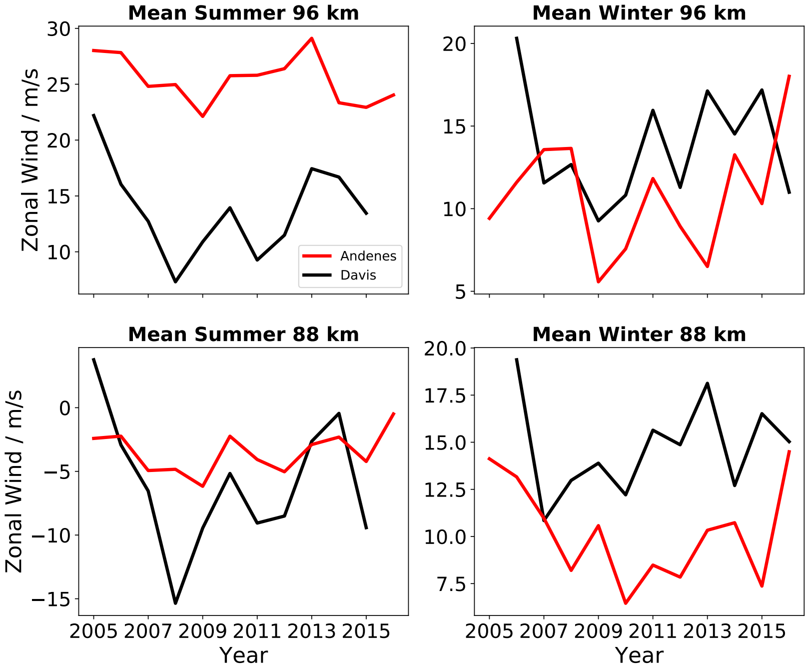

Figure 5. Zonal wind amplitudes for winter and summer season at 96 km and 88 km for Andenes and Davis.

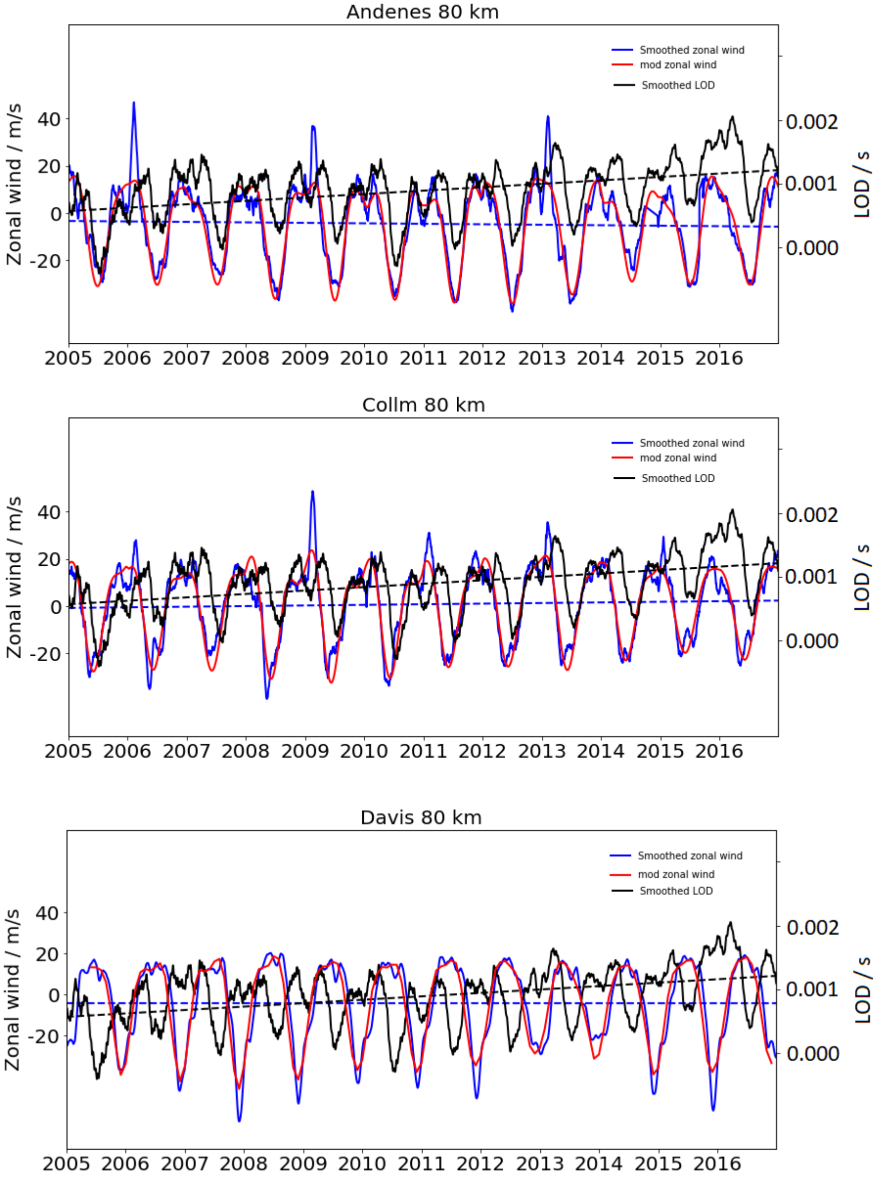

Figure 6. Smoothed zonal wind (blue) values based on meteor radar wind data at 80 km and smoothed LOD (black) values. The modulation of the smoothed zonal wind is displayed in red after removing the impact of the solar cycle, whereby the smoothing is stronger as in blue. All curves are done by a smooth 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.

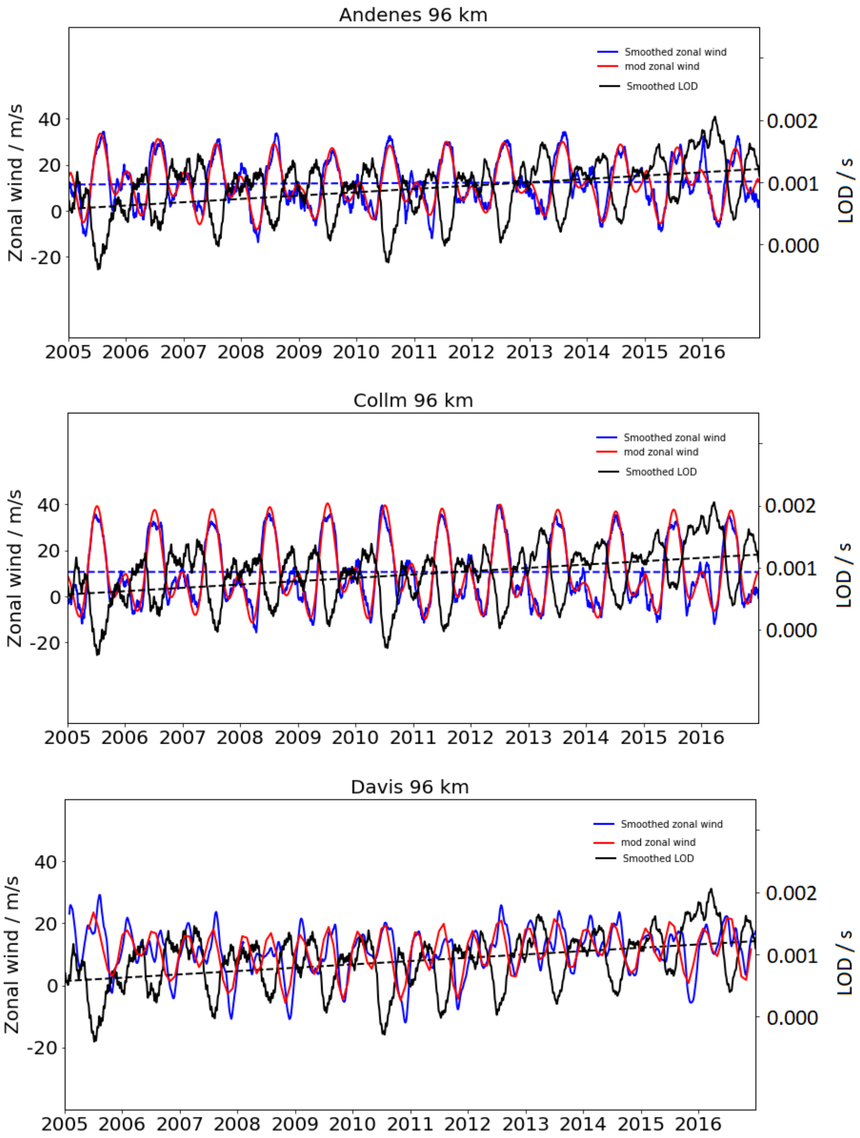

Figure 7. Same as Figure **??**, but for 96 km.

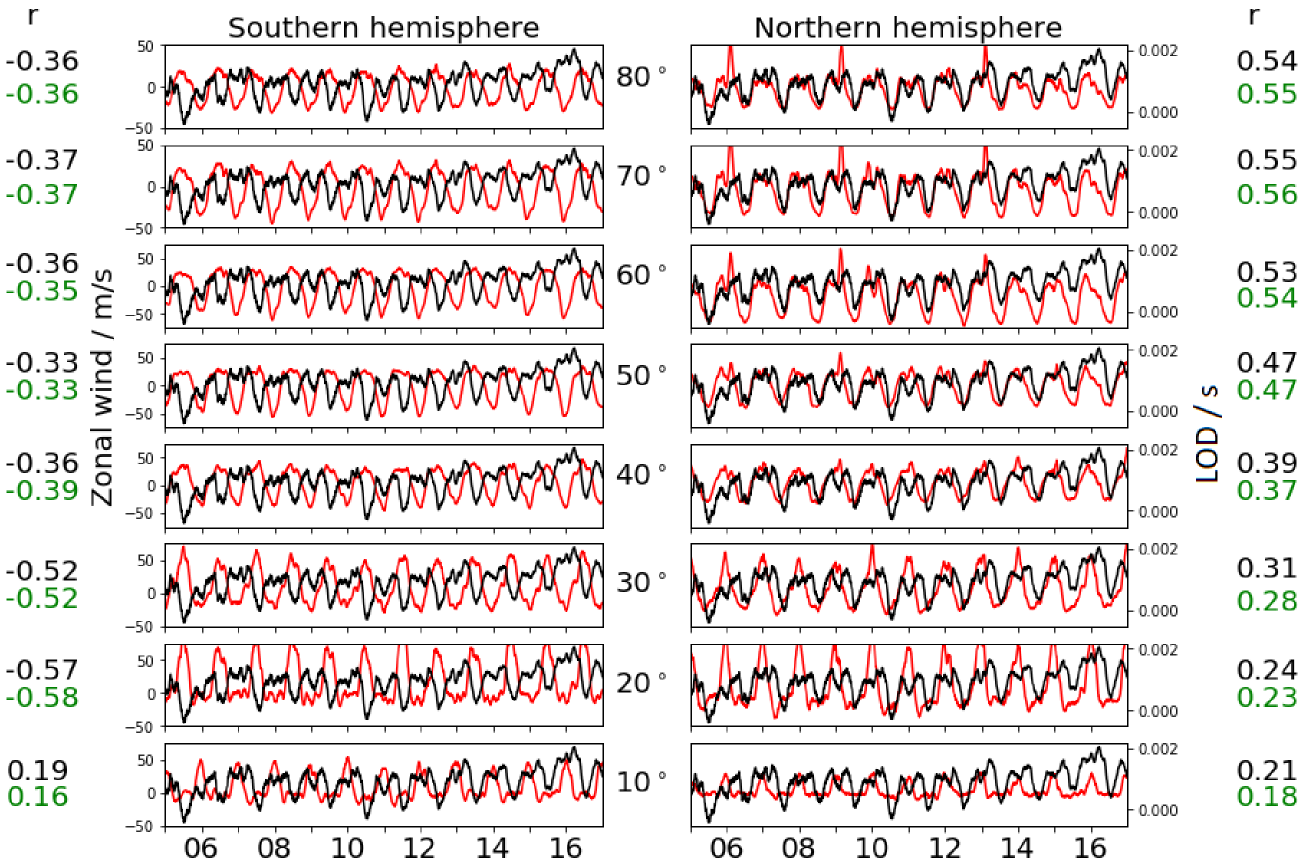

Figure 8. Zonal MLS wind (red) and LOD (black) at ∼80 km geometric height for 0°-20°E. The left part show the values for the southern hemisphere, the right for the northern hemisphere, for every 10° latitude. The black correlation coefficients (r) are estimated for the mean between 0°E and 20°E, and the green coefficients corresponds to global average over all longitudes.

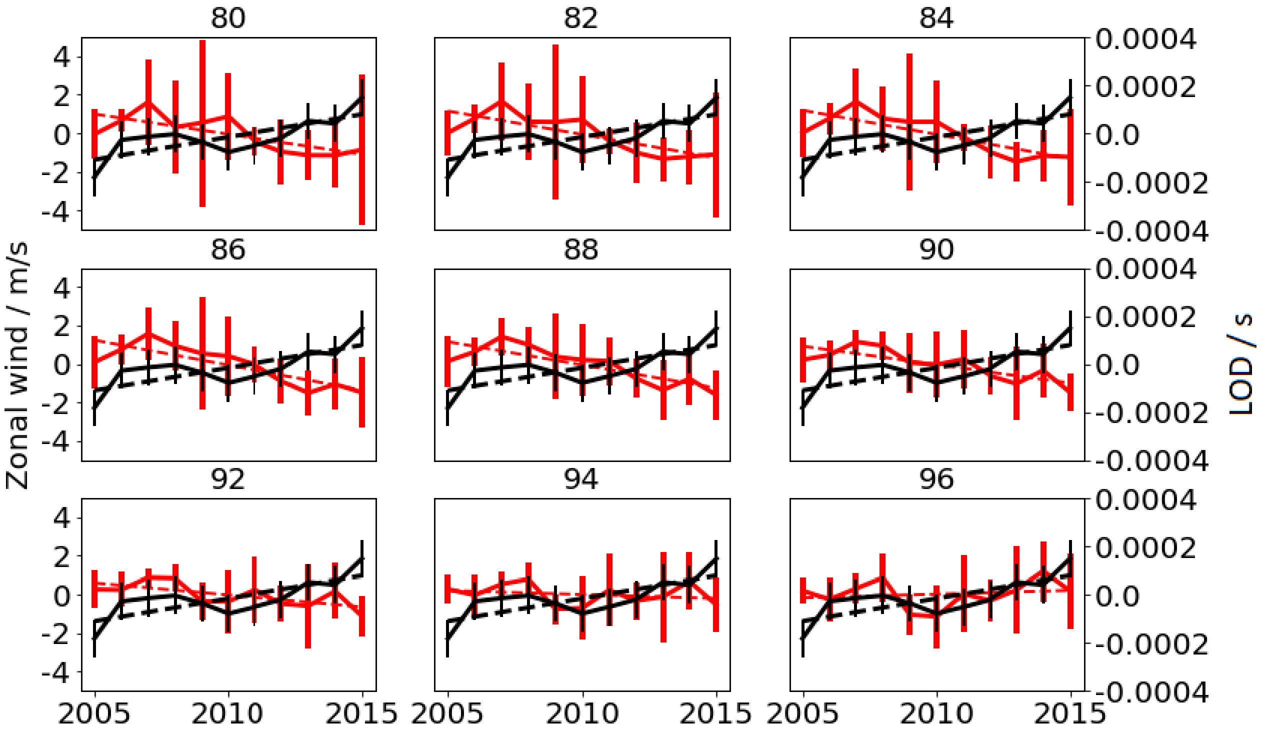

Figure 9. Annual mean values for the LOD (black) and the zonal wind (red), for the station Collm, after removing seasonal variations and the solar cycle for the altitudes between 80 and 100 km. The errorbars corresponds to the standard deviation. The dashed lines represents the tendency.

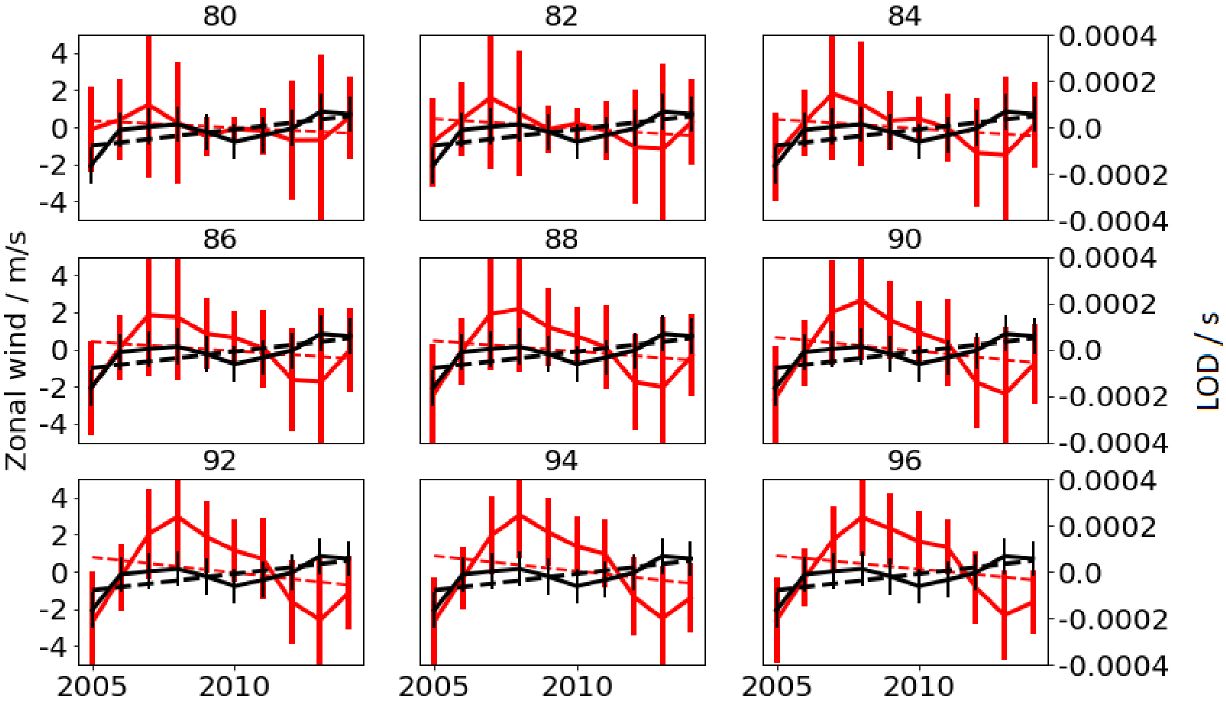

Figure 10. Same as Figure **??**, but for Davis.