Upper stratosphere-mesosphere-lower thermosphere perturbations during the intense Arctic polar night jet in 2019-2020

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Abstract

Thermal and dynamic perturbations at MLT heights during the strong stratospheric polar vortex as measured by the meteor radar at 67°N and the Aura satellite are presented. Mesospheric winds are dominated by vertical shears in the zonal component and the intense alternating north- and southward flows with a period of half a month. A temperature reduction at 90 km height is observed in the mid-winter and likely associated with a localized temperature increase in the upper stratosphere. Throughout January, a long-lived ~20K inversion layer persists just below the mesopause. These features are likely indicative of considerable stratification in the MLT as well as a decoupling of the middle and upper atmosphere.

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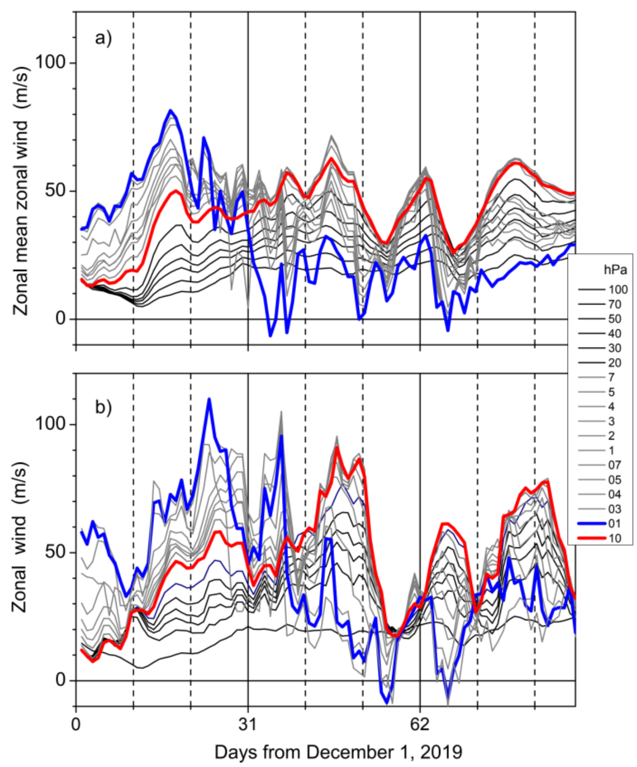
a)
b)
Zonal mean zonal wind (m/s)
Zonal wind (m/s)
0
50
100
0
31
62
Days from December 1, 2019
hPa
100
70
50
40
30
20
7
5
4
3
2
1
07
05
04
03
01
10

Fig. 1

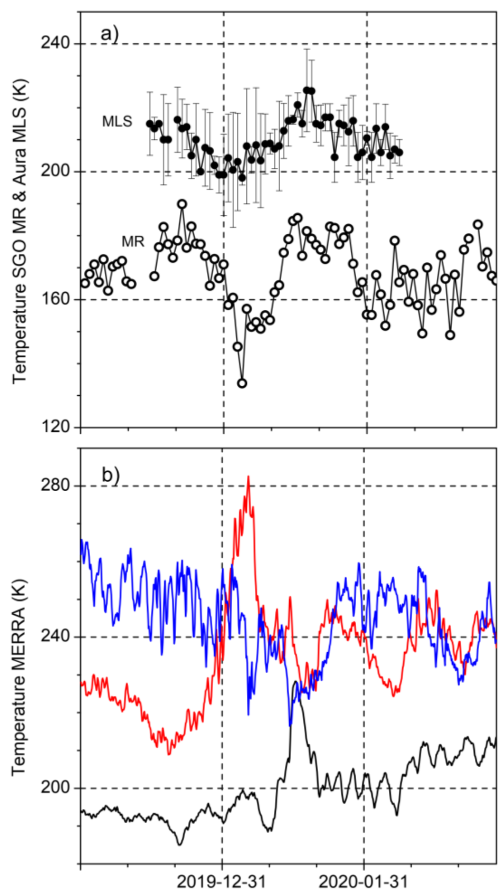
a)
MLS
MR
Temperature SGO MR & Aura MLS (K)
240
200
160
120
b)
Temperature MERRA (K)
280
240
200
2019-12-31
2020-01-31

Fig. 3

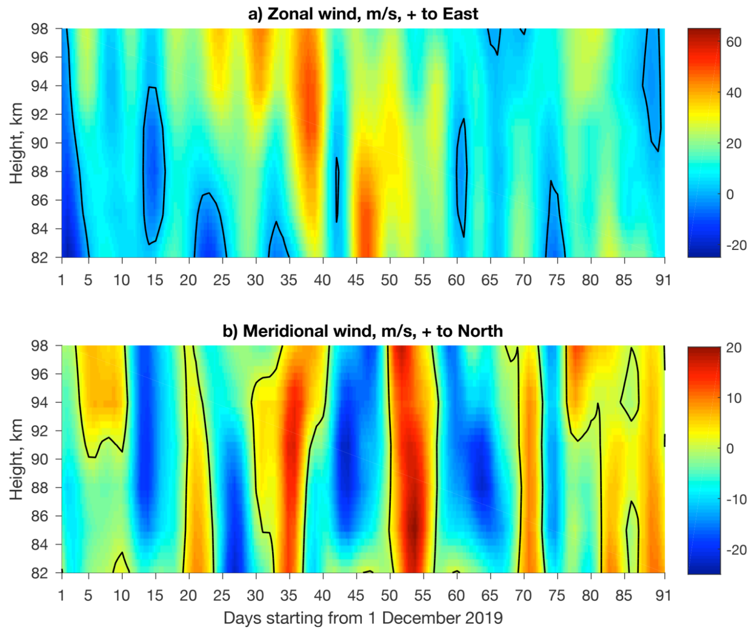
a) Zonal wind, m/s, + to East
Height, km
b) Meridional wind, m/s, + to North
Days starting from 1 December 2019

Fig. 2

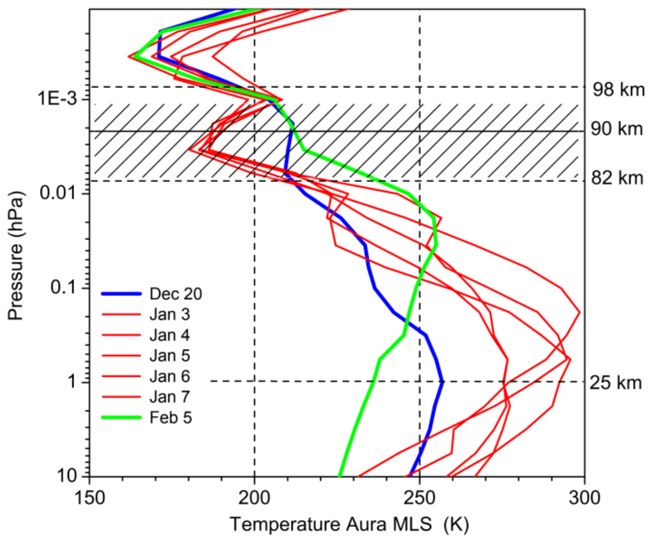
98 km
90 km
82 km
25 km
1E-3
0.01
0.1
1
10
150
200
250
300
Pressure (hPa)
Temperature Aura MLS (K)
Dec 20
Jan 3
Jan 4
Jan 5
Jan 6
Jan 7
Feb 5

Fig. 4

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Key Points:

- Unstable state of the upper atmosphere over a strong stratospheric polar vortex.
- Wind shears, alternating north/southward flows, thermal inversions, and cooling at the mesospheric heights.
- Decoupling of the atmospheric layers.

Abstract

Thermal and dynamic perturbations at MLT heights during the strong stratospheric polar vortex as measured by the meteor radar at 67°N and the Aura satellite are presented. Mesospheric winds are dominated by vertical shearsin the zonal component and the intense alternating north- and southward flows with a period of half a month. A temperature reduction at 90 km height is observed in the mid-winter and likely associated with a localized temperature increase in the upper stratosphere. Throughout January, a long-lived ~20K inversion layer persists just below the mesopause. These features are likely indicative of considerable stratification in the MLT as well as a decoupling of themiddle and upper atmosphere.

Plain Language Summary

Usually, if the stratospheric polar vortex is strong and persistent, it serves as a stable background for the overlying mesosphere-lower thermosphere (MLT) which also remains undisturbed because waves and heat do not penetrate there from below. However, in the Arctic winter of 2019-2020 this regularity seems to be violated. Significant vertical wind shears, alternating north- and southward flows, persistent thermal inversions and transient cooling are observed in the MLT likely indicating a certain degree of decoupling of the atmospheric layers.

1. **Introduction**

In the Northern Hemisphere winter of 2019/2020, a very strong, cold and persistent westerly circulation occurred in the high-latitude stratosphere. Unlike ordinary Arctic winters during which stratospheric warmings (minor or major) are relatively common,in this particular winter the polar vortex was not disturbed or weakenedby upward planetary waves from the troposphere, and the polar stratosphere did not warm.It has been shown that two-way coupling between the troposphere and cold stratosphere resulted in the strong positive phase of the Arctic Oscillation and the deepest ever observed spring-time ozone depletion in the Arctic. A reflective configuration in the upper stratospheric circulation was formed when the upward tropospheric waves did not exhibit much breaking in the stratosphere (Lawrence et al., 2020).

Perturbations in the stratosphere and troposphere as well as the dynamical coupling of these atmospheric layers during the unusual winter of 2019/2020 became the subject of active research. Less attention is paid to the upper atmosphere, which can also be affected. The mesosphere-lower thermosphere (MLT) is located at 60-100 km altitude and coupled vertically to the stratosphere by radiative, dynamical and chemical processes.The phase of thermal regimes in the high-latitude stratosphere and mesosphere is opposite. While the winter stratosphere is cold due to reduced radiative input, the MLT is warm because of downwelling induced by the high-altitude pole-to-pole meridional circulation.The transient-perturbations associated with a major sudden stratospheric warming (SSW) are identified as a sudden cooling of mesospheric temperatures and wind reversals (Matsuno, 1971; Labitzke,1972; Walterscheid et al., 2000; Liu and Roble, 2002; Cho et al., 2004; Siskind et al., 2005; Hoffmann et al., 2007; Lukianova et al., 2015). A SSW is maintained by atmospheric waves of various scales that force the mesosphere from below. At the same time, during the non-SSW winters, the high-latitude MLT is commonly considered stable.Ifan undisturbed eastward polar jet prevails in the underlying stratosphere,the MLT is dominated by the eastward/poleward wind with a speed up to several tens of meters per second and an average temperature of ~180 K (Portnyagin et al., 2004; Lukianova et al., 2017).

However, in 2019/2020, the vertically coherent stratospheric polar vortex greatly exceeded the ordinary level of intensity. The question arises whether the region above the stratopause could also be involved in this climatic extreme.It should be noted that the current period of low solar activity is favorable for a clearer identification of intra-atmospheric variability at higher altitudes. In this letter we explore the structure and evolution of thethermodynamic fields in the MLT during theNorthern Hemisphere winter of 2019/2020.

2. Data

The investigation of the MLT region relies largely on remote sensing techniques. We combine data from several sources, namely, mesospheric winds from the meteor radar (MR) operating by the Sodankyla Geophysical Observatory (SGO, 67°22 N, 26°38 E), the temperature data from the Earth Observing System Microwave Limb Sounder (MLS) on board the Aura satellite (Waters et al., 2006), and the NASA Modern-Era Retrospective analysis for Research and Applications (MERRA-2) reanalysis (Gelaro et al., 2017).

The primary application of MR is to measure neutral wind and temperature in the MLT region. The physical basis behind this facility is that meteoroids entering the Earth's atmosphere form ionized trails at heights between 80 and 100 km, which reflect radio waves. The SGO MR is a commercially-produced SKiYMET all-sky interferometric radar with standardized software for data processing. It consists of one antenna transmitting spherical VHFwaves at 36.9 MHz and five antennas receiving reflections from the meteor echoes. The phase differencesin the signals arriving at each of the antennas are used to determine an unambiguous angle of arrival. The MR observations of the position and radial velocity of several thousand trails per day allow determining the zonal and meridian components of the neutral wind at ~3 km height intervals from 82 km to 98 km altitude with 1 h time resolution. The daily temperature data at the height of maximum meteor detection at ~90 km are calculated from the decay time meteor trails (Hocking, 1999). In the winter of 2019/2020, SGO MR provided measurements near the edge of the stratospheric polar vortex, where the strongest anomaly of geopotential height (GPH) at a pressure level of 10 hPa was about -5 10^4 m.

The Aura satellite has a Sun-synchronous, near polar orbit at ~700 km altitude with 13 orbits per day. The local times when passing the SGO MR location are about 3 and 12 hr local time. The MLS facility on board the satellite observes the faint microwave emissions from the Earth limb viewing forward along theflight direction. Above the stratopause, the vertical resolution is approximately 8 km, the horizontal resolution is ~170 km along the orbital track and 12 km cross track. Temperatures at 54 levels from 1000 to 0.0001 hPa along each orbital track are available from the MLS with 1-2.5 K precision. The MLS data L2 V003 (Livesey et al., 2020) are used to obtain the vertical temperature profiles at latitude 67.5°N and longitudes within 16.4–36.4°E (i.e. 10° to the east and to the west from the SGO MR longitude).

Climate reanalysis data from MERRA-2 beginning in 1980 to the present are used to construct the temperature fields in December 2019-January 2020. The 3-hr temporal and 0.5°×0.625° spatial resolution data are available via a web-based system NASA Giovanni (Geospatial Interactive Online Visualization And aNalysis Infrastructure) developed by the Goddard Earth Sciences Data and Information Services Center (GES DISC).

3. Winds

3.1 Zonal wind in the stratosphere

The stratospheric polar vortex is represented by a circumpolar westerly flow, cold temperatures and small GPHs in the center. **Fig. 1** depicts the daily MERRA-2 stratospheric zonal-mean zonal winds at various stratospheric heights from 100 to 0.1 hPa in December-February. The pressure levels of 10 hPa (this pressure is recommended by the World Meteorological Organization for definition of a polar vortex in association with a SSW) and 0.1 hPa (the uppermost level of the reanalysis) are highlighted in blue and red, respectively. Other lines in the figure correspond to 100, 70, 50, 40, 30 and 20 hPa (black), and 7, 5, 4, 3, 2, 1, 0.7, 0.5, 0.4 and 0.3 hPa (gray). The first plot (**Fig. 1a**) represents the circumpolar flow averaged over 60°–80°N, and the second plot (**Fig. 1b**) shows a portion of the polar vortex just above the SGO MR. The latter winds are averaged over 65°–69°N and 6°–46°E, that is, over the area centered at the SGO MR location and extended to 2° north and south and to 20° east and west. Both the global vortex and its local part are relatively coherent, although the latter has higher velocity and variability. The velocity starts to increase in mid-December. The 10 hPa eastward winds are accelerated up to 50 m/s (the zonal mean zonal wind within the vortex) and 80 m/s (the local part of the vortex). These are relatively high values, and in the winter of 2019-2020 the zonal mean zonal wind is the third largest across all MERRA-2 years.

Eastward winds in the upper stratosphere (between 7 and 0.1 hPa) are faster than those in the middle/low stratosphere (from 100 to 10 hPa) until January, when the upper stratospheric winds became several tens km/s stronger than the underlying winds.While the flow is eastward throughout the stratosphere, the abrupt change in velocities at 10 hPa and 0.1 hPa forms a remarkable vertical wind shear. The shear in the mean circumpolar flow is smoothed and accompanied by wave activity. The shears at specific locations can be much larger than the mean values. At the very beginning of January, the vortex above SGO (**Fig. 1b**) shows a tendency to decelerate, and then its velocity again increases up to 100 m/s. The actual vertical shear (alternation of wind velocities at the lower and upper levels) occurs on January 7, when the difference between velocities is about 70 m/s or vertical shear is ~2 m/s/km.

3.2 Mesospheric winds

Changes in MLT circulation during the December-February are plotted in **Fig. 2** that shows the SGO MR zonal and meridional winds at heights between 82 and 98 km. The climatology of the MLT winds is dominated by seasonal variation. During the winter season the zonal winds are eastward at all heights. The meridional winds are more variable, but typically poleward flow is observed at lower levels, while above 85 km height the flow is equatorward (Lukianova et al., 2018). The wind structure seen in **Fig. 2** differs from the climatological means in strength and direction. Similar to the stratosphere, several intense zonal wind shears occur from late December till mid-January. Apparent in **Fig. 2a** are the strong, short-lived pulses of the eastward wind (up to 55 m/s) propagating from above to the lower boundary of the MR observational area. The largest wind shears occur in the first half of January, and the shear line is located near the mesopause at an altitude of ~ 86 km. The meridional winds are dominated by the wave-like structure with alternating northward and southward flows at all heights. Since the horizontal meridional flow is considered as a part of the global high-altitude circulation, the upper atmospheric layers may also be involved in the disturbances.

4. Mesospheric temperature

Mesospheric and stratospheric temperatures are significantly anticorrelated (Siskind et al., 2005). The annual pattern from the SGO MR temperature related to an altitude of 90 km consists of warm winters (~180 K) and cold summers (~120 K). The daily values are more perturbed in winter andmay suddenly drop down to 150 K during a SSW (Lukianova et al., 2015). Recently, it was also noticed that the temperature during the Geminids meteor shower in December is likely underestimated by the routine MR calculations. This is because of very specific properties of the meteoroids belonging to the shower. The same, albeit much weaker, effect was found in early January during the Quadrantids (Kozlovsky et al., 2016). Keeping these limitations in mind we will estimate the temperature perturbations in the months of interest using the SGO MR and the Aura satellite MLS instrument.

Fig. 3 shows the daily temperatures measured locally. The SGO MR and Aura MLS temperatures are depicted together in **Fig. 3a**. For the MLS, data from latitude 67.5°N and longitudes within 16.4–36.4°E (10° to the east and west from the SGO longitude) are included in the analysis. Temperatures from the two longitudinally spaced tracks (the descending and ascending modes) are linearly interpolated and centered to 26.4°E. For the SGO MR, several days in the mid-December during the Geminids are excluded. The main feature noteworthy in **Fig. 3a**, is a temperature drop that begins in late December, peaks inearly January (down to 150 K, on average), and saturates in mid-January. The timing of the observed cooling corresponds to the largest wind shears in the MLT seen in **Fig. 2b**. The MLS temperature variation agrees in shape and amplitude with that observed by SGO MR, but with about 40 K offset. Most probably, the offset indicates a systematic error in the MR temperature estimate as was previously mentioned (Lukianova et al., 2015).

Quite surprisingly, there is an episode of cooling of the mesosphere, when the stratospheric polar vortex remains undisturbed. However, a localized warming in the upper stratosphere may affect the mesosphere. **Fig. 3b** depicts the MERRA-2 temperatures at three levels: 10, 2 and 0.1hPa. One can see that in early January a warming occurs at 2 hPa, where the temperature increases by about 50 K. Simultaneously, a cooling tendency is observed at 0.01 hPa. There is very little warming at the level of 10 hPa, although somewhat later there is a short increase of about 30 K after the initial warming in the higher stratosphere. The temperature fields from MERRA (not shown) provides an indication that the temperature enhancement may be a signature of wave 1 which extends up through the upper stratosphere to just above 2 hPa.

5. Vertical temperature profiles and mesospheric inversion layers

Fig. 4 showshow the temperature profiles evolve at the peak of the dynamic disturbancesat MLT heights. To obtainthe daily profiles, the values from the ascending and descending nodes are averaged. Overall, seven days are presented: a day prior to the MLT wind shears and cooling (December 20), five consequent days during the peak of the dynamic perturbations in the mesosphere (January 3-7) and a day belonging to the period after relaxation (February 5). The horizontal lines mark the 82–98 km range, in which the MR detects most of the meteor trails, and the 90 km altitude as the reference point for temperature measurements.

In **Fig. 4**, it can be seen that the profiles corresponding to December 20 and February 5 are relatively flat in the mesosphere, showing monotonic cooling with height. On January 3-7, on each temperature profile, a vertically narrow layer of elevated temperatures is observed, which is approximately 20 K above the background profile. Such inversions are located between 85 and 90 km. In the upper part of the layer, where the gradient changes sign, cooling is restored with increasing height up to the mesopause. Overall, the inversions are long-lived, lasting on the order of a month. The temperature enhancements vary slightly in depth but do not appear to move vertically, although any movement on spatial scales less than the 8 km vertical resolution may be missed. It is also noteworthy that a secondary inversion layer sometimes occurs in the upper stratosphere. For example, the secondary layers are seen in the profiles of January 6 and 7, with the first one being at a higher altitude, resembling a descending.

Discussion

The MR and satellite observations presented above reveal that several dramatic meteorological disturbances affecta wide range ofupper altitudes in the high latitude winter atmosphere under conditions of a strong stratospheric jet. The overlying MLT region is disturbed by wind shears, thermal inversion layers and planetary wave activity.

Lawrence et al. (2020) pointed out that the stratospheric polar vortex was extraordinarily strong during the Northern Hemisphere winter of 2019/2020 due to unusually weak tropospheric wave activity. An additional specific feature was that several transient wave pulses created a reflective configuration of the stratospheric circulation by disturbing the vortex in the upper stratosphere. Our results confirm the fact that the upper stratosphere was disturbed in such a way that a strong wind shear occurred above 10 hPa GPH in early January. In particular, prior to this, the velocity of the zonal-mean zonal winds in the upper stratosphere exceeded the velocity of the lower stratospheric winds (on average by 30 m/s), while during the rest of the winter, the wind structure was opposite.

Dedicated observationsof the MLT region (82-98 km height), carried out at a specific location near the edge of the polar vortex, have shown several successive pulses of the eastward wind during the period from late December to mid-January (see **Fig. 2**). The wind cores move downward, producing wind shears, with the first occurring at an altitude of about 94 km or higher, and the next occurring at an altitude of 88 km. Such a signature may be indicative of a waveform whose phase propagates both horizontally and somewhat vertically. To determine the true direction, analysis of multi-radar observations is required.At the current stage, with one-radar observations, it is nevertheless obvious that in the mid-winter, when an extremely strong polar vortex was formed, the impulsive enhancement of the zonal circulation spread over a wide range of heights above 10 hPa. At the same time, the observed vertical wind shears (in order of units of m/s/km) are considerably weaker than those could be sustained at ~90 km before the atmosphere undergoes dynamic instability according to the estimate by Liu (2017) (tens of m/s/km).

During the 2019-2020 winter months, the MLT region is also dominated by approximately 16-day waveforms, which are manifested in the systematic alternation of poleward and equatorward winds. Over the entire period of operation since 2008, such persistent large-scale wave activity in the meridional componenthas not been observed by the SGO MR in no other winter, and, usually, the long-period waves are less pronounced. Instead, the mesosphere is believed to be dominated by inertia–gravity wave (GW) activity (e.g. De Wit et al., 2014).

Another interesting feature of the thermal structure of the MLT is the relatively long-lived thin inversion layer/temperature enhancements superimposed on the slight temperature reduction in January. There are at least two physically different formation mechanisms responsible for thermal inversion layers. First, inversions are generated by GW-tidal interactions that occur at altitudes between 85 and 100 km (Meriwether & Gerrard, 2004). With the usual vertical coupling of the stratosphere and the MLT region, when the polar stratosphere is disturbed by planetary waves destroying the polar jet, a corresponding wind reversal also occurs in the MLT, allowing the GW to break there. However, in the winter of 2019-2020, the situation seems the opposite, since fewer GWs propagate upward through the well-developed stratospheric polar vortex.Another mechanism is chemical heating in the MLT region due to exothermic reactions (Mlynczak & Solomon, 1993; Singh & Pallamraju, 2018). Odd oxygen and odd hydrogen reactions are the most important in the MLT. The heat may be released in exothermic reactions over time and place that can be away from the location of initial absorptionof the solar energyby the atmospheric constituents. In particular, the poleward portion of the meridional winds may play a role in the transport of these species to the high-latitude MLT.

Conclusion

We present observational evidence of the disturbed mesosphere-lower thermosphere region overan exceptionally strong, cold and persistent Arctic stratospheric polar vortex in the winter of 2019–2020. During the period from late December to mid-January the meteor radar of the Sodankyla Geophysical Observatory, Finland, (67°N) observes several successive pulses of the eastward wind velocities up to 50 m/s. These winds first appear at high altitudes so that significant vertical wind shears are generated. In early January, strong shears are also formed in the upper stratosphere. Thus the zonal flow above the core of the stratospheric jet appears to be considerably stratified. The meridional component of the MLT winds is dominated by the alternating north- and southward flows with a period close to a 16-day planetary wave. Temperatures at MLT heights show a decrease, likely associated with a warming in the stratosphere at about 2 hPa GPH. Superimposed on the temperature reduction, the long-lived inversion layer of ~20K persists just below the mesopause. Since thermal and dynamic perturbations in the MLT occur rather independently on the relatively stable underlying stratospheric vortex, the observed features may be indicative of a decoupling of the middle and upper atmosphere.

Data Availability Statement

NASA MERRA-2 data are available from NASA's GES DISC web-based system Giovanni (https://giovanni.gsfc.nasa.gov/giovanni/); AURA MLS temperature data are available from the Open-source Project for a Network Data Access Protocol (OPeNDAP) (https://acdisc.gesdisc.eosdis.nasa.gov/opendap/hyrax/HDF-EOS5/Aura_MLS_Level2/ML2T.005); the data from the Sodankyla Geophysical Observatory Meteor radar are available at https://www.sgo.fi/Data/observations.php.

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Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

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Figure captions

Figure 1. The daily MERRA-2 zonal-mean zonal winds (a) within 60°–80°N and (b) within 65°–69°N and 0°–50°E from 100 to 0.1 hPa in December-February. The red (blue) lines show the winds at 10 (0.1) hPa.

Figure 2. (a) Zonal and (b) meridional winds (in m/s) measured by the SGO MR between December 2019 and February 2020. Positive values correspond to the eastward (northward) zonal (meridional) wind, black lines mark the zero wind.

Figure 3. (a) Daily averaged temperatures at 90 km from the SGO MR (open circles) and MLS (black dots and -intervals); (b) 3-hr temperatures at 10hPa (black), 2hPa (red) and 0.1hPa (blue) from MERRA-2 in December-February.

Figure 4. Vertical temperature profiles over SGO as observed with the MLS at the heights from 10 hPa to 0.0001 hPa on December 20, January 3-7 and February 5. The height range of inversions is shaded.