Multilevel cloud structures over Svalbard

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Abstract

The presented picture of the month is a superposition of space-borne lidar observations and high-resolution temperature fields of the ECMWF integrated forecast system (IFS). It displays complex tropospheric and stratospheric clouds in the Arctic winter 2015/16. Near the end of December 2015, the unusual northeastward propagation of warm and humid subtropical air masses as far north as 80°N lifted the tropopause by more than 3 km in 24 h and cooled the stratosphere on a large scale. A widespread formation of thick cirrus clouds near the tropopause and of synoptic-scale polar stratospheric clouds (PSCs) occurred as the temperature dropped below the thresholds for the existence of cloud particles. Additionally, mountain waves were excited by the strong flow at the western edge of the ridge across Svalbard, leading to the formation of mesoscale ice PSCs. The most recent IFS cycle using a horizontal resolution of 8 km globally reproduces the large-scale and mesoscale flow features and leads to a remarkable agreement with the wave structure revealed by the space-borne observations.

1 Introduction

The "picture of the month" as presented in this short contribution is not a photo of the sky spontaneously shot from a digital camera. The picture as displayed in Figure 1 is a combination of space-borne measurements by the CALIOP (Cloud-Aerosol LIdar with Orthogonal Polarization) instrument onboard the CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations) satellite during one of several Arctic overpasses on 30 December 2015 and a high-resolution short-term forecast of a numerical weather prediction (NWP) model utilizing an unprecedented global resolution of about 8 km (for data sources, see Appendix). In our days of ceaseless swells of pictures taken everywhere and anytime on the planet, a snapshot taken from a sensor much different than a camera, taken from a perspective so much different than from Earth, and superimposed with numerical predictions reflecting the observed flow features with a remarkable realism elicits wonder and admiration.

The selected "picture of the month" displays tropospheric and stratospheric cloud structures which appeared simultaneously during a remarkable meteorological situation in the high Arctic near Svalbard on 30 December 2015. The resulting spectacular and uncommon appearance of diverse cloud types and structures at different layers reaching up to 28 km altitude was documented by the CALIOP measurements of total attenuated backscatter at 532 nm (Fig. 1a). The CALIOP observations show an extensive, elongated structure of cirrus clouds within the upper troposphere up to an altitude of about 13 km. The cirrus clouds are also nicely seen in the infrared satellite image at this time (Fig. 2). Slightly more than 6 km above this cirrus deck, CALIOP detected a nearly 8 km deep layer of synoptic-scale polar stratospheric clouds (PSCs) embedded in an extended cold layer with temperatures less than 191 K. Within this layer, vertically tilted and horizontally separated patterns of enhanced attenuated backscatter are collocated with cold stratospheric temperature values less than 185 K (Fig. 1b). They are reminiscent of mountain-wave induced PSCs (e.g. Maturilli and Dörnbrack, 2006, Fig. 9). This first, qualitative interpretation is supported by the very structured PSCs occurring in a region both above and downstream of Svalbard's mountains and above the underlying clouds near the tropopause as mentioned above. As shown later, the satellite trace as sketched in Figs, 3 and 6 was nearly parallel to the stratospheric winds and the mountain-wave induced temperature are tilted into the ambient wind.

The spectacular display of PSCs[1] has fascinated people for a long time and they have been observed scientifically since the 1880s (e.g. Backhouse, 1885, Geelmuyden, 1885, Mohn, 1893, Stanford and Davies, 1974). A first step to explain the nature of these clouds was the exact determination of their height range between 20 and 30 km by Störmer (1929, 1931). During the recent thirty years, PSCs were systematically monitored because chemical reactions on cloud particles play a major part in the depletion of the ozone layer (Solomon, 1999). The reactions are very efficient at low temperatures due to the increase in particle surface area and in heterogeneous reaction rates (Peter, 1997). The large interannual variability of the Arctic polar vortex and of the polar cap minimum temperatures attained during northern hemispheric winters (Fig. 3) regularly sparks off the scientific interest about the possible formation of PSCs and the consequential ozone depletion in spring. For an overview of the evolution of the recent winter 2015/2016, see the excellent overview by Manney and Lawrence (2016).

PSCs form in a variety of ways. First of all, the ambient stratospheric temperatures must fall below a certain threshold where liquid or solid particles can form. Here, different freezing processes (homogeneous and/or heterogeneous freezing) determine the composition of the PSC particles. Generally, one differentiates between ice PSCs, which can exist at $T < T_{FROST}$, solid nitric acid trihydrate (NAT) PSCs, which can exist at $T < T_{NAT}$ ($\approx T_{FROST} + 7$ K), and liquid

[1] These clouds are often called mother-of-pearl clouds because of their magnificent display of spectral colors.

supercooled ternary solution (STS; $HNO_3/H_2O/H_2SO_4$) PSCs, which can exist at T ≲ T_{FROST} + 3 K. Since T_{FROST} depends on atmospheric humidity it varies with altitude (T_{FROST} ≈ 188 K at 50 hPa and T_{FROST} ≈ 185 K at 30 hPa). PSCs can be observed in-situ by instruments flying on balloons (e.g. Rosen et al., 1992) or by in-situ airborne sensors (e.g. Dye et al., 1996). The high altitudes and vertical extent of PSCs favor remote-sensing systems such as lidars operated on ground (e.g. di Liberto et al., 2014), on aircraft (e.g. Browell et al, 1990), or on satellites (e.g. Strawa et al, 2002). Most of the recent studies on PSCs focused on the composition and sizes of the particles (e.g. Reichardt et al., 2015) and chemical processes occurring at their surfaces that yield ozone-destructive, reactive chlorine species (e.g. Solomon, 1999).

Numerical modelling of PSCs has always been a challenging task as chemical and dynamical aspects of their formation and existence must be combined (e.g., Reichardt et al., 2004). Their formation is primarily influenced by large-scale processes such as the radiative cooling inside the Arctic polar vortex. Moreover, it is known that both synoptic-scale as well as mesoscale weather systems influence the formation of PSCs and the associated chemical reactions (Teitelbaum and Sadourny, 1998, Carslaw et al., 1998). Simulation of mesoscale mountain waves especially posed a challenge, and special methods such as linear wave prediction models and mesoscale forecast models were used in the past to predict their local formation (e.g., Dörnbrack et al., 1998, Eckermann et al., 2006). In this day and age, global operational NWP models use spatial resolutions which hardly could be attained by limited area models several years ago. For example, the European Centre of Medium-Range Weather Forecasts (ECMWF) currently runs its operational predictions of the Integrated Forecast System (IFS) cycle 41r2 at 8 km globally (Hólm, et al, 2016, Malardel and Wedi, 2016). Here, it will be shown that the conditions under which the observed mesoscale ice PSCs formed can be resolved by the IFS..

2. Weather Situation and Gravity Wave Characteristics

Cold Arctic Polar Vortex

The composite "picture of the month" was taken in a period when the temperatures inside the Arctic stratospheric vortex were unusually cold (Fig. 3). In November/December 2015, the Arctic vortex was minimally disturbed by upward propagating planetary waves and the polar cap minimum temperature T_{MIN} between 65°N and 90°N dropped well below the climatological mean. The red T_{MIN}-line in Fig. 3 reveals that the threshold of T_{NAT} at 50 hPa was already reached at the beginning of December 2015, and T_{MIN} dropped below T_{FROST} at the end of 2015. Apparently, the minimum temperatures falling below T_{FROST} at the end of the year constitute a new record. In its further evolution, the Arctic polar vortex remained cold, stable and coherent until end of February 2016 (Manney and Lawrence, 2016). The final warming already occurred early at the beginning of March 2016 in accordance with the findings of the climatological study of Hu et al. (2014). In such a cold stratospheric environment, the period of temperatures below T_{FROST} and T_{NAT} at 50 hPa lasted more than one month and three months, respectively. CALIPSO observations until the end of January 2016 confirm the widespread occurrence of PSCs in the Arctic.

Tropospheric Flow Conditions

Near the end of December 2015, the tropospheric flow over the Northern Atlantic was characterized by an anticyclonic Rossby wave breaking event. Figure 4 illustrates the late stages of this event by means of the height and wind at the 2 PVU surface from the ECMWF operational analyses valid on 29 December 2015 at 18 UTC and twelve hours later on 30 December 2015 at 06 UTC, respectively. A ridge with tropopause heights of up to 13 km extended north to latitudes above 80°N. Between this ridge with high surface pressure (maximum at about 1038 hPa) over Eastern Europe and a surface pressure low over Greenland (minimum at about 968 hPa), a strong south-westerly low-level flow extended over the entire northern Atlantic and the Norwegian Sea towards Svalbard (Fig. 5 a, b). East of Greenland, warm and moist air was advected northwards as shown by the increased values of the equivalent potential temperature (Fig. 5 c, d). Further south near Iceland, a storm with a core pressure of 930 hPa on 30 December 2015 at 06 UTC propagated north. This weather situation led to a combination of two processes relevant for the cloud structures as shown in Fig. 1. First, the increase of the tropopause height associated with the anticyclonic Rossby wave breaking led to a cooling of the air masses in the upper troposphere and lower stratosphere (UTLS) due to adiabatic expansion. Secondly, the strong troposphere-deep pressure gradient between the upstream Greenland/Iceland cyclone complex and the downstream Scandinavian ridge forced a strong flow across the mountains of Svalbard which reached a maximum at 30 December 2015 at 00 UTC with horizontal winds larger 25 m s^{-1} at 700 hPa (Fig. 5 e, f).

A series of five radiosonde ascents from Ny-Ålesund, Svalbard covering the period from 27 to 31 December 2015 (Fig. 6) illustrates the previous findings from the IFS analyses. First of all, the warming of the troposphere by about 15 K due to the warm-air advection can be clearly seen in Fig. 6a. During the same period, the tropopause rose and sharpened dramatically. Indeed, the vertical temperature profiles of 29 and 30 December 2015 at 12 UTC are more typical for a mid-latitude station than for an Arctic location.

Large-scale cooling

An analysis of radiosonde soundings from Ny-Ålesund, Svalbard (79°N, 12°E) reveals a drop of the mean temperature between 10 and 13 km by about 9 K in three days reaching 200 K on 29 December (see Table 1). This strong cooling associated with the tropopause ascent led to the formation of the observed cirrus clouds at these levels. Not only the temperature in the vicinity of the tropopause dropped, but the mean stratospheric temperature between 20 and 25 km altitude also decreased by about 4 K due to the lifting of the atmosphere above the ridge (Table 1). In this way, the mean temperatures near 30 hPa dropped below 185 K, the ice existence temperature T_{FROST}. However, increased backscatter values indicative of ice PSCs appear primarily at and leeward of the wave crests as shown in Figure 1a. The adiabatic cooling by ascending air parcels leads to a local temperature decrease and to ice nucleation which require temperatures $T \lesssim T_{FROST} - 4$ K. Thus, we conclude that the stratospheric ice clouds as seen by CALIOP were generated due to mountain-wave induced temperature anomalies.

Mountain-wave induced cooling

As documented in Table 1, the magnitude of stratospheric temperature fluctuations ΔT^{SP} measured in the layer from 20 to 25 km increased from values of around 5 K on 26 December 2015 to values up to 12 K on 29 and 30 December 2015. These fluctuations are represented by the wave-like temperature perturbations as shown in Fig. 1b. There, the areas of increased backscatter nearly coincide with localized regions of $T < T_{FROST}$. It must be noted that the CALIPSO satellite trace was nearly aligned with the stratospheric winds as indicated by the orientation of the contour lines of the geopotential height in Fig. 7. Therefore, the ice PSCs as well as the simulated mountain waves are tilted into the ambient stratospheric wind which is oriented from west to east in Fig. 1. The tilting into the ambient wind is characteristic for upward propagating mountain waves (Nappo, 2002).

Figure 7 depicts horizontal cross-sections of the stratospheric wave structure at 10 hPa and 30 hPa by means of the vertical velocity and the absolute temperature from IFS analyses. A sequence of northwest-southeast oriented updraft-downdraft couplets extends from Svalbard towards the northeast. Altogether, there are four stratospheric cold anomalies associated with the adiabatic cooling in the mountain waves at 10 hPa (Fig. 7 a, c). Their positions clearly correspond to the areas of T < 185 K and the CALIOP PSC observations as presented in Fig. 1b. At the lower level of 30 hPa (Fig. 7 b, d), similarly oriented structures exist whereby the cold areas are slightly shifted to the northeast in accordance with the tilt of the observed PSCs (Fig. 1).

Gravity Wave Characteristics

Mountain waves are generated and propagate into the stratosphere if there is a major flow across the topography (low-level forcing), the tropospheric and stratospheric winds are large enough to avoid the formation of wave-induced critical levels, and there is no significant turning of the wind with altitude. All these requirements were satisfied in the Svalbard region for the period from 28 to 30 December 2015. The horizontal wind in the lower troposphere (averaged from 2 to 5 km altitude) increased gradually from about 5 m s^{-1} to about 30 m s^{-1} in the period from 25 to 31 December 2015 as shown by the radiosonde data (Figure 8a). Also near the tropopause level, the averaged wind in the UTLS increased markedly after 28 December up to values of 60 m/s and turned from westerly to southwesterly as the ridge propagated over Svalbard (Table 1). Altogether, the directional shear between tropospheric and stratospheric winds weakened in this period (Fig. 6c). The combination of strong winds in the lower troposphere followed by increased mid- to upper tropospheric winds and the presence of wind of about 25 m s^{-1} in altitudes above (15 to 25 km) created a favorable flow situation for mountain wave excitation and vertical propagation to higher altitudes. Indeed, both the temperature and wind profiles reveal wavelike structures in the stratosphere (Fig. 6) which were analyzed to extract the kinetic and potential energies of the gravity waves as well as their intrinsic frequency and horizontal wavelength from the radiosonde soundings.

For this purpose, a polynomial fit is applied to calculate background profiles of the horizontal wind components and the potential temperature from the radiosonde profiles between 15 and 25 km altitude. The perturbations calculated as difference between the background profiles and the actual radiosonde profiles are treated as signatures of internal gravity waves from which the kinetic and potential energies are determined according to Murphy et al. (2014). Figure 8b shows a peak in the stratospheric kinetic and potential energy densities at 30 December 2015. This enhancement as well as the localized wave appearance over and in the lee of Svalbard (Fig. 7) indicate that the waves are generated by the flow above the mountains. Stokes analysis of the velocity perturbations (Eckermann and Vincent, 1989) of the 30 December radio sounding revealed the intrinsic frequency Ω of the dominant gravity wave mode being 6.7 f, where f is the Coriolis parameter. Assuming that the dominant gravity wave mode is a stationary mountain wave its horizontal wavelength can be calculated using the relationship between Ω, horizontal wavenumber k and the background wind U for stationary waves, i.e. $\Omega = -kU$ (Nappo, 2002). Having a background wind of 25 to 35 m s^{-1} (Fig. 8a) the determined horizontal wavelength is approximately 180 … 250 km. The effect of the Coriolis force alters the dispersion relationship of non-rotating hydrostatic gravity waves and allows a slantwise, e.g. horizontal and vertical, propagation (Gill 1980, Chapter 8). This explains the multiple mountain-wave induced temperature anomalies separated by about 180 km (Fig. 1b and Fig. 7d). Another example of a similar stratospheric cloud structure above Scandinavia and a more detailed discussion can be found in Dörnbrack et al. (2002).

The effect of mesoscale temperature fluctuations on the polar cap minimum temperatures T_{MIN} at 50 hPa is illustrated by the new IFS cycle 41r2. Figure 2 contains two T_{MIN} curves for a period of 3 months when the new IFS cycle was not yet operational. The red line depicts the former IFS cycle 41r1 with 16 km horizontal resolution and the shorter black line is T_{MIN} of the new, updated operational cycle 41r2 with 8 km horizontal resolution. After 8 March 2016, IFS cycle 41r2 became operational and continues as red line, Obviously, the higher resolution IFS run achieved much lower T_{MIN} in certain periods, especially at end of December 2015 and at the end of January 2016 when deviations of up to 7 K occurred. These mesoscale temperature fluctuations were generated by mountain wave activities at various places in the Arctic.

4. Conclusions

The uniqueness of this contribution to the “picture of the month” is not only justified by the unusual meteorological situation in the Arctic in mid-winter, but also by the co-existence of tropospheric clouds, i.e. cirrus clouds attached to a 12 km high and sharp tropopause, and different types of PSCs between 18 km and 28 km altitude over a limited area poleward of 80°N. Synoptic-scale lifting was responsible for formation of the ice clouds near the tropopause and NAT or STS PSCs in the stratosphere. The total large-scale ascent was also associated with the formation of an ozone mini-hole observed by OMI[2] which was generally aligned with the tropospheric ridge as shown in Fig. 3, see e.g. Peters et al. (1995) for dynamical aspects of ozone mini-hole formation. Adiabatic cooling in the ascending branches of mesoscale mountain waves dropped the stratospheric temperatures far below the threshold temperature for the existence of ice PSCs. The simultaneous formation of synoptic and mesoscale PSCs inside the Arctic stratospheric vortex happened during a rare meteorological situation during the Northern

[2] http://ozonewatch.gsfc.nasa.gov/Scripts/big_image.php?date=2015-12-31&hem=N

Hemisphere mid-winter. Moreover, it is the remarkable agreement of the simulated wave structure in the IFS short-term forecast and the space-borne observations which indicates a significant trend that the finer resolution and increasing realism of operational NWP model outputs offers a valuable quantitative source for mesoscale flow components which were hitherto not accessible globally.

Appendix

Numerical weather prediction model data

Operational analyses of the integrated forecast system (IFS) of the European Centre of Medium Range Weather Forecasts (ECMWF) are used to provide meteorological data to characterize the atmospheric situation. The operational analyses and forecasts of the deterministic high-resolution (HRES) IFS cycle 41r2 have a horizontal resolution of about 8 km (T_C1279) and 137 vertical levels (L137)[3]. The model top is located at 0.01 hPa. The enhanced horizontal resolution was achieved by changing from linear (T_L) to cubic (T_C) spectral truncation and introducing an octahedral reduced Gaussian grid. With the cubic spectral truncation the shortest resolved wave is represented by four rather than two grid points and the octahedral grid is globally more uniform than the previously used reduced Gaussian grid (Malardel and Wedi, 2016). In December 2015, the IFS cycle 41r2 was not yet in its operational mode but products were disseminated among the users. So, we were able to retrieve forecasts and analysis fields for the current contribution.

CALIPSO data

[3] https://software.ecmwf.int/wiki/display/FCST/Implementation+of+IFS+cycle+41r2 and http://www.ecmwf.int/en/about/media-centre/news/2016/new-forecast-model-cycle-brings-highest-ever-resolution

The primary instrument on CALIPSO is a lidar (CALIOP, or Cloud-Aerosol Lidar with Orthogonal Polarization) that measures backscatter at wavelengths of 1064 nm and 532 nm, with the 532-nm signal separated into orthogonal polarization components parallel and perpendicular to the polarization plane of the outgoing laser beam. A description of CALIOP and its on-orbit performance can be found in Hunt et al. (2009), and details on calibration of the CALIOP data are provided by Powell et al. (2009). CALIOP has proven to be an excellent system for observing PSCs (Pitts et al., 2007; 2009; 2011; 2013).

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Tables

Date	T^{TP} / K	V_H^{TP}/ m s^{-1}	α^{TP} / K	T^{SP} / K	ΔT^{SP} / K
26 Dec 2015	209.3	8.7	254	188.8	4.7
27 Dec 2015	209.6	27.7	296	187.4	6.5
28 Dec 2015	205.9	23.3	268	187.3	8.4
29 Dec 2015	200.0	23.6	240	184.4	12.0
30 Dec 2015	204.7	36.8	241	185.4	10.1
31 Dec 2ß15	204.1	59.8	199	183.9	6.8

Table 1: Mean quantities in the UTLS averaged from 10 to 13 km altitude: absolute temperature T^{TP}, horizontal wind V_H^{TP}, and wind direction α^{TP} from the radiosonde soundings in Ny-Ålesund. The mean stratospheric temperature T^{SP} is averaged from 20 to 25 km altitude and ΔT^{SP} is the difference between the measured maximum and minimum T in this layer.

Figures

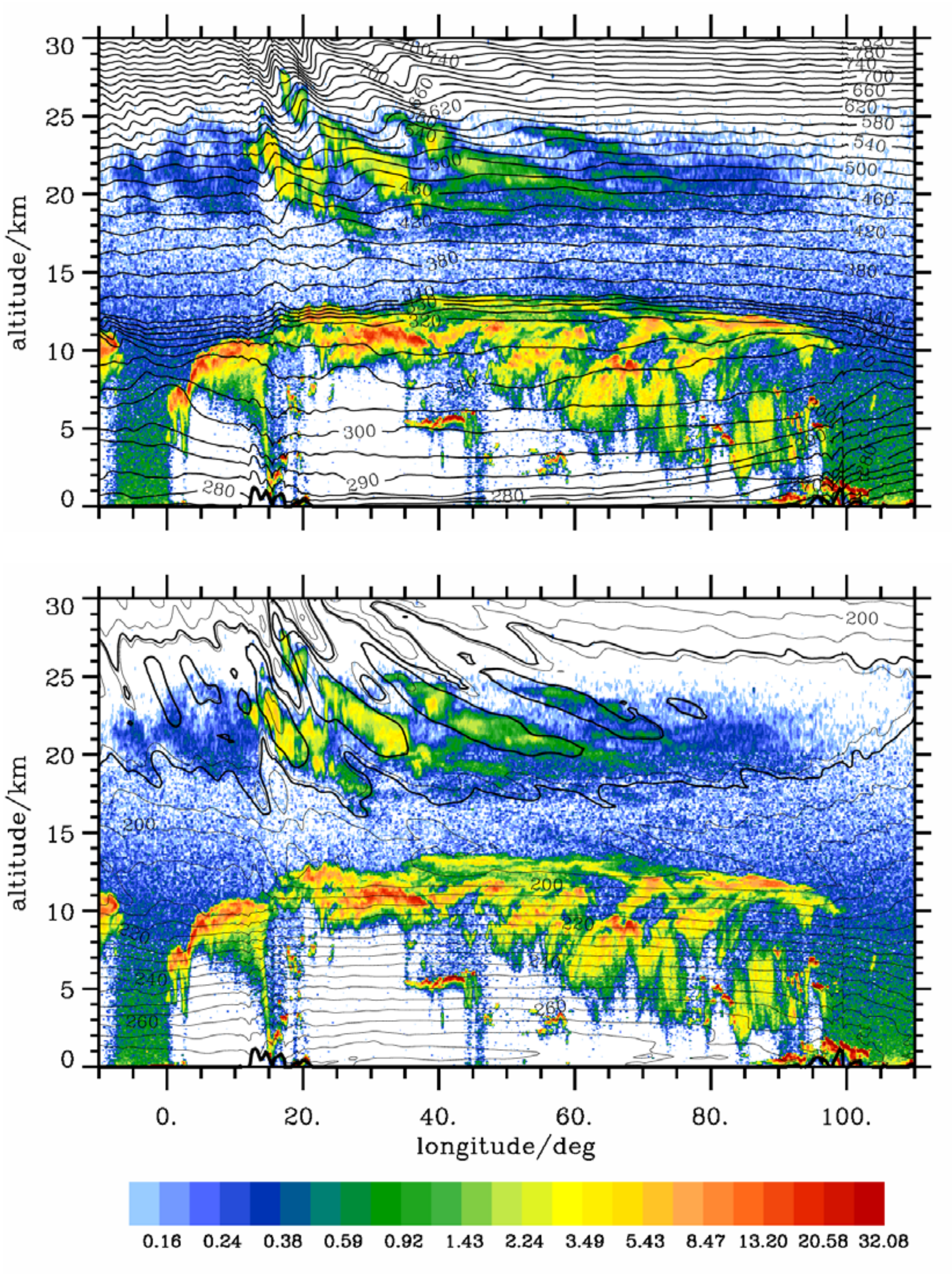

Figure 1: Composite of 532 nm total attenuated backscatter (10^{-3} km^{-1} sr^{-1}, color shaded) from CALIOP and ECMWF potential temperature (top, K, solid black lines) and absolute temperature (bottom, K, thin black lines every 5 K and thick black lines at 185 K and 191 K) valid on 30 December 2015 at 04 UTC (+ 4 h lead time from the 00 UTC high res IFS forecast of cycle 41r2.

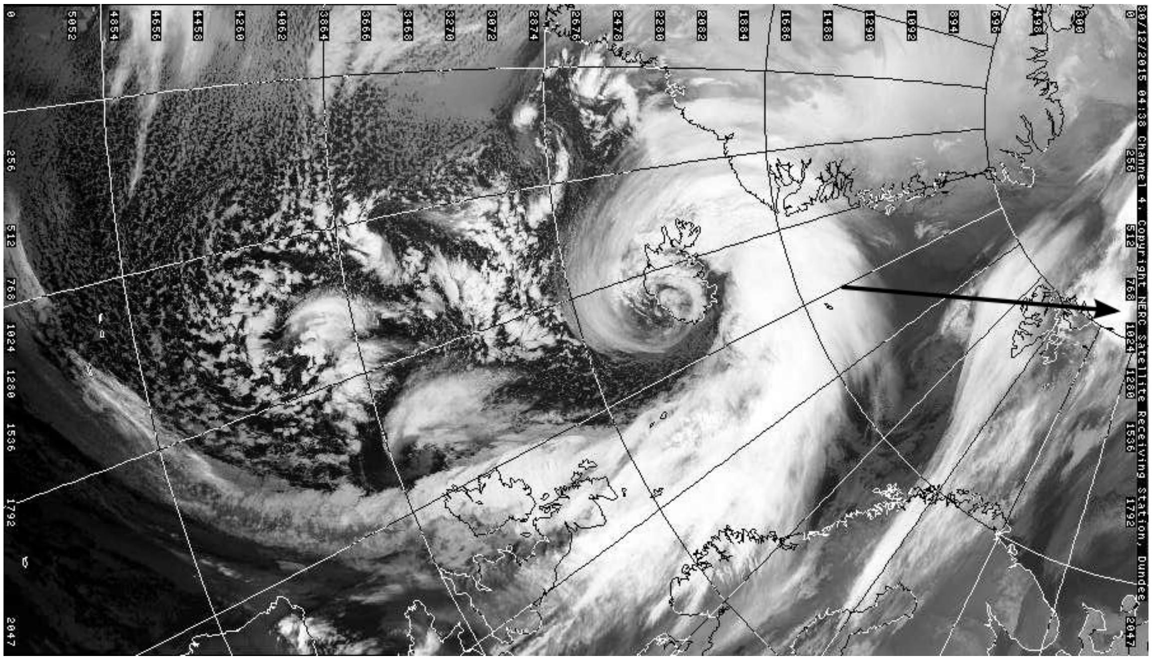

Figure 2: Thermal infra-red image (NOAA 19, channel 4: 10.3-11.3µm) on 30 December 2015 0440 UTC with the first third of the path of the CALIOP measurements (Fig. 1) as black arrow. Image provided by NERC Satellite Receiving Station, Dundee University, Scotland (http://www.sat.dundee.ac.uk).

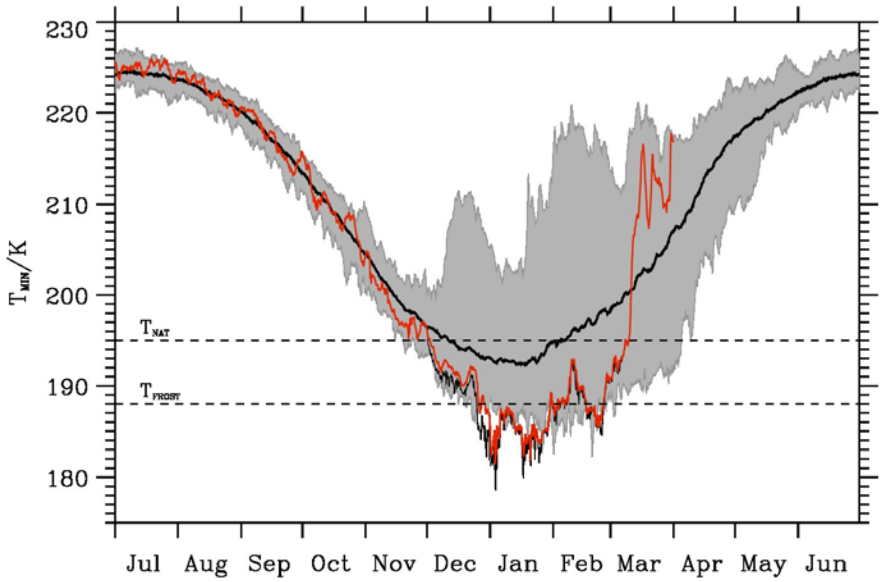

Figure 3: 6 hourly ECMWF reanalyses interim (ERA-Interim, Dee et al., 2011) data retrieved at a horizontal resolution of 1°: Minimum temperature T_{MIN} (K) between 65°N to 90°N at the 50 hPa pressure surface. Thick black line denotes the mean values of T_{MIN} averaged from 1979 – 2015, the shaded areas encompass the minimum and maximum values of T_{MIN} attained at every date between 1979 and 2015. The red line marks the evolution of T_{MIN} from operational analyses of the IFS cycle 41r1 until 8 March 2016. The thin black line indicates T_{MIN} from the IFS cycle 41r2 in the pre-operational phase 1 December 2015 until 8 March 2016 retrieved at a resolution of 0.125°. After 8 March 2016, the black line continues as red curve of the operational IFS cycle 41r2.

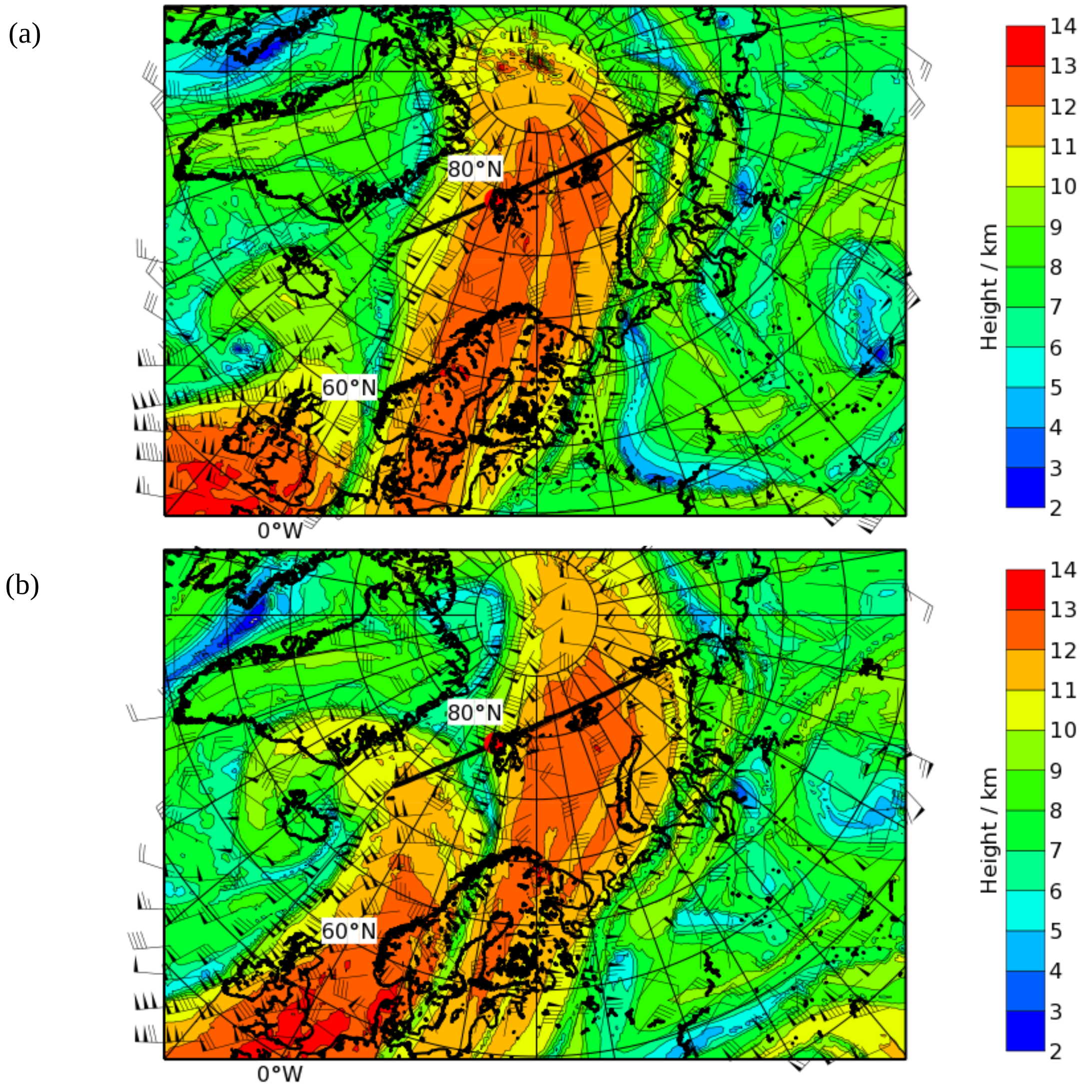

Figure 4: Height of the dynamical tropopause (km, color shaded) and horizontal wind (m s^{-1}, barbs) at the 2 PVU surface on 29 December 2015 18 UTC (a) and 30 December 2015 06 UTC (b). The path of the CALIPSO overpass is plotted as solid black line, the location of Ny-Ålesund, Svalbard is marked by a red dot.

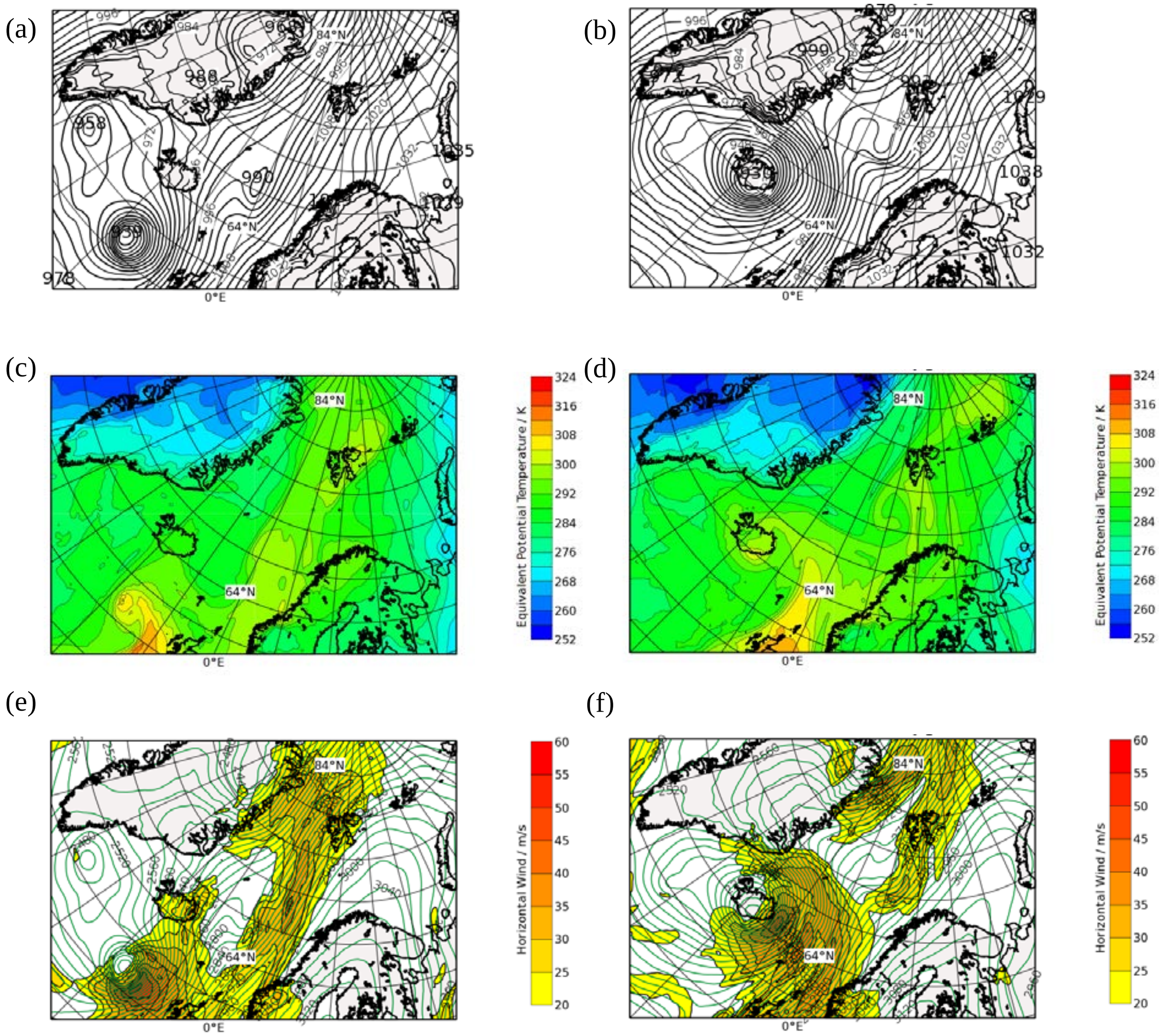

Figure 5: Tropospheric charts valid on 29 December 2015 18 UTC (left column) and 30 December 2015 06 UTC (right column). (a,b): Mean sea level pressure (hPa, contour lines), (c,d): Equivalent potential temperature (K, color shaded) at 850 hPa, and (e,f): horizontal wind (m s^{-1}, color shaded) and geopotential height (m, contour lines) at 700 hPa.

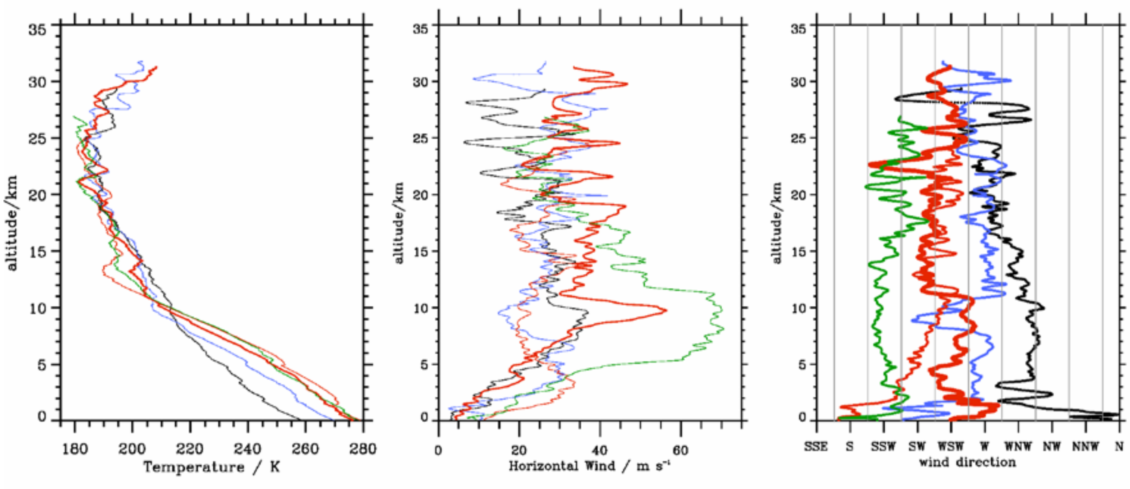

Figure 6: Vertical profiles of absolute temperature (a), horizontal wind (b), and wind direction (c) from radiosonde launches in Ny-Ålesund, Svalbard on 27 December (black), 28 December (blue), 29 December (thin red), 30 December (thick red), and 31 December (green) 2015 12 UTC, respectively.

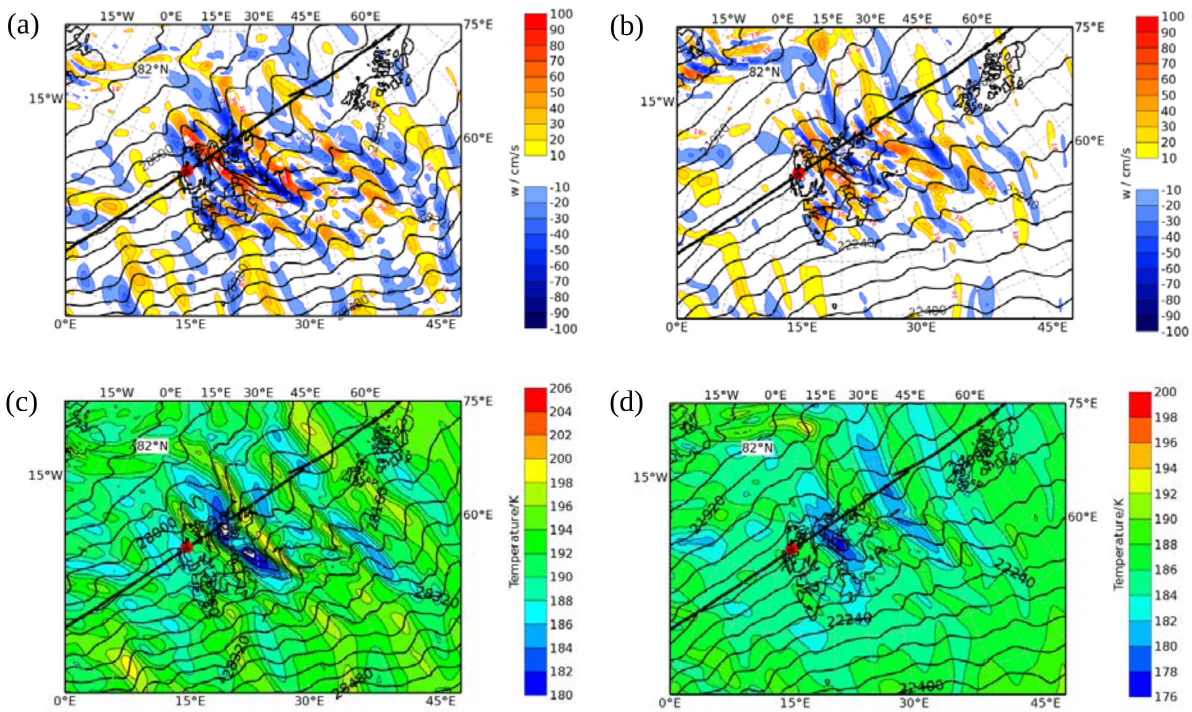

Figure 7: Vertical velocity (m s^{-1}, color shading, top row), absolute temperature (K, color shading, bottom row), and geopotential height (m, black contour lines) from the IFS cycle 41r2 at 10 hPa (a, c) and at 30 hPa (b,d) valid on 30 December 2015 06 UTC. The path of the CALIPSO overpass is plotted as solid black line, the location of Ny-Ålesund, Svalbard is marked by a red dot.

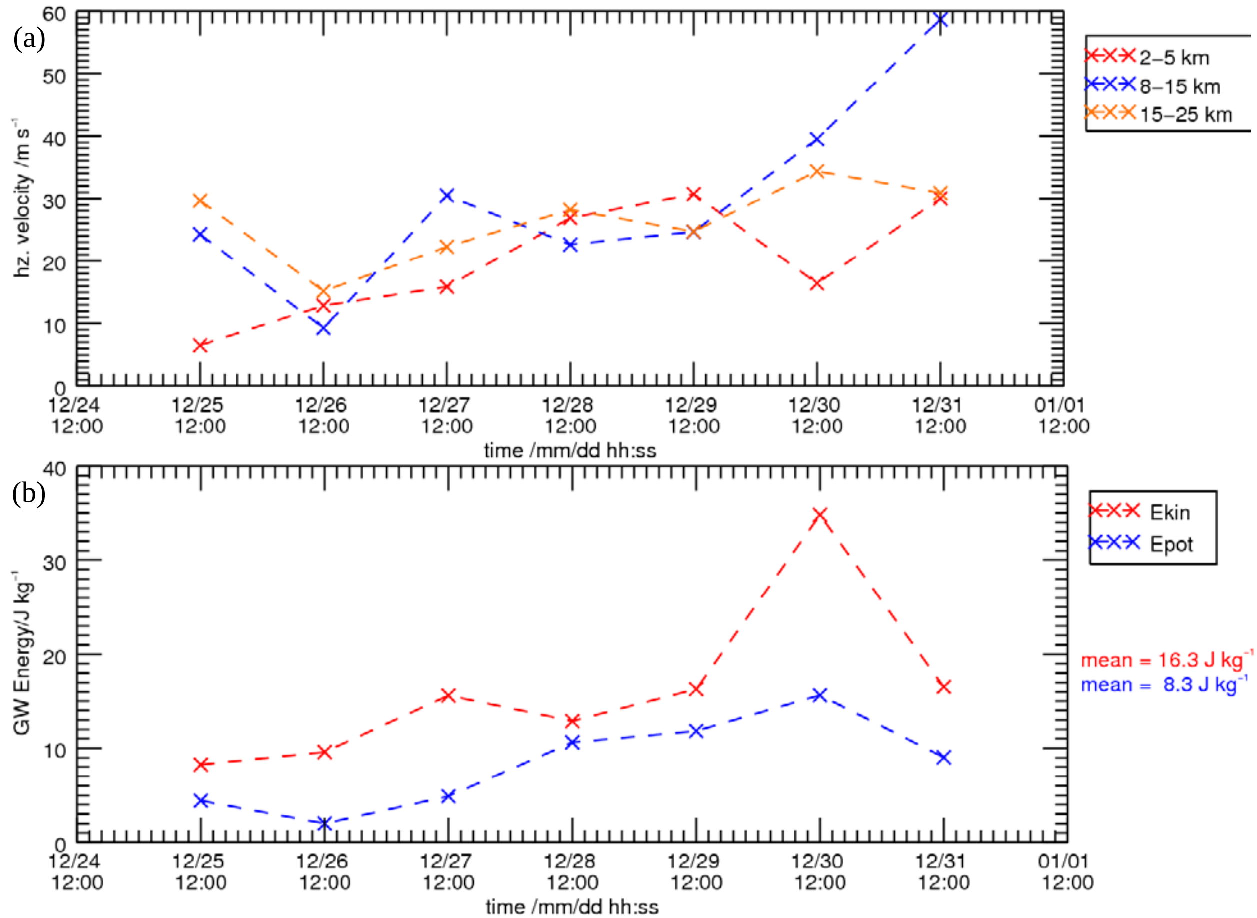

Figure 8: (a) Vertically averaged horizontal wind in the lower troposphere (2 to 5 km, red crosses), the tropopause region (8 to 15 km, blue crosses), and in the stratosphere (15 to 25 km, yellow crosses). (b) Stratospheric gravity wave kinetic and potential energies (red and blue crosses, respectively) determined from the radiosonde soundings of Ny-Ålesund, Svalbard in an altitude range of 15 to 25 km.