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Characteristics of Arctic winds at CANDAC-PEARL (80° N, 86° W) and Svalbard (78° N, 16° E) for 2006–2009: radar observations and comparisons with the model CMAM-DAS

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Abstract. Operation of a Meteor Wind Radar (MWR) at Eureka, Ellesmere Island (80° N, 86° W) began in February 2006; this is the location of the Polar Environmental and Atmospheric Research Laboratory (PEARL), operated by the "Canadian Network for the Detection of Atmospheric Change" (CANDAC). The first 36 months of wind data (82–97 km) are here combined with contemporaneous winds from the Meteor Wind Radar at Adventdalen, Svalbard (78° N, 16° E), to provide the first evidence for substantial interannual variability (IAV) of longitudinally spaced observations of mean/background winds and waves at such High Arctic latitudes. The influences of "Sudden Stratospheric Warmings" (SSW) are also apparent.

Monthly meridional (north-south, NS) 3-year means for each location/radar demonstrate that winds (82–97 km) differ significantly between Canada and Norway, with winter-equinox values generally northward over Eureka and southward over Svalbard. Using January 2008 as case study, these oppositely directed meridional winds are related to mean positions of the Arctic mesospheric vortex. The vortex is from the Canadian Middle Atmosphere Model, with its Data Assimilation System (CMAM-DAS). The characteristics of "Sudden stratospheric Warmings" SSW in each of the three winters are noted, as well as their uniquely distinctive short-term mesospheric wind disturbances.

Comparisons of the mean winds over 36 months at 78 and 80° N, with those within CMAM-DAS, are featured. E.g. for 2007, while both monthly mean EW and NS winds from CMAM/radar are quite similar over Eureka (82–88 km), the modeled autumn-winter NS winds over Svalbard (73–88 km) differ significantly from observations. The latter are southward, and the modeled winds over Svalbard are predominately northward. The mean positions of the winter polar vortex are related to these differences.

Keywords. Meteorology and atmospheric dynamics (Middle atmosphere dynamics; Polar meteorology; Waves and tides)

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1 Introduction

The first paper on wind and tidal characterizations in the high northern Arctic (Manson et al., 2009, hereafter Paper 1) , provided appropriately analyzed data (12 months of 2006/2007) from the Meteor Wind Radars (MWR) at Adventdalen, Svalbard (78° N, 16° E) and PEARL-CANDAC, Ellesmere Island (80° N, 86° W). No additional "80° N" radars have been installed since that time e.g. in the desirable Russian Arctic Islands, and local satellite winds and tidal data for such latitudes are not available with the required temporal and spatial resolution to usefully complement the 36 months of radar data. Instead we use comparative data from a global circulation model (GCM) with a data assimilation system: Canadian Middle Atmosphere Model, CMAM-DAS (Ren et al., 2008).

For numbers of years, radar observations have been made from Tromsø [70° N]. Winds from the Scandinavian Triangle [Tromsø, Andennes and Esrange] by Manson et al. (2004)

for the year 2000 demonstrated differences from middle latitudes: although the winter's zonal winds were positive/eastward until ∼97 km, as expected, the winter meridional (NS) winds from the three radars were southward (<5 m s^{-1}) above ∼80 km. Contrarily, at mid- to high-latitudes, and consistent with relatively warm winter mesospheres, the meridional winds were northward up to ∼90 km (Manson et al., 2003). Most usefully for the present paper, the study by Hall et al. (2003) included the first published background winds from the Svalbard MWR [78° N] in comparison with the zonal [EW] and meridional [NS] winds from the Medium Frequency Radar [MFR] at Tromsø [70° N]. During the years 2001–2002 while the Tromsø winds were only weakly southward (0 to 5 m s^{-1}) in winter, at Svalbard southward winds of 15 m s^{-1} were frequently observed. Thus there is no corresponding indication of convergence toward the winter's pole. The expectation, based upon an increasingly westward vertical shear of the zonal winds throughout the mesosphere (which is associated with gravity wave momentum deposition (Lindzen, 1981)), is for northward winds to develop through the thermal wind relationships, followed by downward motions at Arctic latitudes. This provides for adiabatic warming in the mesosphere. Variations with longitude may be expected, and have recently been demonstrated by Xu et al. (2009), using a single parameter [temperature] from the MLS of Aura. The Interpretation and Conclusions by Hall et al. (2003) included planetary waves, orographic effects, with longitudinal variations in wave drag and momentum transfer. The observations from the Svalbard and Eureka MWR, which are discussed in this paper, allow this matter to be developed more thoroughly and hemispherically.

The radars, GCM models and the Satellite Limb-Sounder, which are sources of data for this Paper, are briefly described in Sect. 2. The focus of Sect. 3 is unique: formation for the first time of the height (82–97 km) versus time (12 months using means from 2006–2009) contour plots of background winds at two High-Arctic (effectively equal) latitudes and differing longitudes (16° E and 86° W). The significant variance that is associated with inter-annual variability [IAV] is provided and discussed. The structures of the winter stratospheric vortex and its upward extension into the mesosphere (80–85 km) for January 2008 are based upon data from the Canadian Middle Atmosphere Model, with data assimilation system (CMAM-DAS). These extensions are used for the first time as explanations for the observed longitudinal variations in the background zonal (east-west, EW) and meridional (north-south, NS) winds. The purpose of Sect. 4 is to effectively compare and contrast, for the first time, the observed High-Arctic mean winds (73–88 km) for a year (2007) from Eureka and Svalbard, with the modeled products from the "state of the art" spectral CMAM-DAS. The SSW that occurred in the January–February months of 2007–2009 are discussed; as well as the characteristics of their short term effects upon mesospheric wind-directions contrasted with the changes in monthly mean directions. In Sect. 5, the high-latitude frequency spectra for Eureka are provided, to display and interpret the presence of planetary waves. "Summary and Discussions" in Sect. 6 addresses progress achieved on the above emerging issues, as well as understanding of the processes at work. These may be thought of as the achieved goals of this research.

2 Description of systems used for the provision of data for this paper

We use two MWR (Meteor Wind) radars of similar design (Hall et al., 2003; Hocking and Hocking, 2002). Commercially the radar at Eureka (80° N, 86° W) is known as a SKiYMET system, which was developed and deployed by MARDOC-Incorporated (Modular Antenna Radar Designs of Canada). It is located at the Canadian Network for the Detection of Atmospheric Change (CANDAC) "Polar Environmental and Atmospheric Research Laboratory" (PEARL) on Ellesmere Island, Canada. The Svalbard (78° N, 16° E) radar was built by Atmospheric Radar [ATRAD] Systems Pty Ltd of Adelaide (2001) and is owned jointly by the National Institute of Polar Research (NIPR) in Japan since 2001. It is called NSMR (Nippon/Norway Svalbard Meteor Radar).

Comparisons of MWR observations with new results from the unique 3-D spectral Canadian Middle Atmosphere Model (CMAM, e.g. Manson et al., 2006) are included in two sections of this paper: provision of "polar-projection" plots up into the mesosphere, to help understand longitudinal variability of background winds in the broad hemispheric context (Sect. 3); and then in Sects. 4 and 5, contours of wind and its variance versus height and month. At this time the Data Assimilation System (DAS) has been developed as an option (Ren et al., 2008); and results for the years 2006–2009 are being used here as part of the Canadian IPY program. It is unique in having the model lid above the mesopause and also possessing interactive chemistry, radiation and dynamics. Standard meteorological observations, plus satellite-data for temperatures, humidity and derived winds in the stratosphere are used within DAS. We have already used such CMAM-DAS data, along with the Saskatoon (52° N, 106° W) medium frequency radar archive, for a study of the semidiurnal tide's "September" amplitude feature (Manson et al., 2010), as well as in a general critique of the model (Xu et al., 2011). These model-data have proved to be realistic and valuable, showing good comparisons with observational data up to high middle latitudes (52° N). The frequently used ECMWF data-assimilation model (European Centre for Medium-range Weather Forecasts) is also used here, comparatively, with CMAM-DAS and the Meteor Wind Radars [MWR].

As part of the research for this paper we have also used temperatures from Microwave Limb Sounder (MLS, Waters et al., 2006) onboard the National Aeronautic and Space

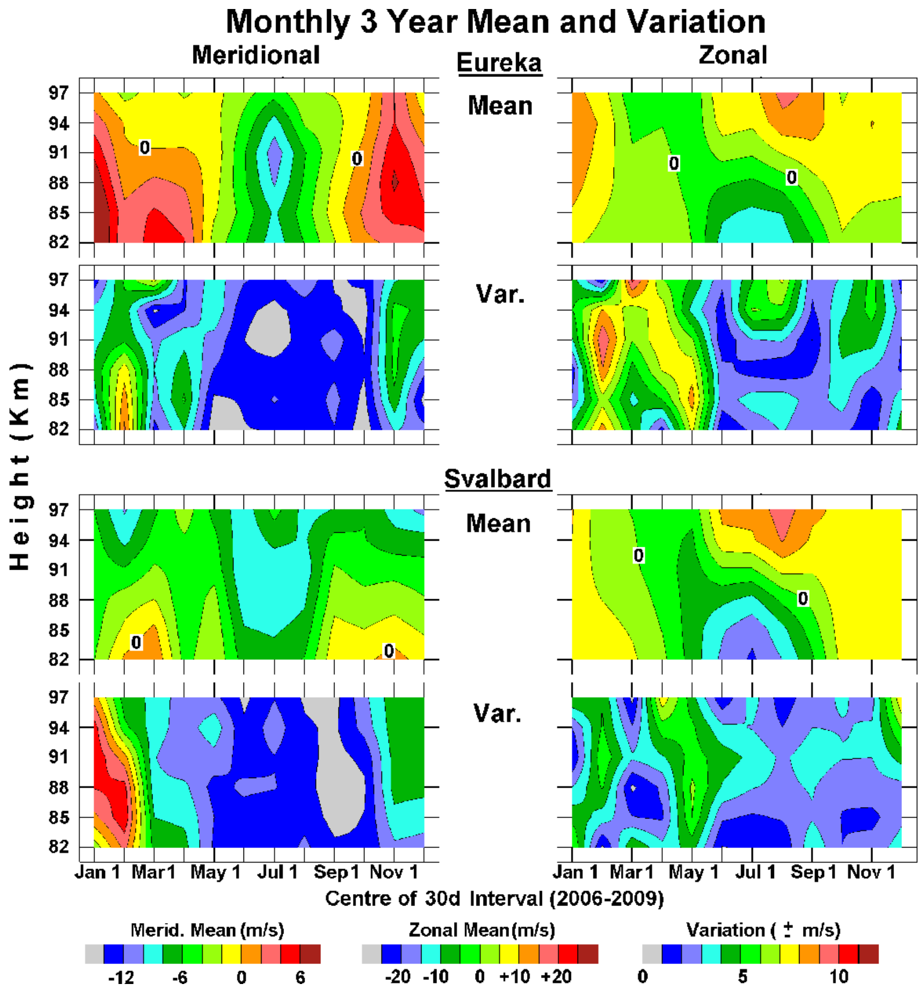

Fig. 1. Three-year means (averages of the background winds) for 30-day intervals between 15 February 2006 and 15 February 2009: these are from fits for the mean winds and 12- and 24-h tidal oscillations. The intervals have the first day of each month as their mid-point, and contours result from a bilinear interpolation procedure. The "variations" of the background winds over three years are provided as well; they are defined as [100(maximum − minimum)/(maximum + minimum)] %, and are used as an indicator of the IAV (Inter-Annual Variability)... year-to-year variations.

Administration (NASA) Aura satellite. The daily data are available for the 316–0.001 hPa (∼8–97 km) altitude region and have coverage from 82° S to 82° N latitudes on each orbit with longitudinal and vertical resolutions of 250 km and 5–15 km, respectively. The first validation results of Froidevaux et al. (2006) show that temperatures and mixing ratios agree well with other satellite and meteorological datasets. We have used MLS hemispheric mesospheric temperatures as part of the justification for the use of CMAM-DAS during the Case Study for January 2008. More extensive comparisons will be carried out eleswhere, as part of studies of planetary waves in the Arctic.

3 Three year means of background winds with model-data aiding interpretations

3.1 Three year means and variations

The figures provided in much of this paper are based upon three years of observations and data from Eureka and Svalbard: mid-February 2006 to February 2009. It is most useful to start by showing three-year averages of the background winds, obtained from thirty-day fits for the mean winds and 12-/24-h tidal oscillations. The fits have the first day of each month as their mid-point, and contours result from a bilinear interpolation-procedure (Manson et al., 2006). The zonal (EW) and meridional (NS) background winds and their "variations" for both Eureka and Svalbard, are provided in Fig. 1: the variation is defined as [100(maximum − minimum value)/(maximum + minimum)] %. The year-to-year variations are generally known as the IAV (Inter-Annual Variability). Results for the tides will be provided elsewhere.

The variations in the summer flows (Fig. 1) are generally small, especially for the meridional component, illustrating very small interannual changes. At both locations and for both wind components there are mid-winter variation-maxima in January–February. These are associated with regional warmings, e.g. Manson et al. (2008), and major or minor Sudden Stratospheric Warmings (SSW).

The differences between the meridional flows at the two sites in winter are quite extraordinary (Fig. 1): with Svalbard having negative/southward flows for all heights except ∼82 km in the equinoxes, while Eureka's flows are strongly positive from late-autumn to early-spring months. The expectation for zonal means (calculated along latitude circles), during non-SSW conditions, is for positive/northward flow in the mesosphere (Manson et al., 1991; Dunkerton, 2000), associated with downward motion at high polar latitudes, and thus the climatologically warm polar mesosphere of winter-like months.

Evidently the asymmetry, with respect to the geographic pole, of the winter polar vortex and its extension into the mesosphere, is considerable. However, the vortex-structure is also apparently regular enough to provide wind-contours of monthly resolution, and at each location (e.g. Fig. 1), which are relatively consistent annually, except for places and times recognized in the discussion above. The years of 2006–2008 have been studied elsewhere by us (Chshyolkova et al., 2009; Manson et al., 2009; and Xu et al., 2009). Firstly, a major SSW warming occurred in late January 2006, so only the after-effects would exist in our 3-year data set. For the intervals of January to February of both 2007 and 2008, minor and major stratospheric warmings occurred (the latter in February of each year); the vortices up to ∼50 km (based on MetO, a model of the "UK Met Office", not shown) were typically elliptical or distorted between warmings; and during warmings the vortices were centered over Scandinavia with westward tilting as heights increased. There were anticyclones in the Pacific-Western Canada sector. The major SSW of 2009 that occurred near 20 January was also regionally (86° W–16° E) very comprehensive, with Eureka's mesospheric winds (80–100 km) showing reversals to westward and southward for 5–10 days. Meanwhile, Svalbard experienced westward flow, while the NS wind was strongly northward during the SSW. This, with Eureka's winds, comprised cross-polar flow. Such short term mesospheric events thus occurred in the January–February intervals of three years, 2007–2009, as the vortex was displaced from the pole and became centred over Scandinavia.

It is notable that the three-year monthly mean background winds (February 2006–February 2009) that are the focus of this paper, provide clear evidence for hemispheric asymmetry in the configuration of the winter's upper (mesosphere) Arctic vortex e.g. typically elliptical streamlines, with a component of poleward/equatorward flow over Canada/Scandinavia. This does not represent cross-polar flow, but changes in direction of the NS flow along the elliptical streamline, at two locations separated by ∼100° in longitude. In contrast during the SSW events (circa 10 days duration in the mesosphere) the meridional Arctic flow is typically cross-polar, from Scandinavian to Canadian sectors (Xu et al., 2009). This first process involving monthly means is demonstrated below.

3.2 Case study for January 2008

We have chosen January 2008 for study of stratospheric to lower mesosphere polar winds (U, V), geopotential height (Z) and temperature (T), as this year was typical of the four mid-winter intervals just discussed, with wind-contours most similar to the 3-year means (zonal U, meridional V) shown in Fig. 1. We show polar plots for latitudes from 50° to 90° and at three constant pressure surfaces (circa 32, 51 and 78 km) from the ECMWF model data (European Centre Medium Range Weather Forecasting) in Fig. 2. The caption describes analytical features of this figure. By simple inspection, the features, color and position of contours (not shown) are very similar to those formed from MetO data up to the maximum height used in our previous studies (∼50 km). At ∼78 km the ECMWF data show that the zonal winds maximize at middle latitudes near 15° W (Fig. 2), with little change in any contour positions between 51 and 78 km. This is surprising, and suggests downward influences of the model's lid. Consistent with the wind fields, the polar vortex (best shown by color plots of ΔZ in km) is elliptical in shape and displaced southward near the Greenwich meridian; the cyclonic temperatures are low at 10 mb, much higher near the stratopause (∼51 km), and relatively warm at the next level in the mesosphere. An anticyclone is perched near the 180° meridian (eastern Russia), as evidenced in distinctive ways in each of the other columns of polar plots (ΔZ, V and U).

To aid in comparisons of Eureka-Svalbard dynamics and of model-types, we provide polar plots, using CMAM-DAS data (Fig. 3), for nominal altitudes of ∼32 km (10 hPa), ∼51 km (0.68 hPa) that is typically a good stratopause height, and ∼86 km (0.0046 hPa) which is a mid-range altitude for meteor wind data. Again, only the high latitudes (50° N to the pole) are shown, to add clarity/resolution to later detailed comparisons between CMAM and observed MWR winds. These two figures are instructive in that they show very powerfully the dipole-like structure of the middle to High-Arctic latitude wind components, which are associated with the displaced and elliptically shaped contours of ΔZ and T. At the two lower heights, the contoured structures of all four variables are very similar to those from ECMWF in Fig. 2; the increased presence of small-scale spatial structure, or noise, in the CMAM plots is apparent at ∼86 km for both mid-latitudes (50–60 degrees) and High-Arctic latitudes. There is also clockwise rotation of features such as the negative Arctic

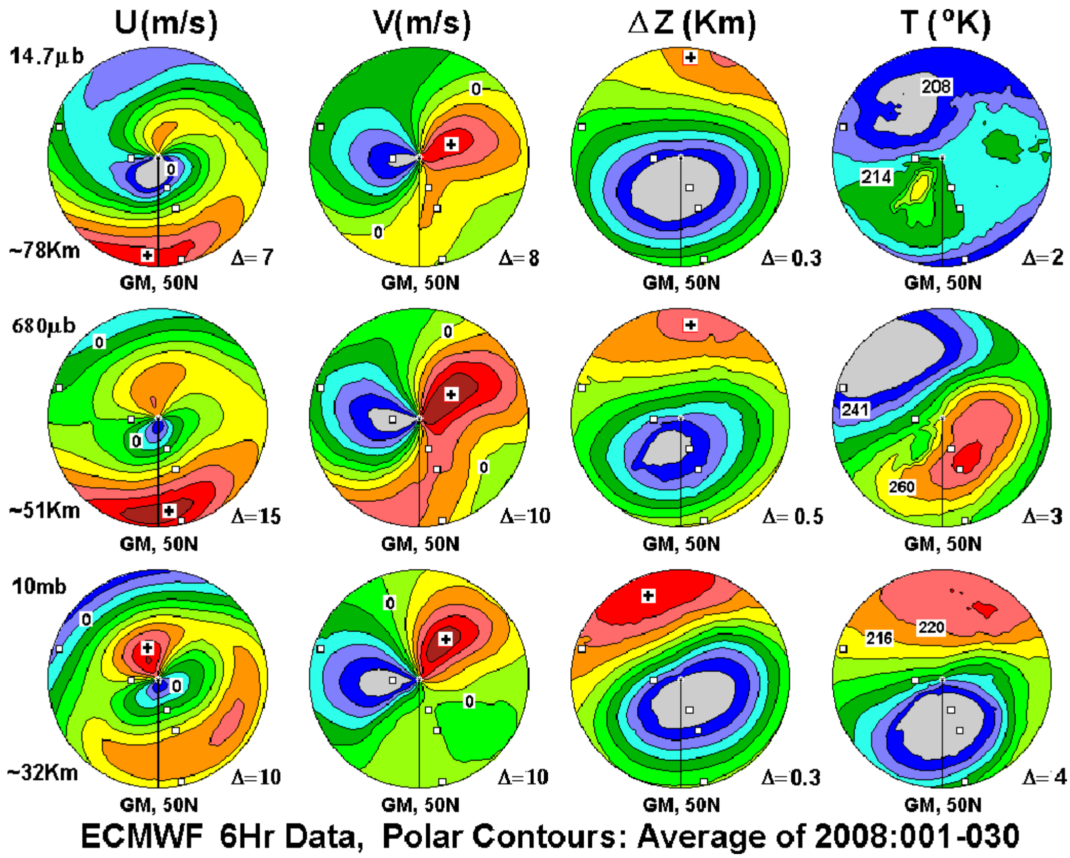

Fig. 2. Polar projection plots, linear in latitude, at three constant pressure surfaces (circa 32, 57 and 78 km) from the ECMWF model data (European Centre Medium Range Weather Forecasting), January 2008, is shown from 50° N to North Pole, with contours of winds (EW, U, zonal; NS, V, meridional), and colored spacing (Δ) of contours in m s^{-1} at each surface; geopotential-height Z contours, with ΔZ provided in km at each surface; and temperature (T), with ΔT provided in degrees Kelvin for each surface. In most cases, qualitative understanding is achieved by noting that red is the largest and/or positive contour, and blue-silver the smallest/negative contour. To reduce clutter, just one or two labels are shown per plot, which along with the contour step (shown at bottom right of a plot) are enough to identify each contour. The locations of Svalbard, Tromsø and Collm in the Eastern Hemisphere; and Eureka and Saskatoon in the west, are shown with open squares. For numbers associated with the variables, these steps are needed: for the plots of winds, the zero contour is marked (0), as well as the sign (+) of the first positive colored contour difference, so that absolute speeds with sign can be calculated as needed; for the plots of geopotential (Z) the contour difference ΔZ of greatest height is marked with the + symbol, so that the "depth" of a vortex can be calculated relative to the provided height for the surface; and the temperature of two contours is provided so that the temperature of any contour can be calculated if needed.

westward/southward winds (blue/blue) and the Atlantic sector of warmer (red) temperatures, by ~90 degrees of longitude, between ~51 and ~86 km. This rotation was also evident in the CMAM-atmosphere at ~76 km (not shown), while in ECMWF (Fig. 2) clockwise rotation between 57 and 78 km is not evident. This speaks to relative strengths of physical processes within each model, which would require a significant and unique study. Comparisons with Aura MLS temperatures for January 2008 (not shown), at heights of circa 32, 51, 78 and 86 km, provide good agreements with regard to sectorial locations of maxima (within 15°) and their values. Compared with the more familiar Cartesian coordinates e.g. site-specific radar-plots with zonal and meridional wind-coordinates, we notice particularly the strong longitudinal variations in CMAM-meridional winds (at 51 and 86 km), and cross polar flows (Scandinavia/Western-Europe to Western Canada/Pacific) at ~86 km for the month of January.

We will compare the 2008 CMAM-modeled (Fig. 3) and observed monthly mean radar-winds (Fig. 4) in the next paragraph, but first, comments on the latter figure are required. It provides zonal and meridional background-winds upward from 76 km (geometric) altitude at Svalbard and from 82 km at Eureka. Notice that in this year the meridional flow at Svalbard is, quite unusually, northward (poleward) during January up to ~100 km, while for February–May it is southward above ~85 km. We have shown and discussed earlier (Fig. 1) that the 3-year average NS winds over northern

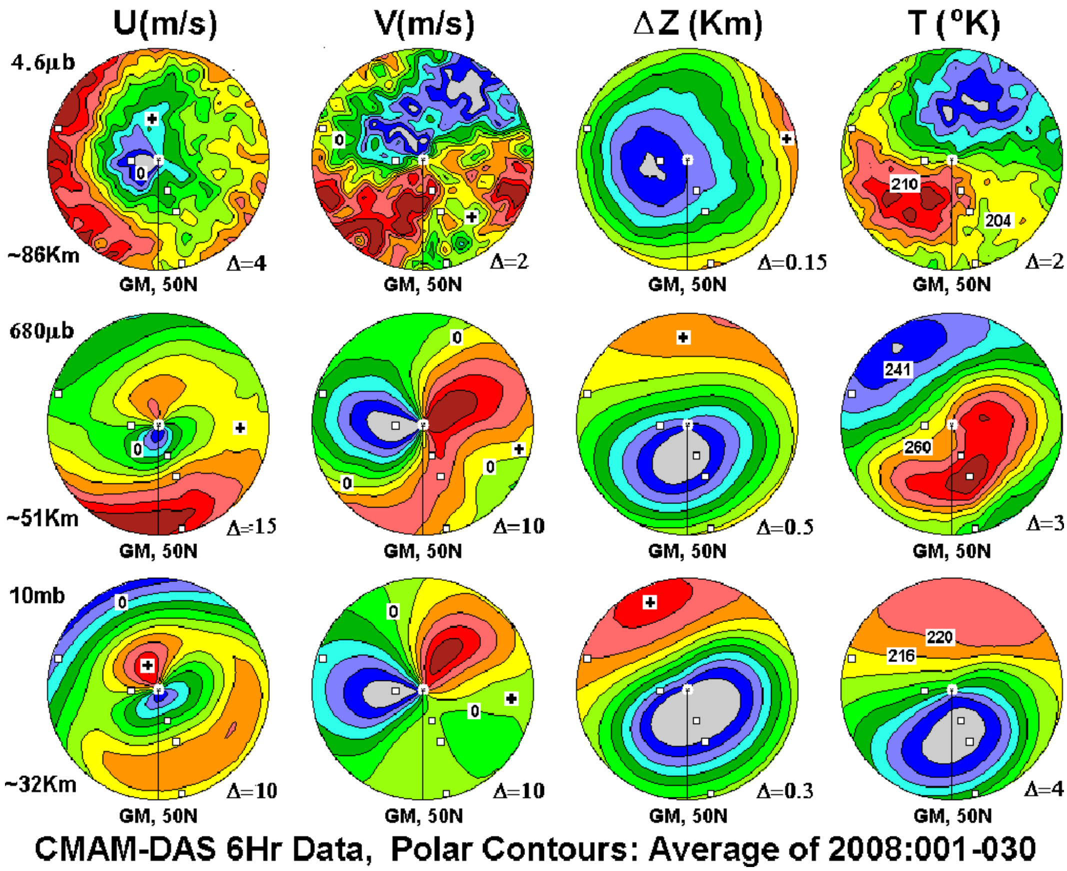

Fig. 3. Polar projection plots, with equidistant latitudes, at three constant pressure surfaces (circa 32, 51 and 86 km) from the CMAM-DAS model data (see text for details). January 2008 is shown from 50° N to North Pole, with contours of winds (EW, U, zonal; NS, V, meridional) and deltas provided; geopotential height Z contours, with ΔZ; and temperature (T) with ΔT. Details for calculations of absolute values are the same as the caption for Fig. 2.

Norway are dominated by southward flow above 82 km for the winter and spring months. For individual years, flows at Svalbard were consistently southward for those same heights and months in 2007, and southward only above ~88 km in 2009. These differences are consistent with the large "variations" for those months and heights in Fig. 1; and also as shown and discussed earlier in some detail by Hall et al. (2003). At Eureka the 2008-meridional flow is dominantly and generally northward for those months and heights (Figs. 1, 4), but with southward flow seen above ~90 km. (Xu et al., 2009; years 2004/2005 to 2007/2008). The radar-derived zonal winds for January 2008 (Fig. 4), and above 76/82 km at Svalbard/Eureka, are eastward, with vertical eastward shear, which is typical over 2006–2009 (Fig. 1). The latter is not the expected or observed shear at middle-high latitudes, due to the climatologically warm winter mesosphere.

Returning to the actual comparison for January using Figs. 4 and 3 respectively: the meridional radar-winds at Svalbard (76–91 km) are weak and (unusually) positive (2–4 m s^{-1}), and for CMAM-DAS, at the nominal ~86 km, they are also northward (8–10 m s^{-1}). However, 86 km is appropriate to the pressure surface 0.46×10^{-2} hPa for a typical winter atmosphere at middle-high latitudes (~50° N), so based upon the ΔZ (gph) values in Fig. 3, Svalbard's geopotential height is ~85 km (gph). There is thus agreement in sign at the same height-ranges between radar and CMAM, and in approximate size. Relevant to this (Fig. 3) the column of plots for NS winds (V) shows that mesospheric northward flow (yellow-green to red-maroon) dominate longitudes including eastern Canada, the Atlantic, Scandinavia, Northern Europe and Western Russia. For the Western Hemisphere in Fig. 4, the meridional radar winds for Eureka at 82–88 km are positive/northward (4–6 m s^{-1}); while the co-located CMAM-DAS meridional winds, adjusted by ΔZ to ~84 km (gph), are negative/southward (4–5 m s^{-1}). However, the symbol for Eureka is less than 10° (light green to yellow-green) westward of the large sector (height interval and longitude) of northward winds that exist through over 90° of longitude to Svalbard. Uncertainties of <10° in modeled values near the boundary of a NS sectorial direction change are not unexpected. Westward in longitude from

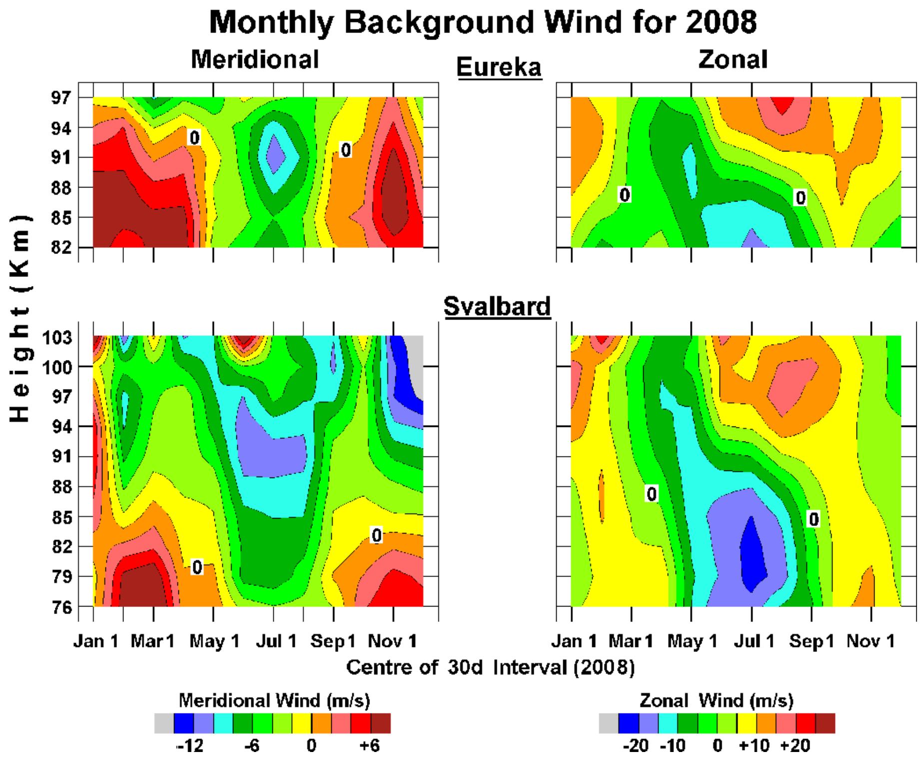

Fig. 4. Background winds for 2008 from the Eureka and Svalbard MWR: these are from thirty-day fits for the mean winds and 12- and 24-h tidal oscillations. The fits have the first day of each month as their mid-point.

Eureka (Fig. 3), over Western Canada and the Pacific, the NS winds continue to be southward/yellow-green to blue-silver (5–10 $\mathrm{m\,s^{-1}}$) at 84–86 km. We have also produced a plot (not shown) at the constant geopotential height of 85 km, wherein the sector-positions alluded to above are insignificantly changed, and the associated discussion above also requires no changes.

Careful comparisons of the 2008 zonal/EW winds at both Svalbard and Eureka for radars (Fig. 4) and for CMAM (Fig. 3) are also favourable near 84–85 km within the vortex, with both observing-systems showing weak eastward winds. Notably, anti-cyclonic rotation of the CMAM-DAS structures (V) in Fig. 3, by as little as 20°, would provide excellent agreement between observations (Fig. 4) and model. Such differences in position of the vortex-structure at mesospheric heights, between a GCM with DAS and direct measurements from a ground-based radar system, can be considered relatively minor. The February 2008 U, V, ΔZ and T plots (not shown) are very similar to Fig. 3, at all three heights, as is expected based upon the small changes of the observed winds (Fig. 4). We have inspected CMAM polar plots, as in the comparative fashion of Figs. 3 and 4, for the winters of 2007 and 2009, comparing again with the MWR monthly mean winds from Eureka and Svalbard. Classifying the three Januaries: 2009 provided the best and clearest agreement between the upper cyclonic vortex of CMAM and the MWR meridional winds; 2007 was the poorest (∼45° westward correction of the vortex needed); and the 2008-year we have chosen for detailed study was very close to being satisfactory, with relatively minor rotation of the ∼84 km vortex (∼20° westward correction) now giving agreement of magnitude as well as direction.

Contrarily, during dynamic and thermal disturbances of shorter time-scales i.e. events of 5–10 days within regional or major SSW, there is again significant but more temporary movement or migration of the stratospheric polar vortex to its frequent position over Scandinavia in January/February (2005, 2007, 2008), and following observed westward rotation of the vortex-structure, the presence of the mesospheric vortex over Eureka-Eastern Pacific (Chshyolkova et al., 2007, 2009; Manson et al., 2008; Xu et al., 2009). Associated with these events, the cross-polar mesospheric wind is often poleward in direction over Scandinavia; while there are the long-observed (Gregory and Manson, 1975; and references just above) reversed southward/equatorward and westward wind-components over Canada (Saskatoon, Eureka) during stratospheric warmings.

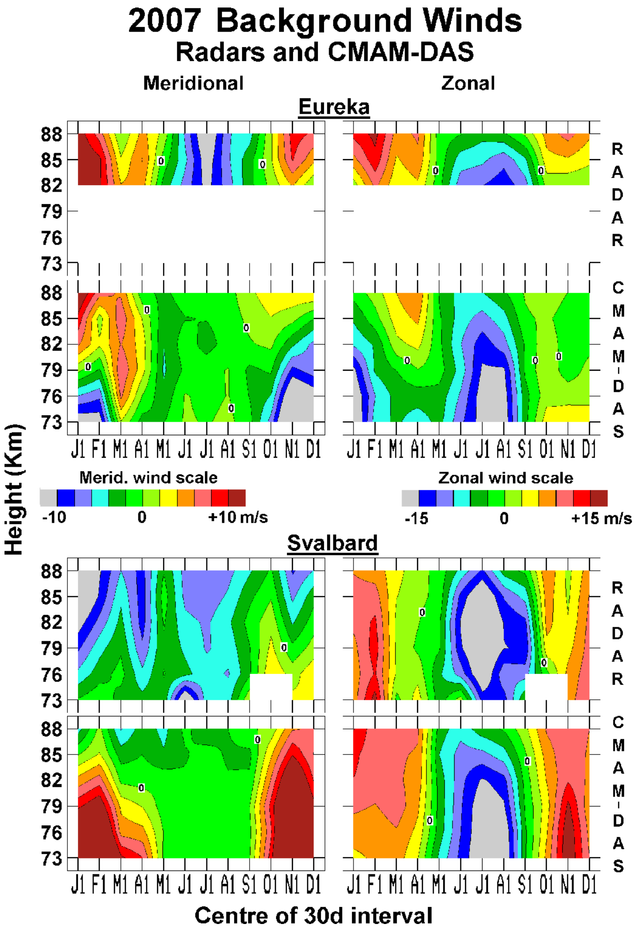

Fig. 5. Background winds for 2007 from the Eureka and Svalbard MWR and CMAM-DAS (see text for more details): these are from thirty-day fits for the mean winds and 12- and 24-h tidal oscillations. The fits have the first day of each month as their mid-point, and contours result from a bilinear interpolation procedure.

4 Characteristics of the Arctic winds in CMAM-DAS as compared with observed winds (from Meteor Radars): Eureka (80° N, 86° W), Svalbard (78° N, 16° E)

4.1 Mean winds (2007): preamble

The year chosen involves the dynamical extremes of observed differences for the meridional winds that occurred between Eureka and Svalbard, over the three years of data. It did therefore include quite dominant negative/southward flows at Svalbard, over broad height-intervals and months, which we now recognize as a frequent and important indicator of polar vortex asymmetry. The ability of CMAM-DAS to reproduce this is certainly desirable. Heights chosen for assessment in this case depend upon the heights available from the model, which extends only up to 88 km for our purposes; hence superficial comparisons with the previous figures (1, 4) require care, since those radar-figures go to 97 km. For the lowest heights shown in Fig. 5, 73 km is chosen due to the greater sensitively of the Svalbard system.

4.2 Background winds (2007) for Eureka and Svalbard: MWR radars and CMAM-DAS model

The radar zonal and meridional mean winds of Fig. 5 (together they constitute the background wind, often discussed in terms of the local wind vector's direction and speed) for Eureka are seasonally similar to the three year means (Fig. 1) with the "negative" green-blue colors inhabiting the summer-centred months. However, although the observed Svalbard zonal wind's contour structures and colors (winter eastward, yellow-reds) are rather similar to its neighbor, the meridional winds of winter-centred months are dramatically different with negative (green-blue) contours. Also, note that color scales differ for EW and NS, due to independent figure-normalizing).

Specifically, for January 2007 at Svalbard, the observed southward winds (green-blue) strongly dominate the mesosphere; in addition, southward winds prevail for all months except autumn ($<$79 km). In contrast CMAM-DAS, for this Scandinavian sector, shows strong poleward flows in winter and neighboring equinoctial months for heights ranging from 73 to 82–88 km (late "winter" 2006/2007). As noted in Sect. 3, the observed mesospheric southward winds for the 3-years of Svalbard's winter data (Fig. 1) differ from those of Eureka and indeed generally other middle latitude observations made during the dynamically active winter atmosphere (Manson et al., 1991, 2003). The difference in direction and strength of CMAM's NS winds at Svalbard, instead showing little difference from those at Eureka, are both interesting and surprising.

This strong lack of zonal symmetry in Arctic meridional background winds for 2007, probably due to stationary planetary waves (SPW) and the nature of the related polar vortex (Sect. 3), is consistent with creation of non-migrating tides (NMT) as will be shown and discussed elsewhere (Manson et al., 2011). At this time the CMAM-DAS assimilates observations only in the troposphere and stratosphere, and the mesospheric response is thus entirely due to vertical connections in model dynamics (Ren et al., 2008; Xu et al., 2011). The 2006/2007 winter experienced a distinctive polar vortex-evolution and the associated complexity of the stratosphere-mesosphere connection, mainly in January 2007 (Xu et al., 2009). This could also be one of the causes for the extreme model-radar differences (Fig. 5).

5 High-arctic frequency spectra (wavelets)

We conclude this study by showing the spectral content of the Eureka-winds from CMAM-DAS and the MWR-radar (Fig. 6), for 365 days (mid-2007 to mid-2008) at 88 km. The

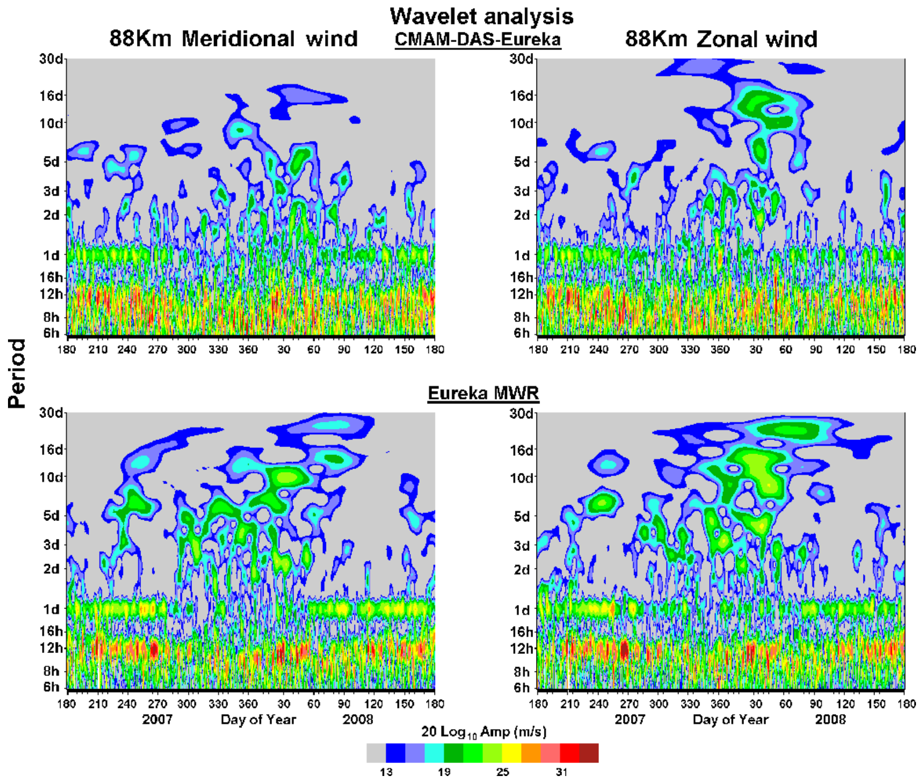

Fig. 6. Wavelet analyses as applied to winds data from the High Arctic radar and CMAM-DAS at Eureka (80° N, 86° W). The observed seasonal tidal variations are larger than modeled, as is the observed planetary wave activity.

planetary waves (PW) of periods $\tau > 2$ days have smaller amplitudes in CMAM (amplitudes ratios of up to ∼2) during the winter months. This amplitude preference is shared at middle latitude locations such as Saskatoon (not shown). However the saucer-shaped (profile view) distributions of contours, associated with the removal of longer PW periods by the summer background winds (Meek and Manson, 2009) is much less obvious in the CMAM-wavelets, likely due to the much weaker winds at Arctic latitudes. Positive comparisons of common features in the two pairs of wavelets are certainly more difficult. For example, the observed zonal/EW wind's ∼10 d oscillation (taken to be the regional response to a Rossby PW) near day 30, is also evident in the NS component. The NS component is typically weaker in a Rossby wave (Luo et al., 2002). However, the feature in the contours near 10 d in the zonal-CMAM wavelet is less coherent and convincing, while it is not present in the meridional-wavelet. More encouragingly, the ∼5 d PW (near day 240) may well be shared responses in the atmospheres of the planet and the model. The ∼2 d wave feature of summer's middle and low latitudes (Manson et al., 2003) is notable by its absence in wavelets from CMAM and the radar.

6 Summary and discussion

The discussions throughout this paper have been quite detailed, so we will not extend them unduly here. Generally the items below follow the sections of the paper and their principal findings; these were also collected in the last paragraph of the Introduction after writing the paper. It is important to state this, out of respect for the philosophy and methodology of science. It is the case that this type of atmospheric science remains a process of discovery, and as such many of the findings above were almost complete surprises to us, as the data presentations and figures evolved, along with our thinking. They certainly were not "goals" that were set at the onset of planning the radar installation on Ellesmere Island. They, the findings, are as follows: assessment of the interannual variations (IAV) in the character of the monthly mean zonal/EW and meridional/NS winds over ∼3 years, also considered here as "background wind"; the influence of the typically asymmetric and displaced mesospheric polar vortex upon longitudinally spaced observations of monthly zonal and meridional winds; and the comparisons between wind observations from the Meteor Winds Radars (MWR) and the model-winds from CMAM-DAS.

1. Characterization of the first 36 months of wind-data (82–97 km) from the Meteor Wind Radars: at Eureka,

Ellesmere Island (80° N, 86° W), within the PEARL-CANDAC laboratory, have been here combined with contemporaneous winds from the Meteor Radar at Adventdalen, Svalbard (78° N, 16° E). This unique combined data-archive is from mid-February 2006 to February 2009. Three year monthly averages of the background winds, along with their variations over the three years (Inter-Annual variations, IAV), have then been formed from thirty-day fits to the mean winds and tides. This provides the first significant characterizations of the background winds and their IAV from longitudinally spaced (102°) radars near 80° N. Over the three years, the zonal winds are structurally similar at Eureka and Svalbard; but with larger winter eastward winds at Eureka, and larger summer westward winds at Svalbard. The variations maximize in late winter and the spring months (Eureka's are generally larger), and also in the fall. Sudden Stratospheric Warmings (SSW) and the final stratospheric warmings/reversals of the winter circulation are responsible for the late winter and spring maxima in the IAV.

The three-year mean-meridional winds provide significantly different locational structures, as is quickly noted by the differing colors and positions of the zeros in the figures. The summer-centred months are dominated by southward flows, especially at the lower mesopause heights, with differing shears (time and height); and the variances are minimal at that time. However during winter months the Eureka flows are poleward for most of the lower and middle mesosphere (the necessary case for the climatological warm polar mesosphere), while over Svalbard the monthly flows are southward except for two small positive poleward spikes near 82-85 km. This is unique information about the Arctic asymmetries. The variations again maximize in the late fall-winter months.

2. The structure of the winter stratospheric vortex and its upward extensions into the mesosphere (~85 km) during January 2008, as provided by the Canadian Middle Atmosphere Model with Data Assimilation System (CMAM-DAS), demonstrated large longitudinal sectors (typically 30 to 90 degrees) of poleward and equatorward flows, along with vortex-related contours of geopotential height and temperature. These extensions have been used for the first time as probable explanations for the observed longitudinal variations in the background zonal (east-west, EW) and meridional (north-south, NS) winds; clockwise rotations of the vortex-system with height led to the irregular-elliptical cyclone/vortex moving from over Svalbard at ~30 km to being centred over Eureka/Thule at ~85 km.

   We have shown that the resulting EW (U) and NS (V) winds have dipole structures of medium (~90°) to small scale (~30°) near 80° N: thus rotation of the structures within the cyclone by only 30° of longitude (~700 km) can move an associated region of southward flow completely across a MWR radar. The agreement between the EW and NS winds from the two radars and the wind patterns in the 2008 CMAM polar plots was quite good, and westward rotation of the vortex structure by only 20° would have improved it to excellent. The CMAM mesospheric polar plots for January 2007 and 2009 are also consistent with this scenario; the vortex-structure's positions in 2009 provided winds that agreed in size and direction with those from the two Arctic radars. The location of the pseudo-elliptical vortex depends upon the propagation path of the disturbing quasi-stationary Planetary Waves ($S = 1, 2$).

   The placement of our radars in northern Scandinavia and Canada is somewhat fortuitous, although oceanic Atlantic currents, the NAO and history play their roles. Based upon observed monthly means, locational differences in mesospheric winds (speeds and especially directions) are such as to provide frequent departures from the now classical picture of consistent winter Arctic northward background flows. It is encouraging that CMAM-DAS has provided satisfactory evidence for these structures, and that they lie frequently over Canada, and specifically PEARL-Eureka. The corresponding anticyclone is found further westward over western Canada and the Pacific. Together these structures play pivotal roles in the distributions of ozone and its destruction by inhomogeneous chemistry, which are necessarily asymmetrically distributed (Manson et al., 2008).

3. Comparison of the observed mean winds at 78–80° N, with those within CMAM-DAS, is a major feature of this paper: height versus time plots of wind contours were used for radars and model. Given the significant inter-annual variability, the year of 2007 was chosen to best represent features that we recognize as typical of the dynamics at these two locations. Although both monthly mean zonal and meridional winds (82–88 km), for radar and model at Eureka in the high Arctic, were respectively quite similar with respect to height, occurrence of changes, as well as direction, the Svalbard (73–88 km) NS observed winds for all twelve months differed strongly from those modeled. Thus observed/radar winds were southward for almost all heights and months, while the modeled winds were strongly northward for winter centred months (October to April) at heights from 73 to 82–88 km.

   Assessments of vortex and internal-structure positions led to probable explanations of direct radar-model (CMAM) differences at Svalbard (78° N), 2006–2009. The CMAM polar projection plots for the stratosphere, stratopause and upper mesosphere (~85 km) regions also revealed the vortex as preferentially over Scandinavia at 30 km (centred near Svalbard), and then by clockwise rotation of the vortex-system with height, centering over Eureka near ∼85 km (gph). The mesospheric extension of the vortex leads to longitudinal variations of the EW and NS monthly mean winds; and the year-to-year variability of the vortex leads to IAV of the Arctic winds. To us, these results are an amazing instance of serendipity regarding the placements of radars and their creator-Universities.

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