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Atmospheric Measurement Techniques
Discussions

Validation of wind measurements of two MST radars in northern Sweden and in Antarctica

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Abstract. Two atmospheric VHF radars: ESRAD located near Kiruna in the Swedish Artic and MARA at Indian research station Maitri in Antarctica perform wind measurements in the troposphere and lower stratosphere on a regular basis. We compared horizontal winds at altitudes between about 0.5 km and 14 km derived from the radar data using the full correlation analysis technique with radiosonde observations and models. The comparison with 28 radiosondes launched from January 2017 to August 2019 showed that ESRAD underestimates the zonal and meridional winds by about 8% and 25 %, respectively. The mean differences between the radar and radiosonde winds are -1.4 m/s and 0.4 m/s. A similar result was found when comparing with the regional NWP model HARMONIE-AROME for the period September 2018 – May 2019. The ESRAD random error was estimated to be 2.8 m/s (2.4 m/s) for the zonal (meridional) component. The comparison of MARA with the ECMWF ERA5 reanalysis for January – December 2019 reveals good agreement between them with the mean difference between 0.1 m/s and -0.5 m/s depending on the component and season. The MARA random errors are 2.6 m/s and 2.3 m/s for the zonal and meridional winds, respectively.

1 Introduction

Atmospheric winds are an essential part of weather and climate, however atmospheric measurements are skewed towards temperature, moisture or pressure (WMO, 2012). This skewness results from the fact that winds are more difficult to measure remotely. Atmospheric radars have been used for wind measurements since the 1950s. The history, design, methods and applications of atmospheric radars are described in the comprehensive book by Hocking et al. (2016). The mesosphere-stratosphere-troposphere (MST) radar ESRAD located near Kiruna in the Swedish Arctic has been in operation since 1996 (Chilson et al., 1999). It has run continuously (with the exception of a few short breaks due to technical problems) and delivers three components of wind. Another wind profiler MARA has been operated at various locations in Antarctica since 2006 (Kirkwood et al., 2007). In some years MARA was able to run for only a few months (due to stations being closed or experiencing severe weather conditions), in other years 12 months of operations have been possible. In August 2018 ESA

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launched the Earth explorer satellite Aeolus with the main objective to provide wind profiles in the troposphere and lower stratosphere (0-30 km altitudes) with global coverage (ESA, 2018; Straume et al., 2019). The satellite mission was specifically designed to address the lack of wind profile observations in many parts of the globe, such as the Tropics and over the oceans. Both radars, ESRAD and MARA, are involved in the Aeolus calibration and validation activities, and scarcity of data at high latitudes makes these radar observations very valuable for validation of Aeolus wind products in these regions. Before making a validation of Aeolus winds we need to evaluate carefully the accuracy of the wind measurements made with the radars themselves. This can be done in comparison with other measurements and/or with established models. When the radars were first deployed at the sites, comparisons with radiosondes were made for this purpose. However, recently ESRAD has experienced some technical problems and conditions at Maitri, Antarctica, where MARA is currently located, have been very detrimental to the antenna hardware so that a new validation is needed. In this paper we aim to validate the ESRAD and MARA winds in the troposphere and lower stratosphere by comparison with winds observed with radiosondes launched recently and/or with models for the period after the Aeolus launch.

2 ESRAD

2.1 Wind measurements

The Esrange MST radar (ESRAD) is an atmospheric radar located at Esrange (68°N, 21°E) in northern Sweden. It is joint venture between the Swedish Institute of Space Physics (IRF) and Swedish Space Corporation (SSC) Esrange Space Center. It began operations in July 1996 and had two major upgrades in 2004 and 2015. The purpose of the radar is to provide information on the dynamic state of the atmosphere – winds, waves, turbulence and layering, from the troposphere up to the mesopause (ca. 0.5-90 km altitude). It operates at 52 MHz and the nominal peak transmit power is 72 kW, however only 30 kW is available at present due to progressive failure of several power blocks. The ESRAD main antenna array, consisting of 288 five-element Yagis, is divided into 12 identical segments each connected to one power block and to a separate receiver. The receivers have 1 MHz bandwidth and separate detection of in-phase and quadrature components. This allows post-detection beam-steering and full spectral analysis of the returned signal. The radar transmits vertically with the whole main antenna array, but for reception one can use 12 segments in different combinations. In 2015 a small separate receive-only array (3 sub-arrays of 4 Yagis each) was constructed about 30 m away from the south-east corner of the main array. In combination with transmitting on only part of the main array, this allows measurements at the lowest altitudes starting at about 0.5 km. However due to intermittent time synchronization errors, we do not use the data from this array in this paper. The parameters of ESRAD are presented in Table 1.

Vertical wind is derived from the Doppler shift of the return signal by combining (coherently) the data from all receivers. The concept behind the radar horizontal wind measurements is the following. A radar transmits electromagnetic waves that are scattered or reflected from inhomogeneities in the atmospheric refractive index. An ensemble of such inhomogeneities in an atmospheric layer works as a diffraction filter that creates a diffraction pattern of return signal on the ground which can be

Radar	**ESRAD**	**MARA**
Geographical coordinates	68°N 21°E	71°S 12°E
Height above sea level	295 m	117 m
Frequency	52 MHz	54.5 MHz
Peak power	72 kW nominal (30 kW now)	20 kW
Antenna effective area	3740 m^2	540 m^2

Table 1: Characteristics of ESRAD and MARA radars.

measured by spaced receivers (antenna segments). Scatterers of the radar wave are advected by wind, and it has been shown that the diffraction pattern moves along the ground with double the wind velocity (Briggs, 1980). Horizontal winds are derived by using cross-correlation technique to find the time it takes for the diffraction pattern of the irregularities to pass the different antenna sub-arrays, corrected for the irregularity decay time. This method is known as full correlation analysis (FCA) and was developed by Briggs et al. (1950) and Briggs (1984). For ESRAD we adopted the FCA algorithm as described by Holdsworth (1995). The FCA is one of two commonly used radar techniques for atmospheric horizontal wind estimation (Hocking et al., 2016). The other is the Doppler Beam Swinging (DBS) method, which is not technically applicable for our radar.

Experiment name	**fca_900**	**fca_150**	**fcx_aeolus**
Pulse Repetition Frequency, Hz	1300	4688	2490
Code	none	none	none
Number of coherent integrations	64	128	256
Number of points	39	39	39
Start height, m	1050	150	1050
Stop height, m	101250	14250	28050
Number of height gates	167	94	45
Height resolution, m	600	150	600

Table 2: Parameters of the ESRAD experiments used in the paper.

Basic software for radar control and data acquisition from the radar manufacturer Genesis Sofware Pty as well as our own software for analysis runs in real-time. The radar runs continuously, cycling between experiments optimized for the lower troposphere, troposphere/stratosphere, or mesosphere. A typical cycle measures for 1-2 minutes in each mode, repeating every 3-6 minutes. Special cycles, optimized for specific goals may be run from time to time, for example in this paper we use data from a special experiment fcx_aeolus designed in support of the ESA Aeolus satellite mission in addition to two common experiments fca_150 and fca_900. The parameters of the experiments are listed in Table 2. We run a sequence of four experiments (one of them is not used in the paper) for two minutes each thus providing wind data every eight minutes. More detailed descriptions of ESRAD can be found in Chilson et al. (1999) and Kirkwood et al. (2010).

2.2 ESRAD versus radiosondes

We use the wind data from 28 radiosondes (ascents) that were launched from Esrange during the period of January 2017 - August 2019. The radiosondes have been launched as support for different balloon and rocket campaigns hold at Esrange. Standard GPS radiosondes from the Vaisala company were used, typically reaching 20 -30 km heights. The raw data were sampled at 2 s intervals, resulting in an uneven vertical interval, which varies from 6 to 9 m.

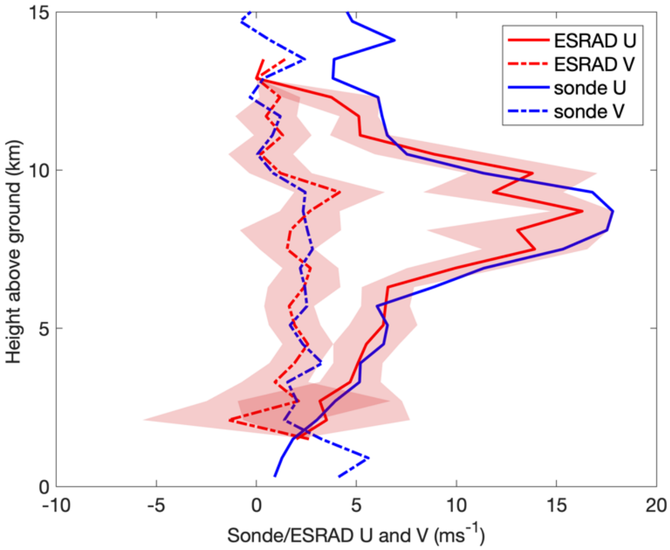

Figure 1: Vertical profiles of the zonal U and meridional V components of wind measured by the ESRAD radar and radiosonde on 15 August 2018. Shading indicates one standard deviation of the ESRAD winds.

An example of the zonal and meridional wind profiles as measured by the ESRAD radar and by a radiosonde on 15 August 2018 is shown in Fig. 1. The ESRAD data for three experiments listed in Table 2 were averaged over the 1-hour interval centered on the radiosonde launch time. Then the radar and sonde wind data were interpolated to the same altitudes starting from 300 m with 600 m resolution. We see that for the altitudes range from about 1.5 km to about 13 km the radar winds are in a good agreement with radiosonde ones, at least within one standard deviation (calculated after averaging over experiments, height and time and marked with shadowed areas).

We did the same averaging for all 28 occasions when radiosondes were launched and the results for zonal and meridional winds are presented in Fig. 2. Our comparisons are focused on U and V components because they will be further used for evaluation of the Aeolus horizontal line-of-sight winds. We also plot in Fig. 2 the linear fits as dotted-dashed lines: the radar on the sondes in blue and the sondes on the radar in green. A robust fitting with bisquare weights was used in order to reduce the contribution of outliers. Two fits were done because the radar and sondes both measure winds with different uncertainties that we do not know absolutely (e. g. additional errors can be due to temporal and spatial separations of the instruments). Then “the best fit” between data from these instruments will be somewhere between these two fits. We do not determine its exact parameters as proposed by Hocking et al. (2001) because both regression lines lie rather close to each other.

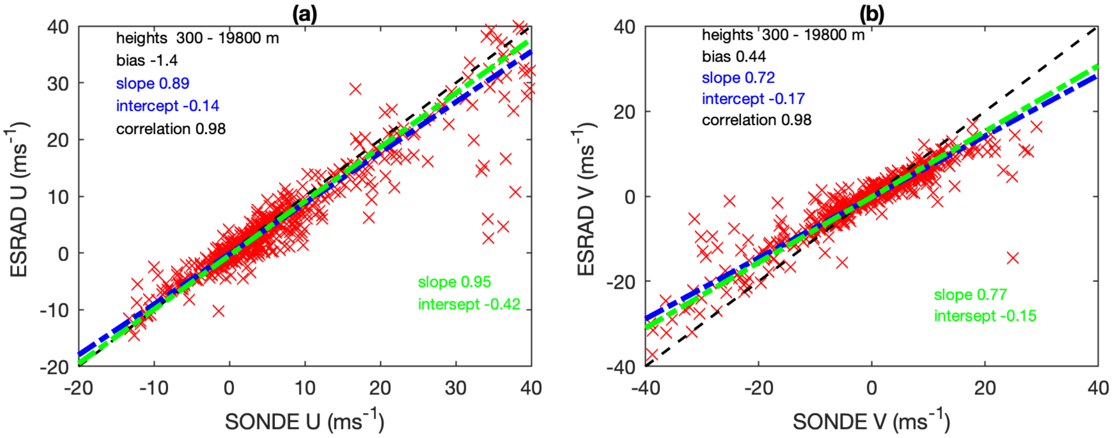

Figure 2: Comparison of the ESRAD and radiosonde (a) zonal and (b) meridional winds. The linear fits are shown as dashed-dotted lines: the radar on sondes in blue and the sondes on the radar in green. The black dashed straight line corresponds to the case when the radar velocity is equal to the sonde velocity. More details of the legend in the inserts are in the text.

The parameters of the linear fits such as slope and intercept are shown in Figure 2 with the same colour as the corresponding lines. The slope is significantly closer to 1 for the zonal wind fit than for meridional one, all intercepts are smaller than 0.5 m/s. We also calculated a mean difference between the radar and radiosonde winds, it is nominated as ‘bias’ and shown in the inserts in the figure. The mean difference for U and V wind components are -1.4 m/s and 0.4 m/s, respectively, and the slopes are less than 1, which implies that the radar underestimates wind compare to the radiosonde. The correlation coefficient between radar and sonde data is 0.98 for both zonal and meridional wind. We also estimated the ESRAD random errors as a mean of standard deviations of each radar wind data in Fig.2. They are 2.3 m/s and 2 m/s for the zonal and meridional wind correspondingly. Behaviour of the inter-comparison parameters as a function of height is shown in Fig. 3. From this figure we see that the parameters vary irregularly with height, however the correlation coefficient and slope of fit tends to decrease with increasing heights, while absolute values of the mean difference for both wind components increase with height. The largest differences between the radar and radiosondes are observed at the lowest and highest altitudes. The former can be explained by poor radar performance at the lower heights, the latter is likely due to increased spatial separation between the radar and radiosonde sampling volumes. These higher altitudes contribute to larger deviations for stronger winds seen in Fig. 2. For altitudes above about 2 km and below about 12 km, where there is enough number of the data for comparison, the agreement between the radar and radiosondes is good similarly as was shown for one day in Fig.1. The radar random errors do not vary significantly with altitude (not shown).

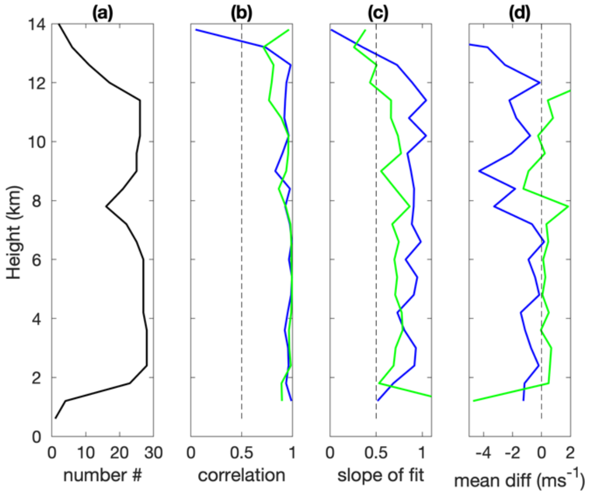

Figure 3: Altitude profiles of (a) the number of ESRAD and radiosonde velocities available for the comparison, (b) correlation coefficient between them, (c) slope of the radar-on-sondes linear fits and (d) mean difference between the radar and radiosonde winds. Blue and green colours indicate zonal and meridional wind, respectively.

2.3 ESRAD versus the HARMONIE model

In order to validate the radar wind over an extended, continuous period of time we made the comparisons with winds produced using the HARMONIE-AROME km-scale NWP model (Bengtsson et al., 2017). It is one configuration of the shared Aire Limitée Adaptation Dynamique Developpement InterNational (ALADIN)-High-Resolution Limited-Area Model (HIRLAM) NWP system, developed jointly by 26 countries in Europe and northern Africa. HARMONIE-AROME is comprised of a data assimilation system for the surface and upper-air together with an atmospheric forecast model, including the SURFEX surface scheme (Masson et al., 2013). To provide the best possible initial model state for the surface and atmosphere, a data assimilation is applied. The surface data assimilation is based on optimal interpolation (Giard and Bazile, 2000) while a 3-dimensional variational data assimilation scheme is used for the upper atmosphere (Fischer, 2005). Operational ensemble forecasts are produced within the collaboration MetCoOp (Meteorological Co-operation on Operational NWP), including the national meteorological services of Sweden, Norway, Finland and Estonia (Müller et al., 2017). The operational domain covers Fenno-Scandinavia and has 960 x 1080 horizontal grid points with a resolution of 2.5 km for each of the 65 vertical levels. The model top is at approximately 10 hPa and the vertical model level separation is about 50 m close to the surface and up to 1 km in the stratosphere.

We looked at the period from 1 September 2018 to 31 May 2019. The choice was motivated by changes in operation of the Aeolus satellite - during this interval the Doppler lidar on the board of Aeolus satellite used laser A (it was switched to laser B in June 2019). Again, the ESRAD winds were averaged over three experiments, over 1-hour centered on 00 UT, 06 UT, 12 UT and 18 UT, which are the times of the model output, and over 1-km altitude gates starting from the ground. Then model winds at the grid point closest to ESRAD were interpolated for the same altitudes.

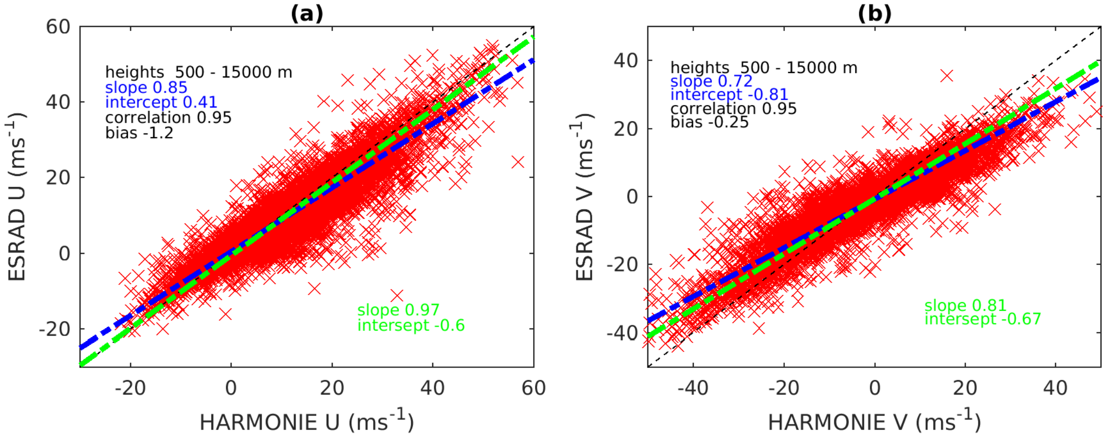

Figure 4: Comparison of the ESRAD and HARMONIE model (a) zonal and (b) meridional winds for period of September 2018 – May 2019. The designations are the same as for Fig. 2.

Before making a comparison for all nine months we looked at seasonal behaviour of winds at altitudes from 5 to 15 km at the ESRAD site using the European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis. On the basis of the horizontal wind speed and direction averaged over 2005-2016 (not shown) we can distinguish two seasons when winds show different behaviour: from September to April and from May to August. We decided to group our data altogether because only one month (May) belongs to another season. The ESRAD zonal and meridional winds versus the HARMONIE corresponding winds are shown in Fig. 4, where all data for nine months are presented and the linear fits are drawn. In general, there is a good agreement between the radar and model winds, however it is better for the zonal component than for the meridional one. As in comparison with radiosondes, ESRAD underestimates both wind components compared to the HARMONIE: the slopes for the zonal wind fits are 0.85/0.97 and mean difference is -1.2 m/s whereas they are 0.72/0.81 and -0.3 m/s, respectively, for the meridional wind. The radar random errors estimated as a mean standard deviation are 2.8 m/s and 2.4 m/s for the zonal and meridional components, respectively. We also computed the slope of fit of the radar on the model, their correlation and mean difference as a function of height and presented in Fig. 5. At altitudes above about 2 km the agreement between the radar and the model is very good with an average correlation of 0.95. Below 2 km the ESRAD winds appear to be poorly correlated with the HARMONIE winds, similarly as in comparison with the radiosondes (Fig. 3). The radar random error variation with height is 1.9-3.3 m/s for the meridional wind and 2.3-3.7 m/s for the zonal wind (not shown).

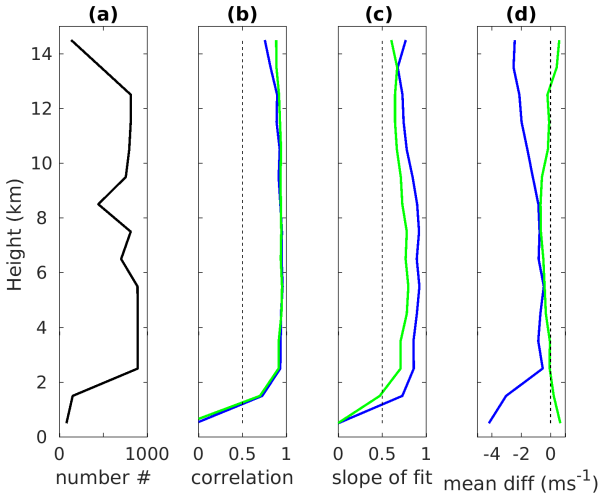

Figure 5: Altitude profiles of (a) the number of ESRAD and HARMONIE velocities available for the comparison, (b) correlation coefficient between them, (c) slope of the radar-on-model linear fits and (d) mean difference between the radar and model winds for period of September 2018 – May 2019. Blue and green colours indicate zonal and meridional wind, respectively.

3 MARA

3.1 Description of the radar

MARA (Moveable Atmospheric Radar for Antarctica) is a 54.5 MHz wind-profiler type radar. It is in many ways a smaller, movable clone of ESRAD (Kirkwood et al., 2007). MARA is less powerful than ESRAD, having peak power of 20 kW. The antenna consists of 3 adjacent square arrays, each with16 tuned dipoles (see Table 1 for the main parameters of MARA). However, common experimental modes and analysis are the same or very similar for both radars. In Table 3 the parameters of the MARA experiments used in this study are presented. Starting in 2006, MARA has been operated at various locations in Antarctica. Since 2014 it has been located at the Indian research station Maitri (71°S, 12°E) (http://www.ncaor.gov.in/antarcticas/display/376-maitri-) and in November 2017 IRF transferred the ownership of MARA to the National Centre for Polar and Ocean Research, India. Weather conditions at Maitri so far have been very harsh for MARA's antenna hardware which leads to interruptions in the MARA observations, with sometimes long breaks since repairs are only possible during the Antarctic summer.

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Experiment name	fcw_150	fca_75	fca_4500
Pulse Repetition Frequency, Hz	10300	10300	1300
Code	none	none	8-bit complementary
Number of coherent integrations	512	512	32
Number of points	39	39	39
Start height, m	100	100	4800
Stop height, m	13700	6250	105000
Number of height gates	136	123	167
Height resolution, m	100	50	600

Table 3: Parameters of the MARA experiments used in the paper.

After MARA was first deployed at Maitri in 2014, the radar winds were validated using radiosondes launched from the nearby (4 km to the east) Russian station Novolazarevskaya. Comparison revealed overall good agreement in both wind speed and direction between the radar and sonde measurements (not shown), though there is some spread in the data and there are a number of outliers. However, since July 2018 the radio soundings were interrupted and not started again so far.

3.2 MARA versus ECMWF ERA5

Because of lack of recent radiosonde data close to Maitri we compare the MARA winds with those from the ECMWF reanalysis ERA5 (Hersbach et al., 2020). The data cover the Earth on a 30-km grid and resolve the atmosphere using 137 levels unequally spread from the surface up to 1 Pa pressure level at about 80 km altitude. We use 1-hourly data for the altitude range 0-20 km at the grid point closest to the Maitri location, from January until December 2019, when the MARA data were available. We divided data into two groups: 1st - from March to September, 2nd – January, February, October, November and December. This corresponds to generally different behaviour of winds over Maitri as seen from the ECMWF data (not shown here). Plots of MARA versus ERA5 for the zonal and meridional winds as well as the linear fits for these two intervals are presented in Figures 6 and 7. In general, there is good agreement between the radar and model for both intervals. The best linear fits, which lie somewhere between the green and blue lines, have likely a slope close to or less than 1. This implies the radar slightly underestimates horizontal wind compared to the model. The correlation is high (92-95%) and the biases are small (< 0.5 m/s) and negative (with one exception). The correlation is higher and the slope is closer to 1 for the zonal component compared to the meridional one. There are no essential distinctions between the statistics for the two intervals, while the range of velocity values changes from one period to another and the bias of the meridional wind changes the value from small positive to small negative. Additionally, there are visually more outliers for data from March to September 2019. The radar random errors for the horizontal wind components estimated from standard deviations are 2.6 m/s and 2.3 m/s for the zonal and meridional wind, respectively, and they are about the same for both intervals. We can conclude that MARA measures horizontal winds with a good accuracy: with mean random error less than 2.6 m/s and mean systematic error less than -1 m/s.

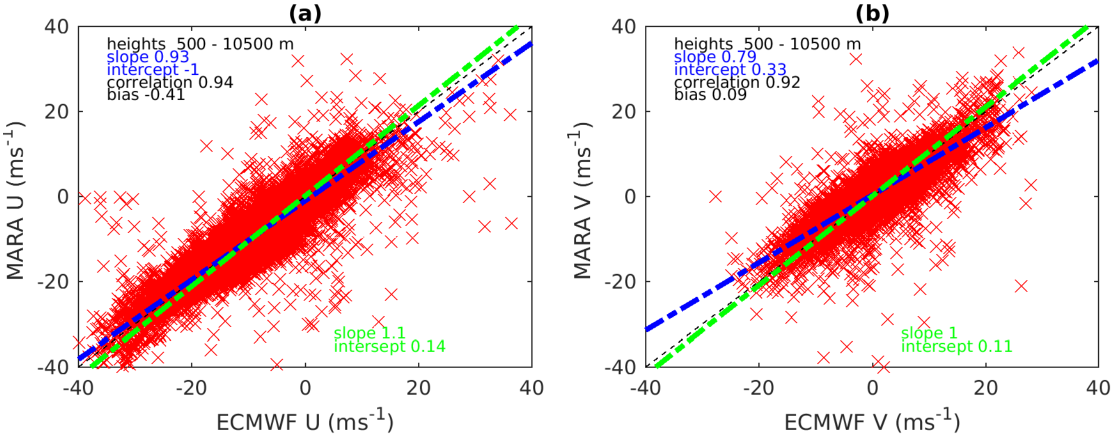

Figure 6: Comparison of the MARA and ECMWF ERA5 model (a) zonal and (b) meridional winds for period of January, February, October – December 2019. The designations are the same as for Fig. 2.

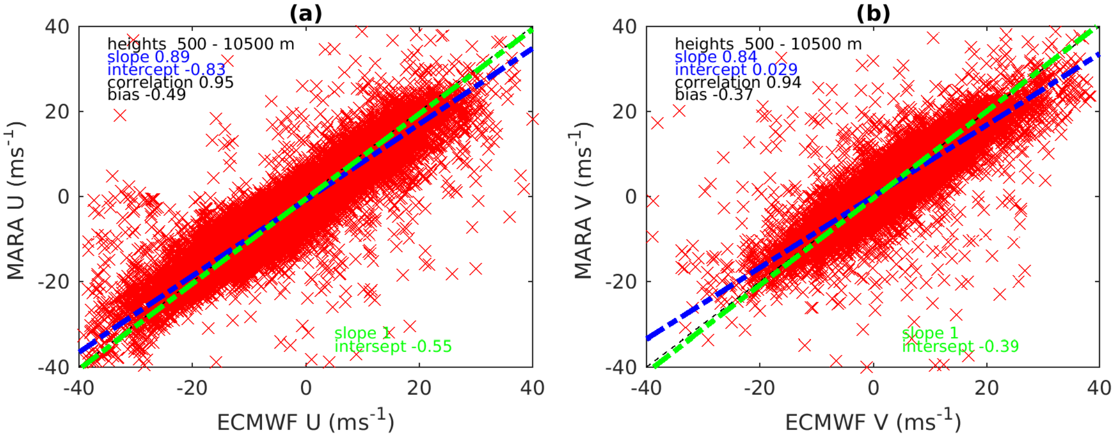

Figure 7: The same as Figure 6 but for period of March – September 2019.

In Fig. 8 and Fig. 9 we present the vertical profiles of the inter-comparison statistics for two periods. The agreement between the radar and model is good for all heights from 500 m until 10.5 km above which there are not so many radar data, radar-model correlation weakens and absolute values of biases increase. The difference between the two periods under consideration is only seen in the altitude profiles of the radar-model biases: they vary from negative to positive for the 1st period and are negative (with a few exceptions) for the 2nd period. The standard deviation of the MARA wind varies between a maximum of 3.4 m/s at 0.5 km to minimum of 2 m/s at 6 km attitude. Significantly more wind data for the lower heights (< 2 km) are available for MARA than for ESRAD.

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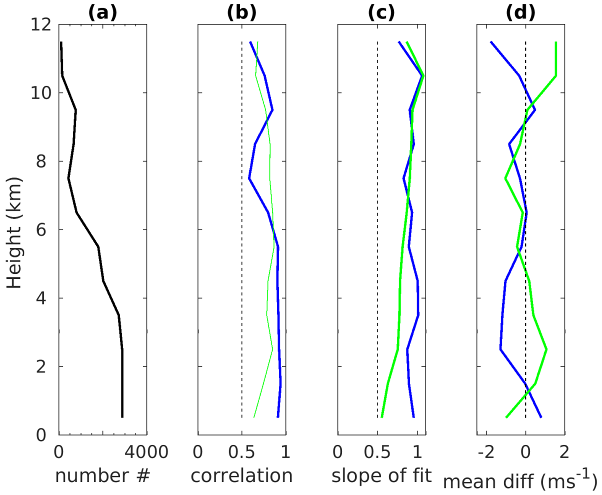

220 **Figure 8: Altitude profiles of (a) the number of MARA and ERA5 velocities available for the comparison, (b) correlation coefficient between them, (c) slope of the radar-on-model linear fits and (d) mean difference between the radar and model winds for January, February, October – December 2019. Blue and green colours indicate zonal and meridional wind, respectively.**

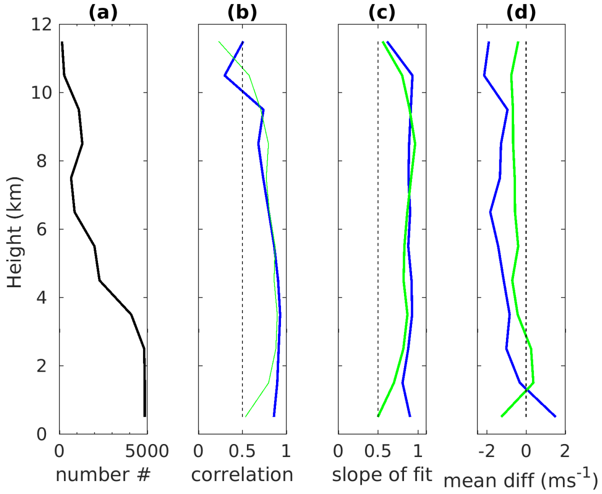

Figure 9: The same as Fig. 8 but for March – September 2019.

4 Discussion

225 Several studies have been published on inter-comparison of windprofiler and radiosondes, models and different radar techniques for deriving winds (e. g. Vincent et al. 1987; Gage et al. 1988; Kudeki et al. 1993; MacKinnon 2001; Stober et al. 2012). Some of them were reviewed by Reid et al. (2005) where the authors also presented their own comparison of the Mount Gambier wind profiling radar in Australia using FCA with 3000 radiosondes. The authors confirmed the other studies and found that the FCA winds underestimate in magnitude by about 3-7 % relative to the radiosonde winds in the planetary 230 boundary layer, troposphere and lower stratosphere. The reasons given for this bias in the FCA technique are that noise and

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antenna coupling tend to reduce cross-correlation values, and hence, estimated wind speeds (Holdsworth, 1999). Other possible reasons of differences between profiler winds and other techniques is spatial and temporal separation between measurements (e.g. Jasperson 1982) as well as faults and errors in all instruments (e.g. Rust et al. 1990). Belu et al. (2001) explain better correlation between the radar and radiosonde zonal winds than meridional ones due to the latter usually being smaller than the former, and the same absolute errors for the two components results in more significant relative errors for the meridional component. The authors also compared the winds measured with the CLOVAR windprofiler near London, Canada using DBS technique with winds from the Canadian Meteorological Centre operational model for eight months. Very good agreement was shown in general, however the radar overestimated the winds relative to the model by 5-20% (more for the meridional than for the zonal component). Comparisons of windprofilers with other models have been carried out. For example, Gage et al. (1988) found very good correspondence between winds measured with the VHF radar on Christmas Island in the central Pacific and the ECMWF analysis. Schafer et al. (2003) compared winds between 1.5 km and 12 km measured by the windprofilers at four sites in the tropical Pacific between 8 and 13 years to the NCEP-NCAR reanalysis. Closer agreement was found for the sites where radar data or/and data of nearby located rawinsondes were assimilated by the model.

Our results of inter-comparison of the ESRAD FCA winds and winds from radiosondes that show systematic underestimation by the radar are consistent with others presented in literature. Moreover, difference in the results for the zonal and meridional components is qualitatively the same as in other studies. When compared with the models over several month period: ESRAD with regional HARMONIE and MARA with global ECMWF reanalysis, both radars show predominantly smaller winds in the troposphere and lower stratosphere. This might result from limitations in the ability of the model to provide a good description of wind at particular location that, in turn, might depend on how many local wind data e.g. from radiosondes were assimilated in the model. For Antarctica the data from radiosondes at only few locations are available on regular basis (http://weather.uwyo.edu/upperair/sounding.html). However, we found surprisingly very good agreement between the MARA and ECMWF model winds (correlation of 92-95%), as well as for ESRAD and HARMONIE above 2 km height (correlation of 95%). A lot of different types of observations, including radiosondes, are used within the MetCoOp HARMONIE-AROME modeling system (Muller et al., 2017). Three radiosonde neighbouring stations to Kiruna are Luleå (69.32N, 16.13E), Sodankkylä (67.37N, 26.65E) and Andoya (69.31N, 16.13E).

In the altitude-resolved comparison between ESRAD and the HARMONIE model as well as radiosondes (Fig. 3 and Fig. 5) we found that below about 2 km the agreement is not good. This is due to technical limitation of ESRAD and other radars, which use the same antenna array for transmission and reception, for measurements at the lowest heights where a received signal can be contaminated with a transmitted pulse. For MARA we used a small additional receiving-only array that allow accurate derivation of winds at the lower altitudes too that are in good agreement with the ECMWF model (Figs. 8 and 9). The ESRAD remote receive-only array deployed for the same purpose has had time synchronization problem during the period of interest and these data were not included in our analysis.

5 Summary and outlook

The performance of two MST radars: ESRAD in Kiruna, Swedish Arctic and MARA at Maitri, Antarctica in measuring horizontal winds in the troposphere and lower stratosphere have been evaluated by comparison with radiosondes and/or NWP models. The inter-comparison with 28 radiosondes launched from January 2017 to August 2019 showed that the ESRAD FCA method underestimates zonal and meridional winds by about 8% and 25 %, correspondingly. We estimated the ESRAD random and systematic errors as 2.3 m/s (2 m/s) and -1.4 m/s (0.4 m/s), respectively for the zonal (meridional)+ component. The ESRAD winds were also compared with the winds computed using the regional NWP model HARMONIE-AROME for the period September 2018 – May 2019. We found again that ESRAD winds are underestimated by 9% and 24% compared to the model, while showing a very high correlation between ESRAD and model winds.

The MARA horizontal wind components have been compared with those from the ECMWF ERA5 reanalysis for the period January - December 2019. In general, the MARA FCA winds are in a good agreement with the model winds. However, the radar zonal winds can be, on average, a bit lager (2%) as well as smaller (6%) than the model ones. In turn, the radar meridional winds are 8-11% smaller. The MARA random errors are estimated to be 2.6 m/s and 2.3 m/s for the zonal and meridional wind, respectively.

On the basis of this analysis we conclude that both radars ESRAD and MARA provide measurements of horizontal winds in the troposphere and lower stratosphere of a good quality with reasonably well-known bias and uncertainty. We plan to use the radars for validation of winds measured by Doppler lidar on the board the Aeolus satellite in a forthcoming study.

Data availability

ESRAD data are available from PV on motivated request. MARA data can be obtained on reasonable request from SC. HARMONIE historical forecasts can be ordered via SMHI's open data service: https://www.smhi.se/en/services/open-data/search-smhi-s-open-data-1.81004.

ERA5 is taken from Copernicus Climate Change Service (C3S) (2017): ERA5: Fifth generation of ECMWF atmospheric reanalyses of the global climate. Copernicus Climate Change Service Climate Data Store (CDS), date of access 20 December 2019 (https://cds.climate.copernicus.eu/cdsapp#!/home).

Author contribution

SK, EB and PV developed the codes and conducted the data analysis. SH, MK and HK provided the HARMONIE model outputs. SC and KS provided the MARA data. All co-authors discussed the results. EB prepared the manuscript with contribution from all co-authors.

Competing interests

The authors declare that they have no conflict of interest.

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