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# Reaching the lower stratosphere: validating an extended vertical grid for COSMO

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## Abstract

This study presents an extended vertical grid for the regional atmospheric model COSMO, used for numerical weather prediction, reaching up to 33 km. The extended setup has been used to stably simulate eleven months in a domain covering central and northern Europe. Temperature and relative humidity have been validated using radio sonde data in polar and temperate latitudes, focussing on the stratosphere. Temperature values are reproduced very well by the model. Relative humidity could only be met in the mean over the whole time period after excluding data from Russian stations, which showed significantly higher values. A study of orographically induced lee waves over Iceland, well visible in the model but not in the regrided boundary data (ERA-Interim and NCEP reanalysis), showcases the advantage and applicability of the model in the extended vertical grid.

## 1 Introduction

The upper troposphere and lowermost stratosphere is a place of sharp gradients in many constituents of air and of the physical parameters used to describe its state. Temperature and ozone are textbook examples, but methane, water and many more species also show a strong gradient. At the same time, being the boundary to the lower atmosphere, this is an area where small scale fluctuations can have a strong influence on the stratosphere and its composition (Zahn et al., 2004).

In order to simulate this highly vulnerable and influential layer directly, a model with high vertical and horizontal resolution is needed. Global models usually are too coarsely resolved and cannot model the small scale processes. In extending the vertical layering of the regional model COSMO to 33 km, we present here a model that can fill the gap.

After an introduction to the model and an exact definition of the extended vertical grid in Sect. 2, the measurement data is introduced in Sect. 3. COSMO is shown to

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be able to run stably for almost a year with the extended layering. Using radio sonde data and regrided data from meteorological reanalyses, it is shown that the model is able to reproduce temperatures very well (Sect. 4.2) while relative humidity is more difficult (Sect. 4.3) and only its mean value could be reproduced. By looking at an example of orographic waves in Sect. 5, the strength of COSMO with its high resolution is illustrated.

## 2 The model: vertical grid, boundary data and domain

This section gives a short introduction to COSMO and explains the changes made to the standard vertical grid as well as the boundary data used and the specified domain.

### 2.1 Introduction to the model

COSMO (COnsortium for Small-scale MOdelling) is a regional atmospheric model that has been developed by a consortium lead by the german weather service DWD (Deutscher Wetterdienst). DWD uses the model for its regional numerical weather forecast of Europe and Germany with a resolution of 7 and 2.8km respectively (Baldauf et al., 2011). Many extensions have been developed for the model, for example COSMO-ART including chemistry and aerosols (Vogel et al., 2009).

The standard setup of COSMO used for the forecast of central Europe (DWD domain COSMO-DE) reaches to a height of 22.0 km (Baldauf et al., 2011). But the model has also been used to study greater heights in tropical latitudes in the AMMA (African Monsoon Multidisciplinary Analyses) project (Gantner and Kalthoff, 2010), reaching 28.0 km, and a tropical setup reaching up to 30.0 km has also been developed (Krähenmann et al., 2013). With the extended vertical grid presented in this study, it becomes possible to simulate the lowermost stratosphere in polar latitudes. This validation study opens the door to new applications of COSMO.

## 2.2 The extended vertical grid

The standard vertical grid of the COSMO model reaches up to 22.0km in 50 layers. The vertical structure is visible from Fig. 1, exact values are given in Table A2. The damping layer in the top layers begins at 11.357 km in standard setup.

5 The vertical layering of the new grid introduced in this study is also given in Fig. 1 and Table A2. It is focused on the lower stratosphere, with the highest of the 60 layers at 33km, the damping layer beginning at 28 km (rdheight = 28 000.0 in the namelist). Not only is the top layer of the new grid about 10km above that of the old grid, but the resolution is also better in all heights above the lowest kilometer.

## 10 2.3 The analyses used as boundary data

In order to examine the influence of different boundary data on the model results, the model was run twice, using ERA-Interim and NCEP reanalysis data for starting and boundary values. The vertical layering of the two reanalyses is displayed in Fig. 2. In order to better evaluate the model, the reanalysis data was also interpolated to the vertical grid used for the output of the model.

15 The reanalysis project of the National Center for Environmental Prediction (NCEP) provides data starting on the first of January 1948, giving global fields every six hours (00:00, 06:00, 12:00 and 18:00 UTC) at a resolution of T42, which corresponds to approximately 2° (Kalnay et al., 1996). The upper boundary is at 2.7 hPa, which is just within the limits of the new vertical grid reaching up to 33 km.

20 ERA-Interim is the reanalysis project of the European Center for Medium Range Weather Forecast (ECMWF) (Dee et al., 2011). The data was used in this study at a resolution of T255 (corresponding to approximately 0.75°) and up to 0.2 hPa. So both the vertical and horizontal resolution are higher than those of the NCEP reanalysis.

25 ERA-Interim is available for the same timestamps as the NCEP reanalysis.

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## 2.4 The model domain

The model domain used in this study is shown in Fig. 3. It covers most of Europe with a focus on the polar latitudes, stretching from northern Africa in the south and covering Svalbard, east of Greenland at 74° N, in the north. The resolution was set to 0.2°. The COSMO model is operationally used by DWD to produce regional weather forecasts for central Europe, but not in polar latitudes (Baldauf et al., 2011).

So the domain chosen here can be used to assess the performance of the model in polar latitudes, since a direct comparison to an area of regular use is possible. The required namelist parameters needed to reproduce the model domain are given in Table A1.

The first timestep simulated by the model runs used in this study is 1 October 2010 00:00 UTC and the last output is for 1 September 2011 00:00 UTC. The cold temperatures that can be expected in the polar stratosphere especially in winter and the warming in spring both lay well within the simulated time. Output was produced on an hourly basis, the model timestep was set to 60s, using the namelist parameter  $dt = 60.0$ . It could be shown that the model runs stably for eleven months in this setup by validating the whole timeperiod with radiosonde data.

The timespan of eleven months is due to the time limit applied to the calculation. The model was run with a time limit of two days, reaching a total number of 8076 output hours. The last output then turns out to be on 2 September 2011 at 11:00 UTC, but the authors decided to perform this study for the exact eleven months, as given above.

## 3 Measurements

This study validates the output of the COSMO model using the temperature ( $T$ ) and relative humidity (rH) recorded by radiosondes of stations within the model domain.  $T$  and rH are regularly observed values and are here considered basic physical parameters whose distribution well represents the physical state of the model. The measurement

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data used in this study was taken from the ESRL (Earth System Research Laboratory) radiosonde database provided by NOAA (National Oceanic and Atmospheric Administration) (Schwartz and Govett, 1992).

The location of the 24 stations is given in Fig. 3, exact values and the names being given in Table B1. This choice includes all polar stations in the domain and the same number of temperate stations with good data coverage.

All stations typically release one radiosonde every twelve hours, at 00:00 UTC and 12:00 UTC, so 671 ascents can be expected from each station during the period of 335 simulated days. The actual number of ascents for each station is also given in Table B1. All stations except Ny Alesund, which has a little more than one ascent per day, come close to or exceed this number, the average being at 673 ascents.

In order to compare sonde and model data, the grid point closest to each station was used to compare the simulation with measurements. Since the resolution is only  $0.2^\circ$ , the error made by this simple identification is small. The latitude and longitude of the closest grid point can also be found in Table B1. An interpolation to the exact location was not considered necessary as the radio sondes drift with the wind, an effect not accountable, since the exact geographic location of each measurement taken by the sonde is not available. This is also the reason why no interpolation in the vertical was done.

In each ascent, the value closest to each model output layer at even kilometers was identified with the height of that layer, the maximum difference allowed having been set to 500m. Since there are typically more than 20 measurements taken in an ascent, the error was much smaller than this value, reaching only 156.0m on average, with a SD of 126.3m.

The data was used as downloaded from the server, only excluding values in  $rH > 100\%$ . It was found that all stations in Russia give much higher humidity values than the other stations, which is the reason why the humidity data of all Russian stations were excluded from the investigation. This will be further discussed in Sect. 4.3.1.

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## 4 Results

This sections presents the results of the model validation study. Two questions are to be answered: Is the model able to simulate the polar latitudes and the stratospheric heights? And what is the influence of the boundary data on these results? Following the questions, the answers will also have to be twofold.

After presenting the output grid, the results in temperature are presented. Those of relative humidity are described in the following section. The latter is preceded by the explanation why it seemed reasonable to exclude the data of Russian stations when examining relative humidity.

### 4.1 The output grid

In order to compare the model results to the measurements, model output on a vertical grid of whole kilometers from 8 to 33km was used. The values given out above 27 km are already within the damping layer and the results can no longer be considered to come genuinely from the model, so measurements were only compared up to 27 km.

As noted above, the boundary data was also interpolated onto the output grid, using the same program that is used to prepare the boundary data for running the model, called INT2LM (Schättler, 2013). COSMO uses terrain following coordinates. Above a certain value specified in the namelist, the layers become smooth and are no longer terrain following. This height has to be higher than the highest mountain tops in the domain and in this case was set to  $vcflat = 7000.0$ , given in the namelist in m.

This is the reason why all analyses done in this study only start at 8 km, just 3 km below the lowest free running level of the standard vertical grid at 11 km.

### 4.2 Temperature

To begin the discussion, a look at Fig. 4 exemplifies the basis of this study. It shows all the soundings of the station Jan Mayen during the time considered here. The warming

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at the end of the polar winter is well visible. Most striking are the many white areas in the image, showing the lack of measurement data. The bottom figure shows the corresponding result of the model run with boundary data by ERA-Interim. The image is filled, but the data was only used for the following analysis if measurements were also available at the timestamp.

To compare the data in a more quantitative manner, Fig. 5 shows the mean ascent at Jan Mayen for both model runs. The boundary data is also included in the image. All three soundings lay on top of each other, the model is able to simulate mean temperature well in all heights. The minimum temperature in the lowermost stratosphere is well reproduced. In order to compare to a temperate station, Fig. 5 also gives the mean ascent of the station in Madrid. The minimum is more pronounced, but also reproduced by the model. There is no difference visible between the model run forced by ERA-Interim and that forced by NCEP reanalysis data.

Figure 6 gives exemplary timeseries of Jan Mayen and Madrid in 26 km height, approximately 2.5 km above the model top of the standard vertical COSMO grid for both model runs. When comparing the two figures, temperature values reflect the different latitude: winter temperatures above Jan Mayen are much colder than above Madrid, the warming in spring much more pronounced. The good correspondance of model and measurement not only shows that the two model runs and also the boundary data are very similar, but also that the model performance does not change during the whole simulated period. There is no greater offset in the end than in the beginning.

In order to further compare the performance of COSMO, Fig. 7 shows the scatterplots of all measured against modelled temperature values with colorcoded height intervals for all polar stations. The variability in higher altitudes is lower, which is why the scatter is reduced with height. Both model runs with different boundary data simulate temperature very well, reaching  $r^2 = 0.98$ . The results of the model in temperate latitudes was just as good and the correlation does not reach higher values when using the regridded boundary data (not shown).

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When reducing the data to values of descriptive statistics, all stations can be easily compared. Figure 8 shows the mean of  $T_{\text{model}} - T_{\text{meas}}$  and  $T_{\text{bound}} - T_{\text{meas}}$  for all levels and for stratospheric levels with  $z \geq 11$  km. The stratospheric layers are also those layers added when using the extended instead of the standard vertical grid. In both cases, the values are well reproduced by the model. When considering all layers, the mean values of the boundary data are lower than those of measurement, the model output actually being closer to the measurement. When considering the new stratospheric layers, the model performance is just as good as it is when considering all layers. The boundary data is now closer to measurements than for all levels. Overall, COSMO is able to reproduce measurements in temperate as well as polar latitudes in all heights, the mean difference never exceeding 0.5 K.

The spatial distribution for the run forced by ERA-Interim is shown in Fig. 9, the figure being very similar when looking at the results of the run using the NCEP reanalysis as boundary data. It now becomes clear that the slight outliers of stations 7, 16 and 21 also visible in Fig. 8 are all close to the eastern border of the model domain. By looking at the stations used to examine the problem of Russian humidity data however, it could be shown that this effect is not visible when considering more eastern stations. It is not due to the relative location of the three stations within the model domain but more likely to the measurement data.

## 4.3 Relative humidity

### 4.3.1 Excluding the Russian humidity data

When examining the relative humidity of the 24 stations chosen for the validation of the model, it became apparent that the model could not reproduce the relative humidity data of any station within Russia (or of Gomel, the only station in Belarus with data during the modelled period, as became clear when examining more stations).

As there was no apparent reason for this offset and only 7 stations lay within Russia in the original set (5 polar and 2 temperate), this issue needed further investigation.

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The data of all 23 Russian stations well within the model domain and Gomel in Belarus (see Table B2) was compared with 24 stations in the eastern part of the domain but not in Russia or Belarus (see Table B3). The result is best illustrated by the mean over all rH values of all ascents in each group. Figure 10 shows the result for the Russian stations and the 24 stations outside of Russia that had been chosen. While the model reproduces the values of the stations outside of Russia, the measurement values of those stations within Russia are very different from the model values but also from the regrided analysis or the measurements of those stations outside of Russia.

In addition to the mean, the station Kaliningrad (no. 8), surrounded by the non-Russian stations Leba (no. 11), Kaunas (no. 12), Visby (no. 13) and Tallin (no. 16), also allows a spatial investigation. While the results of Kaliningrad are similar to the mean of Russian stations, the mean ascents of the surrounding stations are all similar to the mean of the non-Russian stations.

These two findings are in line with Balagurov et al. (2006) and Moradi et al. (2013). The authors of these studies come to the conclusion that the measurement technique used in radio sondes of Russia give values that are significantly too high for low pressure. Altogether, this lead to the decision to exclude Russian stations from the further investigation of the performance of COSMO with respect to relative humidity.

#### 4.3.2 Results when excluding Russian data

When excluding the Russian stations (no. 7, 10, 13, 16–18 and 21), 10 temperate and 7 polar stations remain to examine relative humidity.

The mean values of the ascents of temperate and polar stations for both model runs is given in Fig. 11. The low stratospheric values are well reproduced by the model in all four cases, while the tropospheric offset is larger. In heights lower than 13 km, the model is too humid on average, the values being approximately 10% too high. The mean of tropospheric values seems to only be well reproduced for polar stations when using the NCEP reanalysis.

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However, when looking at the scatter plot of the polar stations, given in Fig. 12, it becomes clear that the model is only able to reproduce a mean value that is similar to the measurements. There is no notable correlation in any height. The variability in the measurements is simply too high to be reproduced by the model. This is also visible in the figures showing the mean ascents. The SD of the model and the regrided analysis is much smaller than that of the measurements in stratospheric layers. Figure 13 shows the timeseries of relative humidity in 10 and 21 km height. In 21 km height, the values are very low most of the time. Only large scale fluctuations like those at the end of the year 2010 can be captured by the model, while smaller perturbations are not reproduced.

Figure 14 shows the spatial distribution of mean  $rH_{\text{meas}} - rH_{\text{model}}$  over all layers. The Russian stations have been excluded, but two other stations also show an offset compared to the other stations: Thorshaven (no. 11) and Scoresbysund (no. 23). The modelled values are higher than measurements, with  $\Delta rH = 4\%$ . This again is probably not an effect of the model, but more likely of the measurements since surrounding stations do not show similar effects.

Relative humidity is on the one side very variable, so that it becomes hard to model exactly, on the other side seems not an easy parameter to measure, as shows the problems first found in Russian data, but apparently also present in the data of other stations.

### 5 Case study: orographic waves

So far a validation of temperature and relative humidity using radio sonde data has been presented. The model is able to reproduce measurements of temperature very well, the highly variable relative humidity is more difficult to model, but also to measure.

Results show that the regrided boundary data also reproduces the measurements. It may not be independent of the radio sonde data, since it was taken from reanalysis projects which use radio sonde data in their data assimilation cycle. Still the question

seems adequate what the added value of the computationally much more expensive model is compared to simply regridding the boundary data.

To answer this question, we present an example of orographically induced lee waves. On 8 April 2011 00:00 UTC, a strong westerly flow was present over the Norwegian Sea, the center of the low being situated over Greenland. The southern part of the jet was situated over Iceland, the region this example is focused on. The jet system is well visible in Fig. 15, showing the wind speed  $V = \sqrt{u^2 + v^2}$ . The focus here is on model level 48 in 20.5 km height. This would be almost out of view in the standard setup and far in its damping layer, while it is situated in the middle of the extended vertical layering presented here. The height is above 18 km, so the regridded data on the model level is precisely in the same height as the model output, since the model uses terrain following coordinates only up to 18 km.

The model and reanalysis fields of  $V$  in Fig. 15 compare well with one another. The jet is located in approximately the same place, but the model field looks more detailed and the edges are very jagged, especially over Iceland. When looking at temperatures, shown in Fig. 16, the advantage of the model over the regridded data becomes more apparent. While ERA-Interim has a resolution of  $0.75^\circ$ , COSMO is almost four times as good and resolves and generates the structures above and east of Iceland. The reanalysis does not contain much information on the waves induced by the flow, while the model shows a strong disturbance of the temperature field of almost 10 K.

The most prominent mark is found in the vertical wind field, see Fig. 17. The wave structure is very well visible as elongated areas of upward and downward winds. Similar structures are visible over southern Greenland and over the North Sea, south of Sweden.

## 6 Summary and conclusions

This study presents a new, extended vertical grid for the regional model COSMO. The extended grid reaches up to 33 km, almost 10 km more than the standard vertical setup.

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By reducing the magnitude of the damping layer to 5 km, the added layer that can be considered to be free running reaches 28 km, compared to 11 km in the standard setup. This is already well in the lowermost stratosphere.

This new extended vertical grid was tested using a domain spreading over central and northern Europe. To assess the influence of different boundary conditions, two model runs were compared with measurements, using ERA-Interim or NCEP reanalysis as boundary conditions for the model. Both model runs covered the same period, from 1 October 2010 to 1 September 2011. The model simulated this period stably.

The output was compared with measurements of temperature and relative humidity from all 12 polar radio sonde stations in the domain and as many in temperate latitudes.

The measurements of temperatures are well reproduced by the model for all stations and heights. This is not only true for the mean, but also for the comparison of single ascents. The error in heights above 11 km is even smaller than that when considering all layers, probably because the variability is not as high as when including the tropospheric values. The mean error made by the model is smaller than 0.5 K for all stations. The boundary data, which was regridded to the output grid, reaches similar values.

When comparing relative humidity values, it was found that Russian stations (and Gomel in Belarus) had systematically submitted higher values. This finding was strengthened by comparing all 23 Russian stations in the domain and Gomel to 24 stations not in Russia, but in the eastern part of the domain and considering model and boundary data. After excluding Russian stations from the analysis of relative humidity, it became apparent that the model is not capable of reproducing the exact values of each measurement, and neither is the regridded boundary data. But it does reproduce the low stratospheric values and fits measurements well when taking a mean over the whole time period. In the tropospheric layers, the model values are more humid than measurements.

In order to show the advantage of the model over simply regridding the boundary data, a case study of lee waves above southern Iceland was presented. The general features of the synoptic situation could be found in both the model and the regridded

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reanalysis data. But the analysis lacked every trace of lee waves, while they were well visible in the model fields of temperature and vertical wind speed.

The vertical grid for COSMO presented in this study seems a good alternative to the standard vertical layering when focusing on the upper troposphere and lower stratosphere. It has been shown to run stably, simulating almost a year. By comparing with data from synoptic radio sondes and regrided reanalysis data, it could be shown that the model is able to reproduce measurements of temperature well and produce reasonable values of relative humidity. At the same time, the model resolves features not visible in the reanalysis data, like orographically induced lee waves. Using this extended vertical grid expands the possible applications of COSMO into the stratosphere. With its high resolution it could be used to study cross-tropopause transport or simulate the chemistry of the lower stratosphere in polar latitudes when also including COSMO-ART.

## Appendix A: Model specifications

This part of the appendix specifies the model setup. It gives the namelist settings for the preprocessor int2lm needed to reproduce the geographic model domain in Table A1 and the exact values of the vertical grids – the new, extended grid as well as the standard grid used for COSMO-DE – in Table A2.

## Appendix B: Specifications of the stations

This part of the appendix specifies the stations of which data was used in this study. Table B1 lists the information for those stations used for the original study, while Tables B2 and B3 list the information of those 48 stations that were used to investigate the bias in relative humidity of the stations in Russia.

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**Table A2.** Heights of the layers of the standard and the extended COSMO grid, specified in m.

no.	extended	standard	no.	extended	standard
0	0.00	0.00	31	8711.53	7539.64
1	70.00	20.00	32	9255.31	8080.00
2	151.86	51.43	33	9818.03	8642.86
3	245.82	94.64	34	10399.91	9228.57
4	352.10	150.00	35	11001.17	9837.50
5	470.92	217.86	36	11622.05	10470.00
6	602.52	298.57	37	12262.76	11126.43
7	747.13	392.50	38	12923.55	11807.14
8	904.97	500.00	39	13604.64	12512.50
9	1076.27	621.43	40	14306.25	13242.86
10	1261.25	757.14	41	15028.62	13998.57
11	1460.15	907.50	42	15771.97	14780.00
12	1673.20	1072.28	43	16536.53	15587.50
13	1900.61	1253.57	44	17322.52	16421.43
14	2142.63	1450.00	45	18130.19	17282.14
15	2399.47	1662.50	46	18959.74	18170.00
16	2671.37	1891.43	47	19811.42	19085.36
17	2958.56	2137.14	48	20685.45	20028.57
18	3261.25	2400.00	49	21582.05	21000.00
19	3579.68	2680.36	50	22501.46	22000.00
20	3914.09	2978.57	51	23443.90	
21	4264.68	3295.00	52	24409.61	
22	4631.70	3630.00	53	25398.80	
23	5015.37	3983.93	54	26411.71	
24	5415.92	4357.14	55	27448.57	
25	5833.58	4750.00	56	28509.60	
26	6268.57	5162.86	57	29595.03	
27	6721.12	5596.07	58	30705.08	
28	7191.47	6050.00	59	31840.00	
29	7679.83	6525.00	60	33000.00	
30	8186.44	7021.43			

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**Table B1.** Specifications of the stations of which data was used in this study. Stations 1–12 are in temperate, 13–24 in polar latitudes. The international countrycode is also given. Real coordinates are those of the true location, model coordinates those of the closest grid point used to compare measurements and model data.

no.	name	country	WMO no.	lat real	lat model	lon real	lon model	ascents
1	Madrid	ES	8221	40.470	40.494	−3.580	−3.521	654
2	Pratica di Mare	IT	16245	41.650	41.562	12.430	12.537	995
3	Bucharest	RO	15420	44.500	44.554	26.130	26.168	670
4	Stuttgart	DE	10739	48.830	48.796	9.200	9.107	674
5	Legionowo	PL	12374	52.400	52.428	20.970	21.112	671
6	Castor Bay	IE	3918	54.300	54.247	−6.190	−6.178	495
7	Moscow	RU	27612	55.750	55.859	37.570	37.458	633
8	Stavanger	SE	1415	58.870	58.929	5.670	5.735	623
9	Jokioinen	FI	2963	60.820	60.721	23.500	23.588	652
10	Kargopol	RU	22845	61.500	61.441	38.930	38.903	593
11	Thorshavn	DK	6011	62.020	62.007	−6.770	−6.783	651
12	Keflavik	IS	4018	63.970	63.951	−22.600	−22.593	649
13	Kandalaksa	RU	22217	67.150	67.136	32.350	32.366	670
14	Bodo Vi	NO	1152	67.250	67.137	14.400	14.601	651
15	Sodankyla	FI	2836	67.370	67.390	26.650	26.677	663
16	Nar'Jan Mar	RU	23205	67.650	67.662	53.020	52.948	636
17	Sojna	RU	22271	67.880	67.946	44.130	44.126	650
18	Murmansk	RU	22113	68.970	68.963	33.050	33.004	672
19	Scoresbysund	GL	4339	70.480	70.642	−21.970	−22.020	657
20	Jan Mayen	NO	1001	70.930	70.911	−8.670	−8.860	1040
21	Malye Karmakuly	RU	20744	72.380	72.285	52.730	52.609	591
22	Bjornoya	NO	1028	74.520	74.640	19.020	18.792	986
23	Danmarkshavn	GL	4320	76.770	76.759	−18.670	−18.470	644
24	Ny Alesund	NO	1004	78.920	78.994	11.930	11.981	352

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**Table B2.** Specifications of the Russian stations of which data was used in this study, liste from south to north. Real coordinates are those of the true location, model coordinates those of the closest grid point used to compare measurements and model data.

no.	name	country	WMO no.	lat real	lat model	lon real	lon model	ascents
1	Voronez	RU	34 122	51.670	51.608	39.270	39.392	640
2	Kursk	RU	34 009	51.770	51.865	36.170	36.056	603
3	Gomel	BY	33 041	52.450	52.595	31.000	30.948	468
4	Suhinici	RU	27 707	54.120	53.983	35.330	35.341	587
5	Rjazan	RU	27 730	54.630	54.651	39.700	39.578	668
6	Kaliningrad	RU	26 702	54.700	54.696	20.620	20.733	442
7	Smolensk	RU	26 781	54.750	54.680	32.070	32.131	671
8	Moscow	RU	27 612	55.750	55.859	37.570	37.458	633
9	Niznij Novgorod	RU	27 459	56.270	56.330	44.000	43.869	654
10	Velikie Luki	RU	26 477	56.380	56.450	30.600	30.566	649
11	Bologoe	RU	26 298	57.900	57.877	34.050	34.220	639
12	Vologda	RU	27 037	59.230	59.217	39.870	39.908	300
13	St. Petersburg	RU	26 063	59.970	60.054	30.300	30.348	656
14	Kargopol	RU	22 845	61.500	61.441	38.930	38.903	593
15	Syktvykar	RU	23 804	61.720	61.672	50.830	50.748	668
16	Petrozavodsk	RU	22 820	61.820	61.926	34.270	34.313	666
17	Arhangelsk	RU	22 550	64.530	64.405	40.580	40.568	296
18	Kem	RU	22 522	64.980	65.083	34.800	34.658	645
19	Pecora	RU	23 418	65.120	65.044	57.100	57.081	670
20	Kandalaksa	RU	22 217	67.150	67.136	32.350	32.366	670
21	Nar'Jan Mar	RU	23 205	67.650	67.662	53.020	52.948	636
22	Sojna	RU	22 271	67.880	67.946	44.130	44.126	650
23	Murmansk	RU	22 113	68.970	68.963	33.050	33.004	672
24	Malye Karmakuly	RU	20 744	72.380	72.285	52.730	52.609	589

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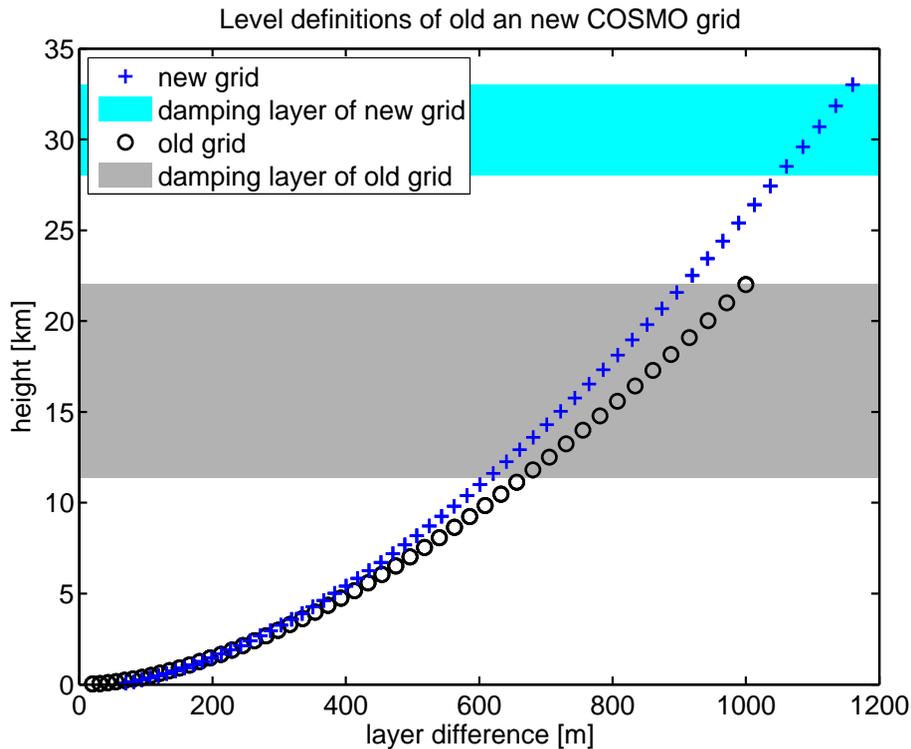
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**Table B3.** Same as Table B2 but for those stations outside of Russia used to compare to those in Russia.

no.	name	country	WMO no.	lat real	lat model	lon real	lon model	ascents
1	Bucharest	RO	15 420	44.500	44.554	26.130	26.168	670
2	Cluj Napoca	RO	15 120	46.780	46.839	23.570	23.496	336
3	Poprad	PL	11 952	49.030	49.073	20.320	20.240	672
4	Prostejov	PL	11 747	49.450	49.337	17.130	17.256	656
5	Prague	CZ	11 520	50.000	49.896	14.450	14.589	1341
6	Wroclaw	PL	12 425	51.130	51.169	16.980	16.949	668
7	Lin	DE	10 393	52.220	52.118	14.120	14.197	1348
8	Legionowo	PL	12 374	52.400	52.428	20.970	21.112	671
9	Greifswald	DE	10 184	54.100	54.149	13.400	13.399	668
10	Schleswig	DE	10 035	54.530	54.599	9.550	9.656	671
11	Leba	PL	12 120	54.750	54.747	17.530	17.609	667
12	Kaunas	LT	26 629	54.880	54.757	23.880	23.914	336
13	Visby	SE	2591	57.650	57.725	18.350	18.255	594
14	Goteborg	SE	2527	57.670	57.580	12.300	12.237	331
15	Stavanger	NO	1415	58.870	58.929	5.670	5.735	623
16	Tallin	EE	26 038	59.450	59.574	24.800	24.733	333
17	Jokioinen	FI	2963	60.820	60.721	23.500	23.588	652
18	Jyvaskyla	FI	2935	62.400	62.346	25.670	25.642	670
19	Sundsvall	SE	2365	62.530	62.610	17.470	17.398	598
20	Orland	NO	1241	63.700	63.599	9.600	9.551	667
21	Lulea	SE	2185	65.550	65.542	22.130	22.085	331
22	Bodo Vi	NO	1152	67.250	67.137	14.400	14.601	638
23	Sodankyla	FI	2836	67.370	67.390	26.650	26.677	663
24	Bjornoya	NO	1028	74.520	74.640	19.020	18.792	986

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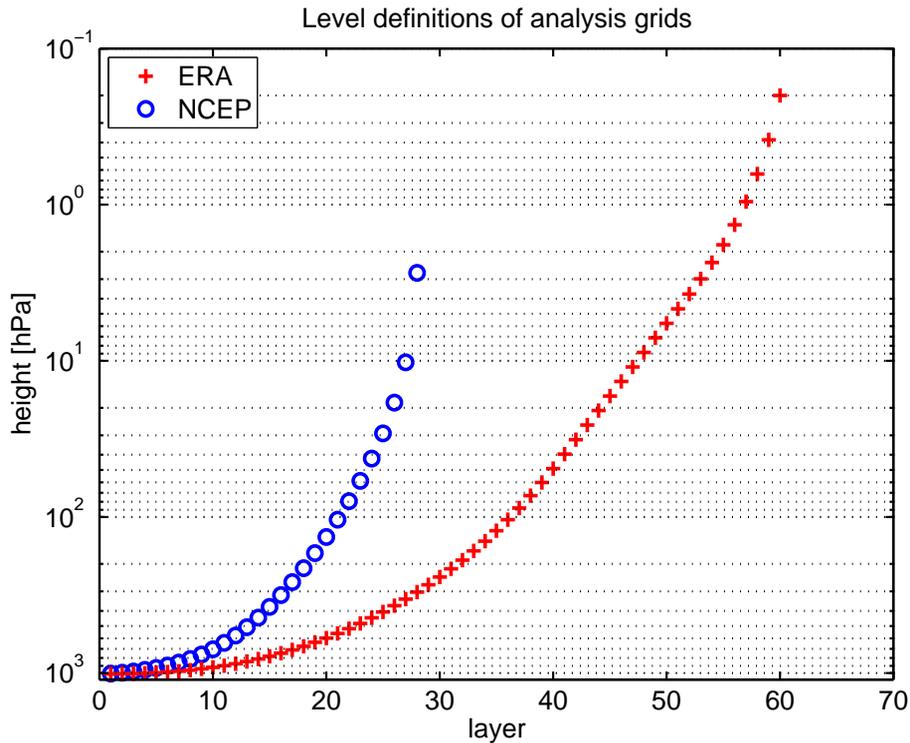


**Figure 1.** The vertical grids of the COSMO model considered in this study. The damping layer is also given as shaded area.

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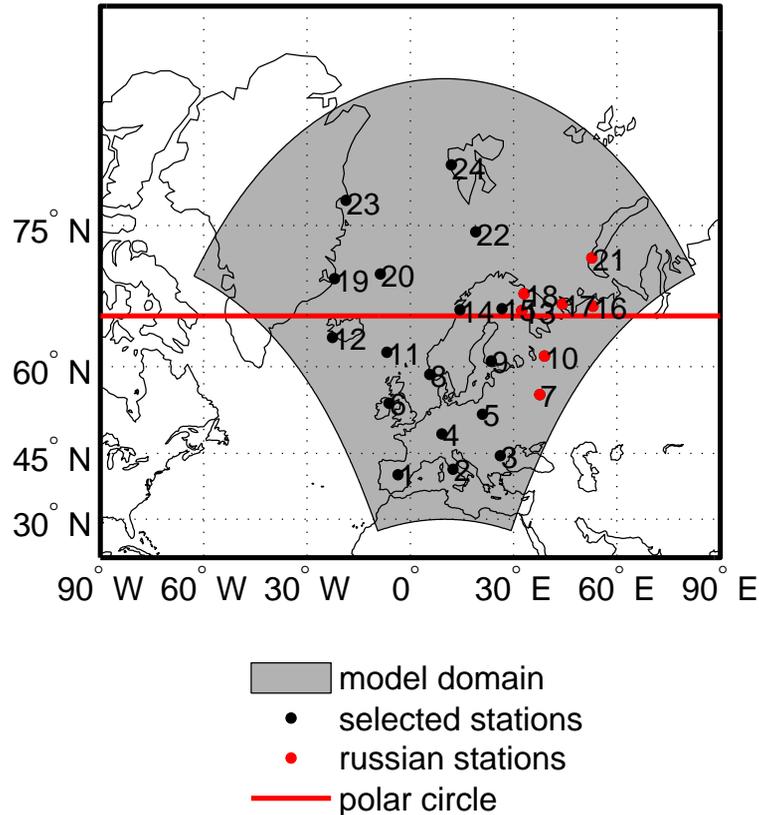


**Figure 2.** The vertical structure of the NCEP and ERA-Interim reanalysis used as boundary conditions.

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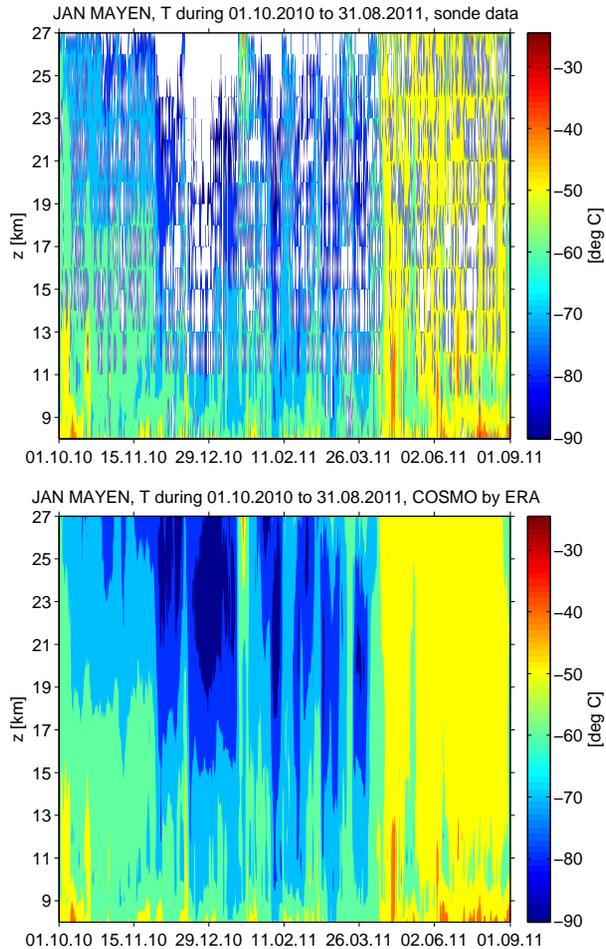
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**Figure 3.** The model domain and the radio sonde stations used in this study. The domain is displayed as gray shading, the radiosonde stations are numbered from south to north, numbers also referring to Table B1. Russian stations are marked in red. These stations showed problems in their measurements of relative humidity.

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**Figure 4.** Temperature values of all soundings of the station Jan Mayen (no. 20). Measurements are displayed on the top, the image below shows the corresponding model values.

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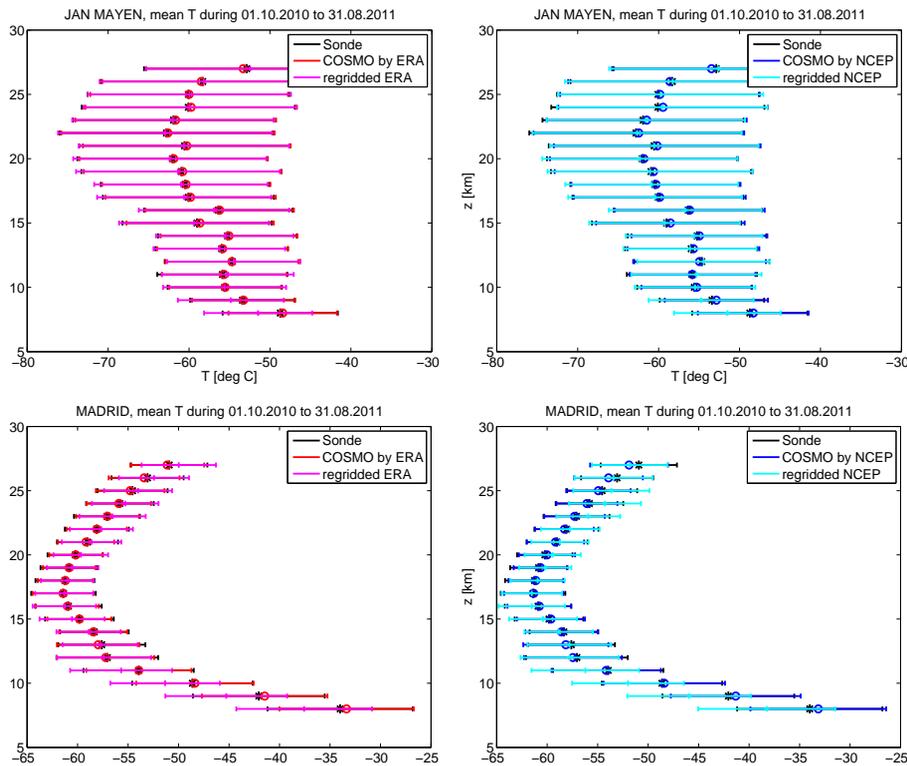
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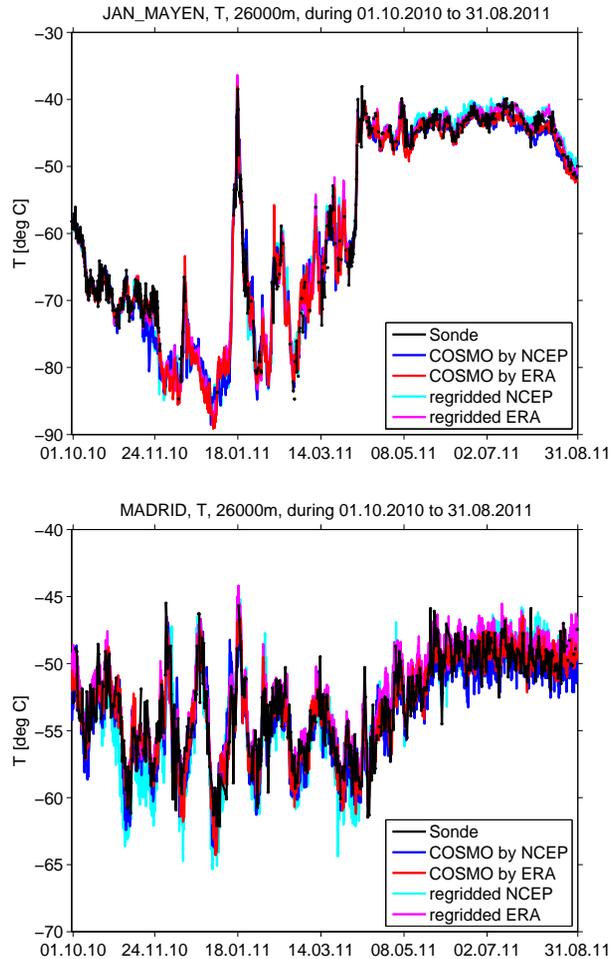
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**Figure 5.** Mean temperature values at each height for the station on Jan Mayen (no. 20) on the top, and for Madrid (no. 1) on the bottom, showing results of the run forced by ERA-Interim (left) and NCEP (right). The horizontal lines give the  $1\sigma$  SD.



**Figure 6.** Timeseries of measured and modelled temperature, 26 km above Jan Mayen (top) and Madrid (bottom). Interpolated reanalysis data is also shown.

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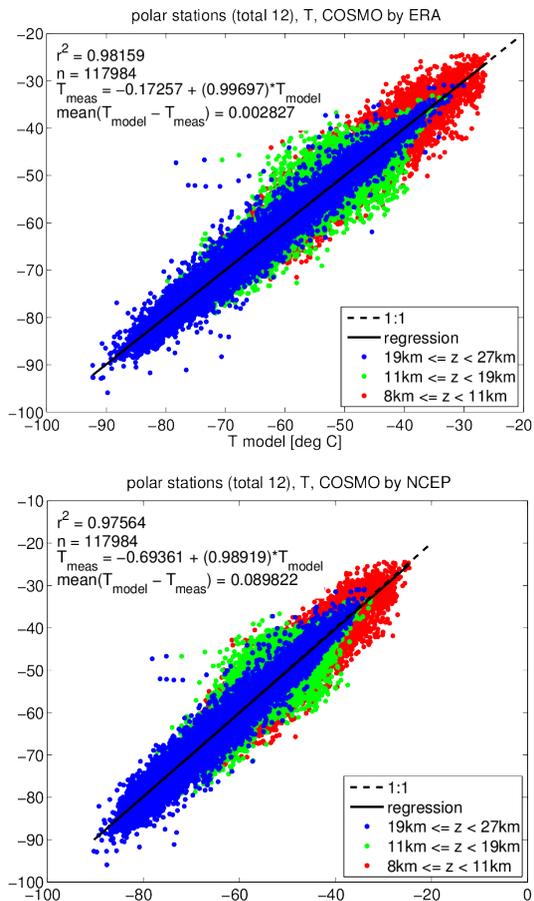
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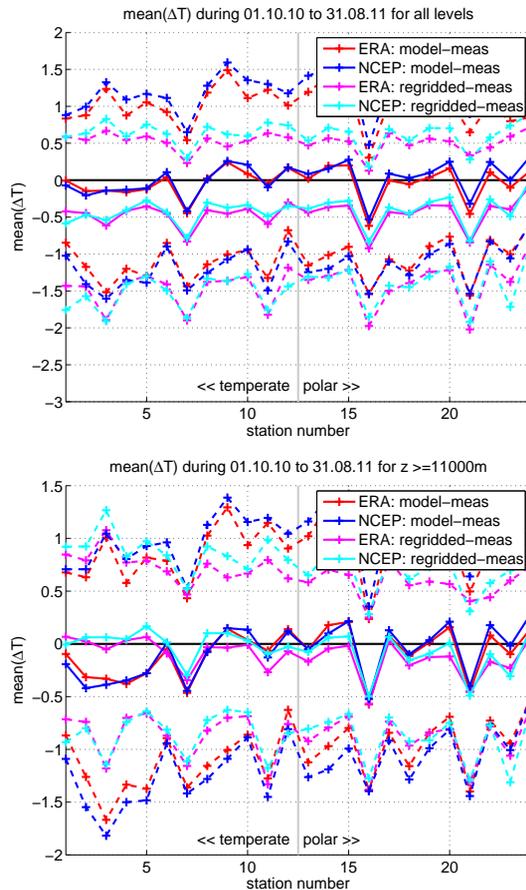
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**Figure 7.** Scatter plot of modelled against measured temperature for polar stations when forcing the model with ERA-Interim (top) and NCEP reanalysis data (bottom).



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**Figure 8.** Mean difference in temperature over all heights (top) and heights with  $z \geq 11$  km (bottom) for each station. The dashed line corresponds in color to the full line is always half the SD of the difference above and below the mean value.



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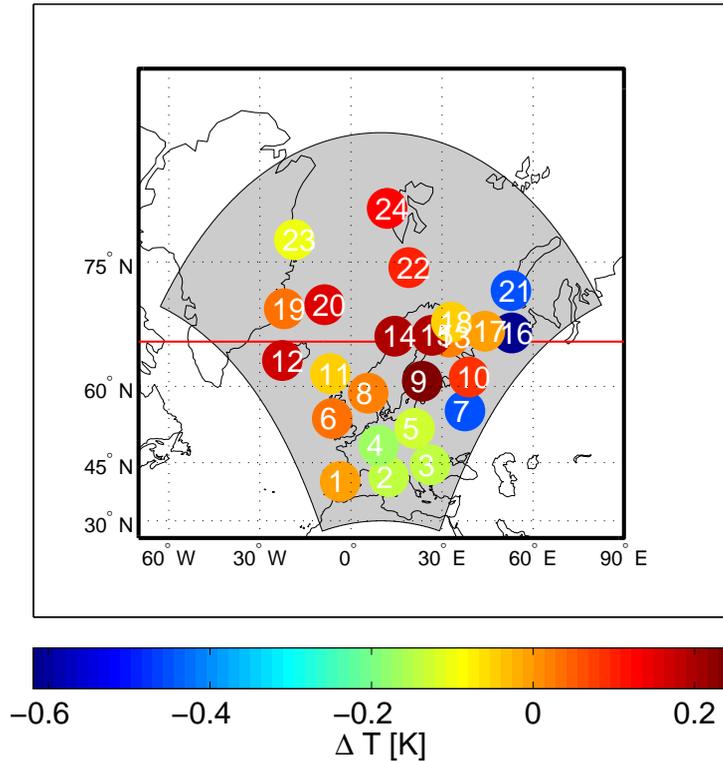
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meas-COSMO by ERA, 01.10.10 to 31.08.11, mean( $\Delta T$ ), all levels



**Figure 9.** Mean difference of model values and measurements of temperature for each station over all levels when using ERA-Interim as forcing data. The picture is similar when using NCEP reanalysis data.

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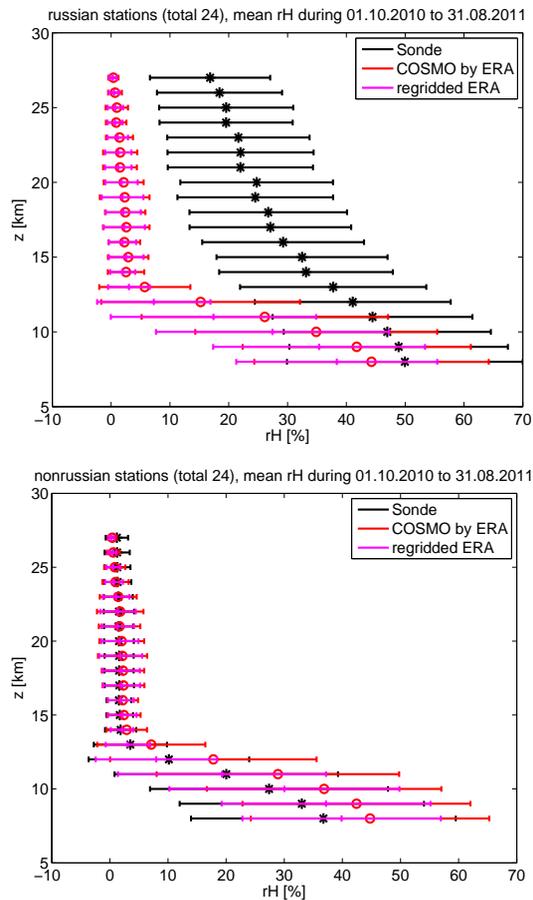
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**Figure 10.** Mean relative humidity values of the 23 Russian stations and Gomel (BY) on the top, 24 stations outside of Russia but in the eastern part of the domain on the bottom. The horizontal lines give the  $1\sigma$  SD.

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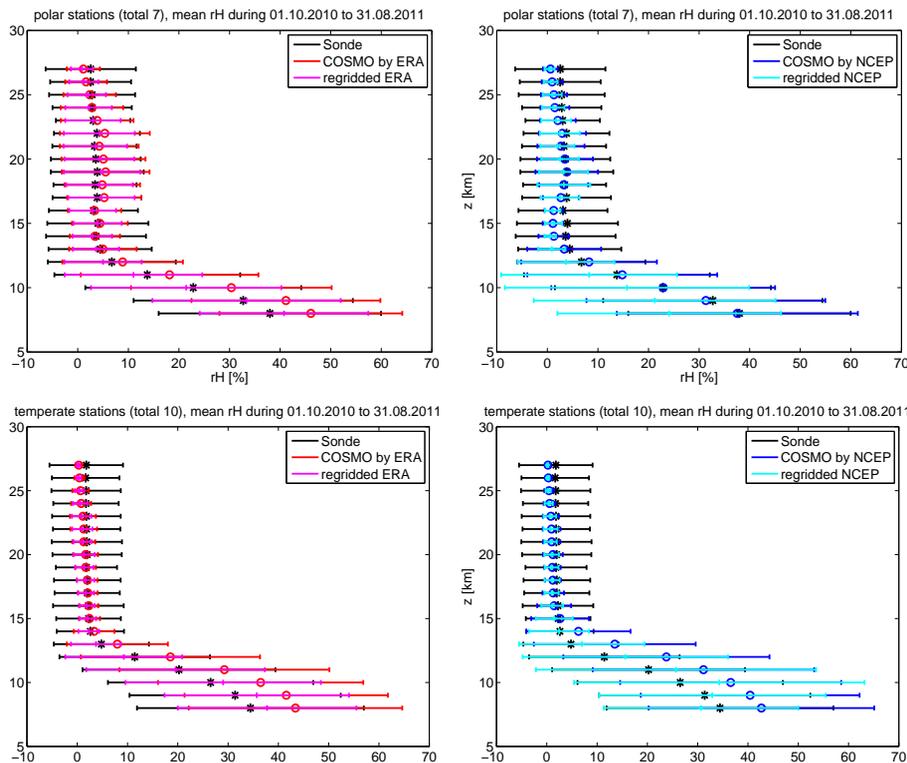
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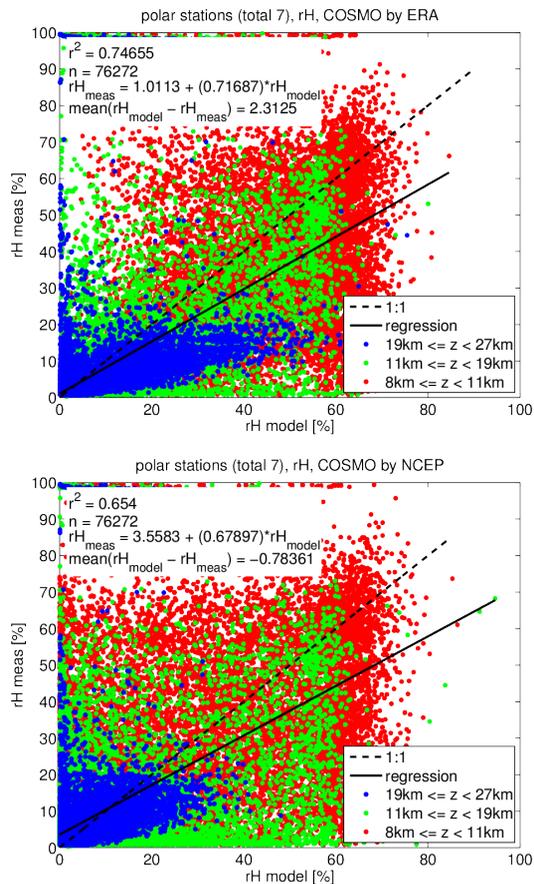
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**Figure 11.** Mean values of relative humidity for polar (top) and temperate (bottom) stations for the model run forced by ERA-Interim (left) an NCEP (right) reanalysis data. Russian stations were excluded from this analysis, as described in the text. The horizontal lines give the  $1\sigma$  SD.

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**Figure 12.** Scatterplots of modelled against measured relative humidity for the run forced by ERA-Interim (top) and NCEP (bottom).

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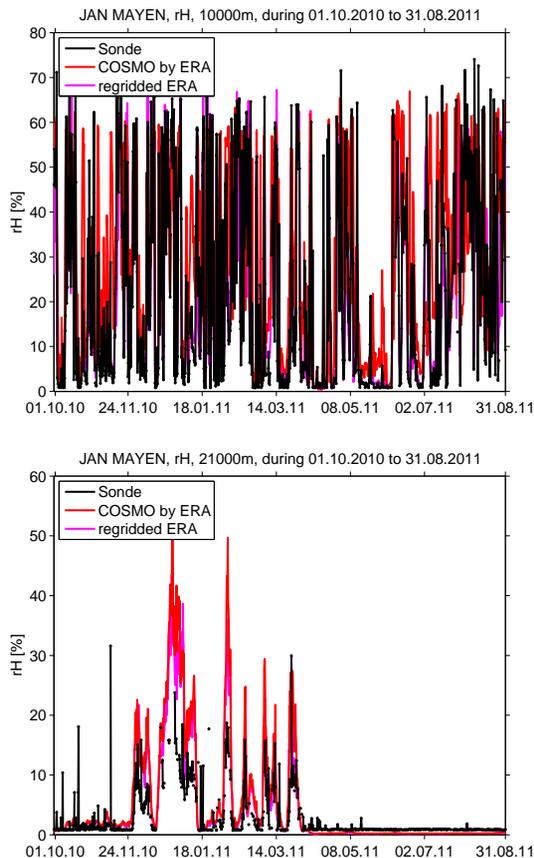
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**Figure 13.** Timeseries of relative humidity in 10 km (top) and 21 km (bottom) height above Jan Mayen for the model forced by ERA-Interim data.



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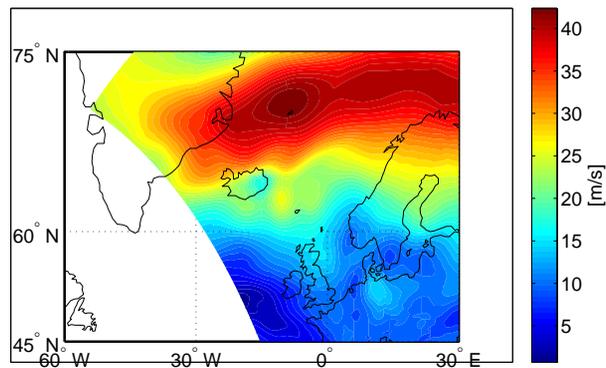
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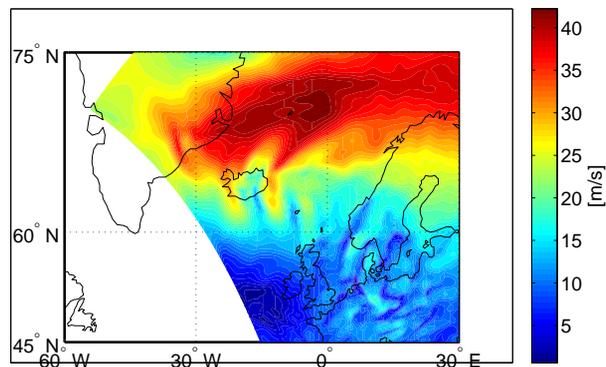
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regridded ERA, V, Apr. 08, 2011, 00UTC, level 48 (~20.5 km)



COSMO, V, Apr. 08, 2011, 00UTC, level 48 (~20.5 km)



**Figure 15.** The jet system of the low pressure system located over Greenland, visible in the regridded ERA-Interim data (top) and model output (bottom). Shown is the wind speed, calculated from  $V = \sqrt{u^2 + v^2}$ .

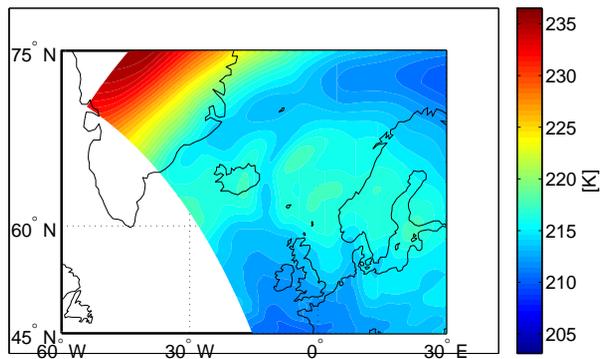
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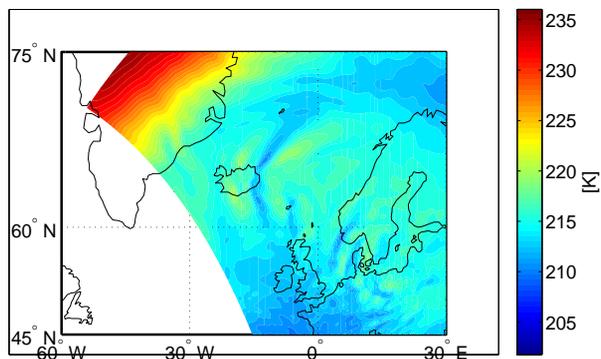
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regridged ERA, T, Apr. 08, 2011, 00UTC, level 48 (~20.5 km)

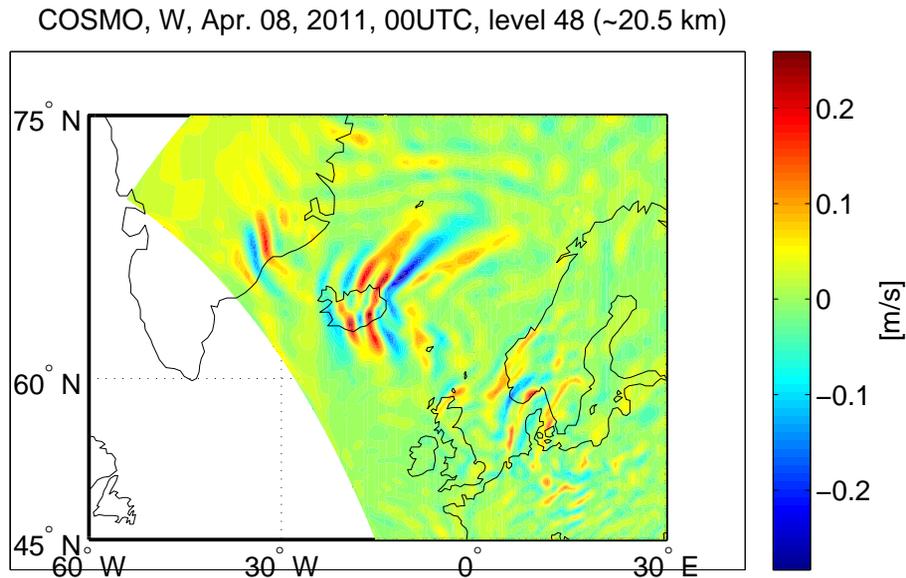


COSMO, T, Apr. 08, 2011, 00UTC, level 48 (~20.5 km)

**Figure 16.** Same as Fig. 15, showing temperature.

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**Figure 17.** Vertical wind speed of COSMO, showing fluctuations interpreted as orographically induced lee waves. This field is not present in the reanalysis data.

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