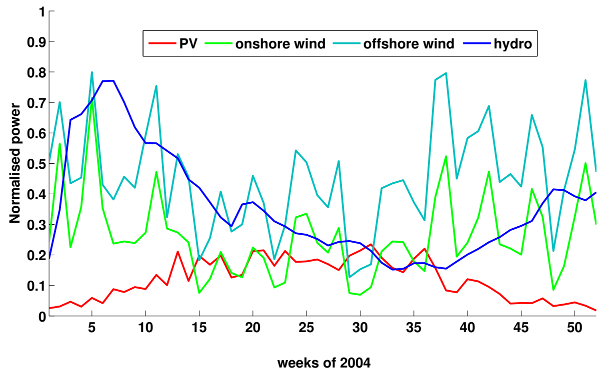


Figure 26: Weekly PV, wind and hydro time-series for Germany during 2004

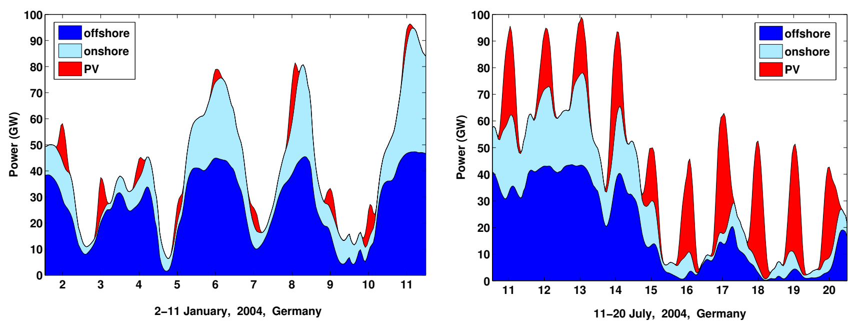


Figure 27: PV, offshore and onshore wind power productions for ten days in January (left) and ten days in July (right), in 2004 for Germany

from solar PV. Onshore and offshore wind produce high share of renewable generations during these days. With high solar elevation and mostly clear-sky days, the PV share is very high for most of the days in July. The wind production strongly reduces in July and shows significant fluctuations from one day to the next.

The diurnal pattern of power from different technologies can have significant impacts on storage size and the mismatch between load and power generation. The diurnal variations of ten years average PV, wind and load profiles of Germany are shown in Fig. 28. Whereas the daily course of PV is very strong, the daily course of wind is quite week. The PV curve shows strong hourly gradients, particularly after sunrise and before sunset hours. On the other hand, the average hourly gradients of wind is very week compared to PV and the average production is almost independent of the time of the day. Interestingly, the diurnal average load profile shows an asymmeric two-hump curve, with the major peak in the late afternoon (Fig. 28). This can have a significant effect on hourly mismatch and storage size calculations.

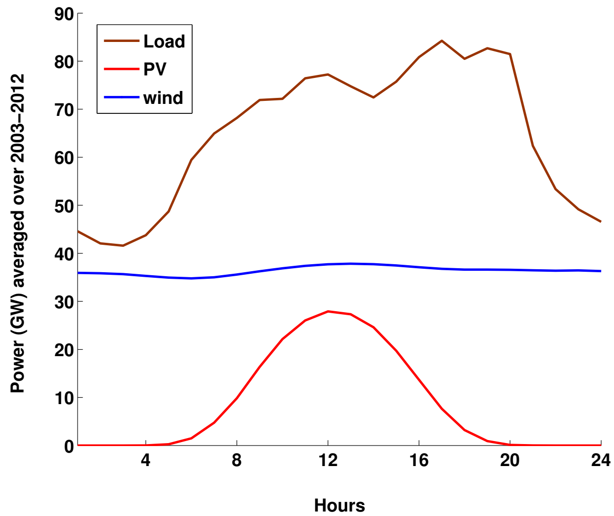


Figure 28: Diurnal variation of average load, PV and wind power for Germany

Fig. 29 summarises the cumulated distribution of power from PV and onshore wind at different temporal resolutions for Germany. It also includes the cumulated distribution of the incremental time-series, i.e., changes from one time step to the next. For hourly PV power, the night-time zero values are filtered out for the incremental distribution functions. Due to no power contribution from solar at night, the average power generated by PV is always much lower than that of wind. The strong diurnal pattern introduces two sharp gradients for hourly PV. Sunrise (the positive x-axis in hourly incremental distribution function) and sunset (the negative x-axis in the same function), which occur over a very short time, lead to a broad range of PV compared to wind for hourly incrementals. On other temporal resolutions, the opposite is true and wind has higher changes from day to day as well as from week to week compared to PV (Fig. 29).

The cumulated distribution function of PV and wind power for Germany, Spain and Europe can also be used to demonstrate the effects of spatial smoothing (Fig. 30). The PV curve of Europe is steepest in the beginning but then gradually gets less steeper than the curves from single countries. For wind, the shape is fundamentally different. The curve for Europe has a very smooth slope in the beginning but increases rapidly from ~ 0.15 onwards.

Depending on geographic locations and weather conditions, all European countries have different renewable resources. Fig. 31 summarises the interannual variation of PV and wind for different countries, sorted in ascending order of mean capacity factors. For wind, countries with low capacity factors (for example, Cyprus) show less interannual variations while those countries with very high capacity factors (for example, Great Britain and Ireland) have highest interannual variations. On the contrary, countries with

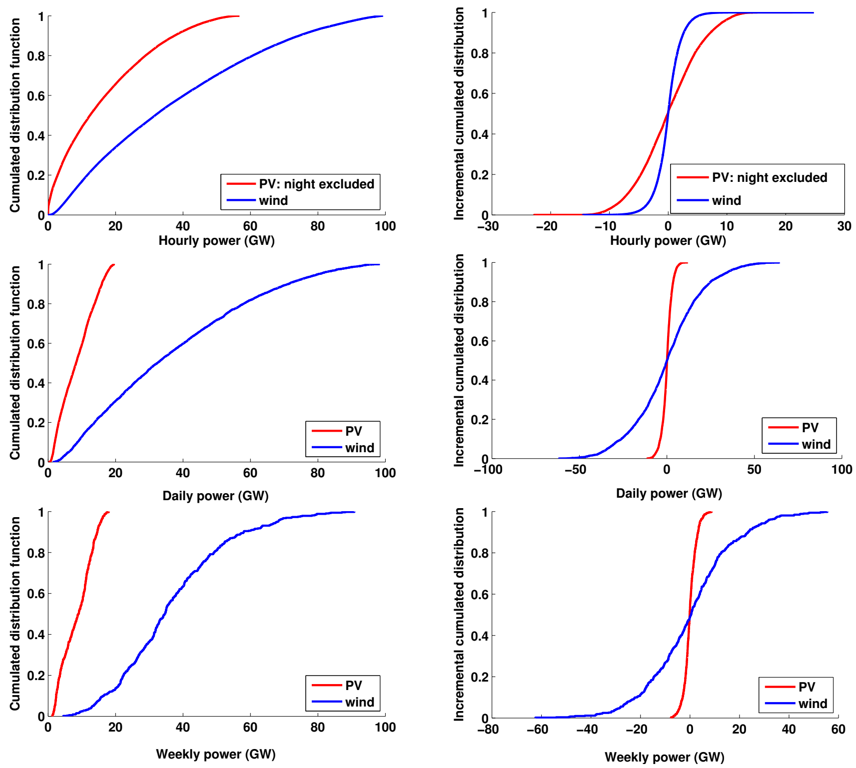


Figure 29: Cumulated distribution (left) and incremental cumulated distribution (right) of hourly (top panel), daily (middle panel) and weekly (bottom panel) PV and wind power for Germany

very high PV capacity factors (for example, Malta and Spain) show least interannual variations. Fig. 31 supports that for PV, 2003 and 2010 ('purple flower' and 'charcoal' lines) were two very significant years with substantially different PV production compared to the other years.

3.4. Comparison of statistical downscaling with dynamical downscaling

It was described in section 2.1.1 how the MERRA Reanalysis data was spatially downscaled to match the 7×7 km grid chosen for the Restore 2050 project. This section will compare the statistically downscaled wind speeds with dynamically downscaled wind speeds. Dynamical downscaling uses the output of global numerical weather prediction models to drive a regional numerical model in higher spatial resolution to derive local phenomena in greater detail. The comparison was performed in the Bachelor Thesis by Steffen Schroedter "Vergleich von dynamischem und statistischem Downscaling zur

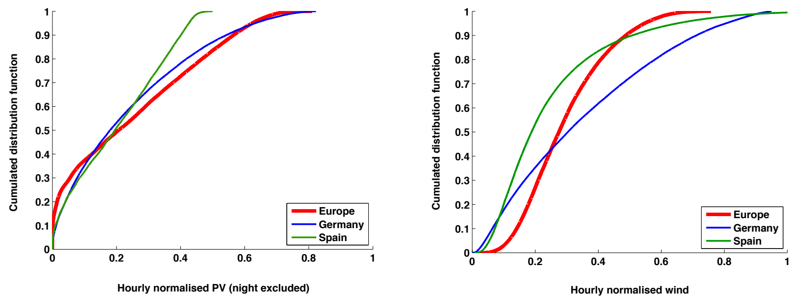
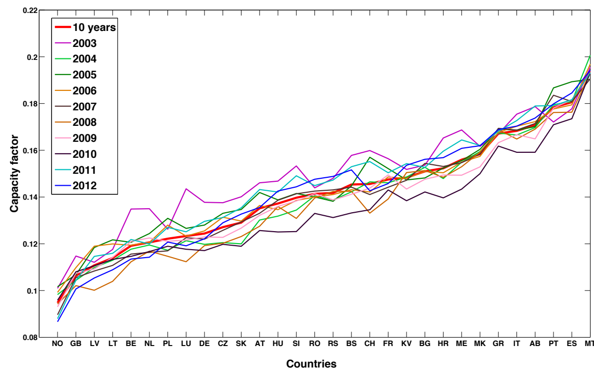
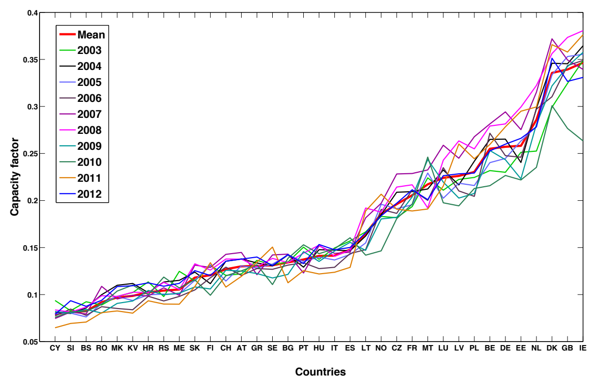


Figure 30: Cumulated distribution of hourly normalised PV (left) and wind (right) for Europe, Germany and Spain

Generierung von Windeinspeisezeitreihen", finished in August 2014, which investigated statistical and dynamical downscaling in comparion for the purpose of wind feed-in calculations. Some results of this Thesis are being presented in this section. In the Thesis the approach for statistical downscaling is compared to results of a Weather Research and Forecasting Model (WRF) simulation for February to November 2009. The results are then compared to the data from the COSMO-EU analysis. The investigated domain coveres roughly 10% of the COSMO-EU domain. It can be seen in Figure 32.



(a) PV



(b) wind

Figure 31: Interannual variation of (31a) PV and (31b) wind capacity factors for European countries, arranged in ascending order of ten years average

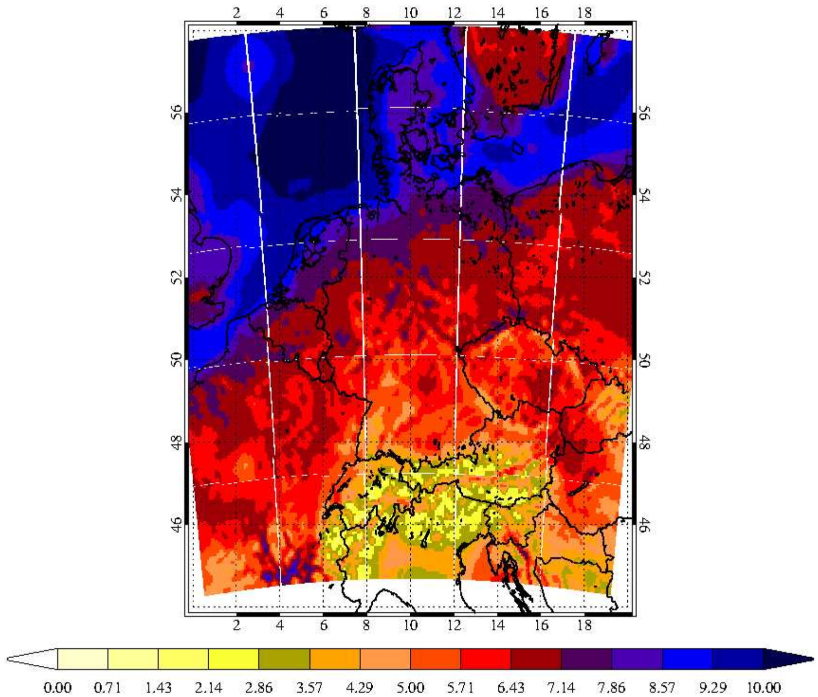


Figure 32: Average wind speeds in [m/s] from the COSMO-EU analysis model for the investigated domain for the comparison of statistical and dynamical downscaling at 140 m height for February to November 2009..

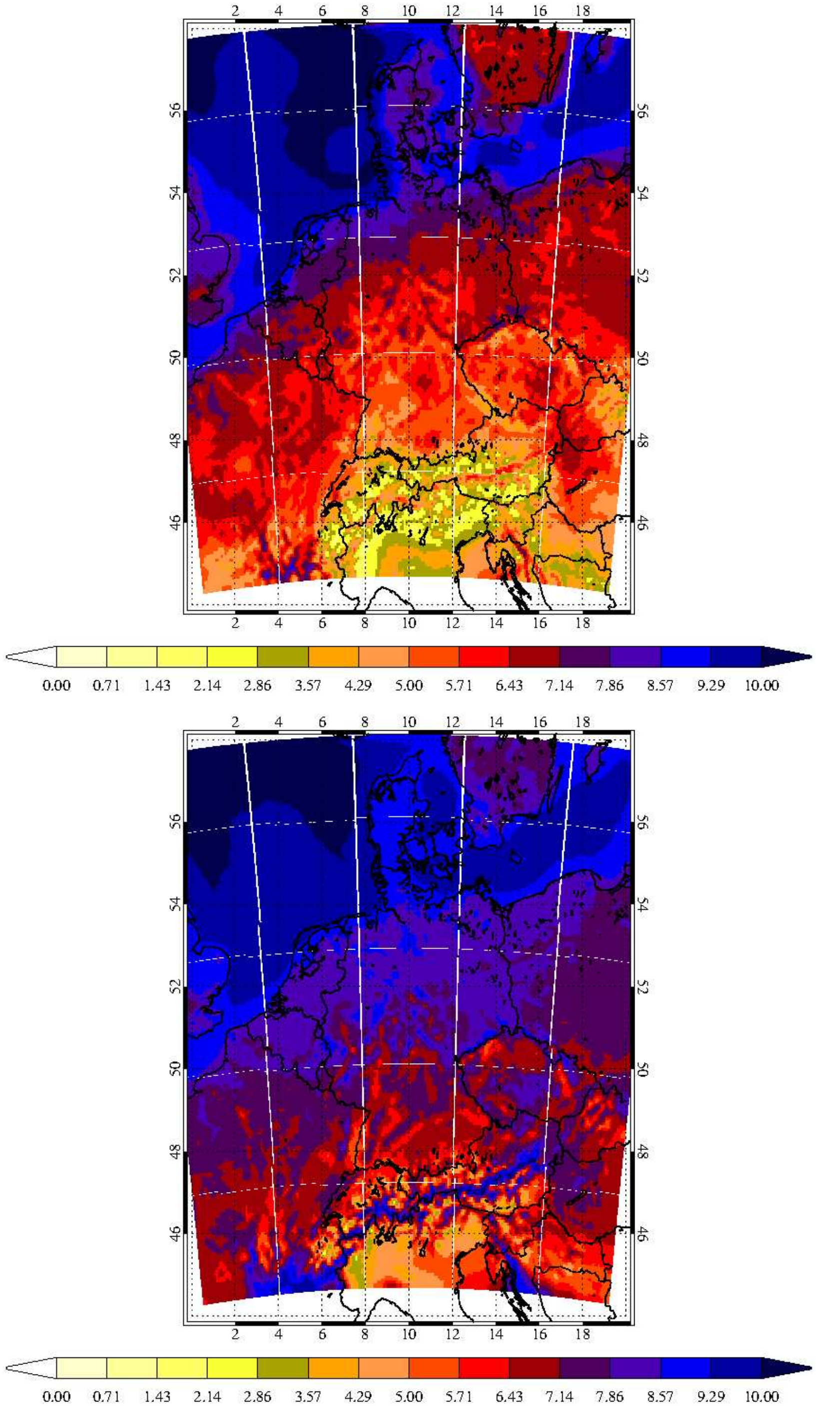


Figure 33: Average wind speeds in [m/s] from the stat downscaling (top) and dynamical downscaling (bottom) at 140 m height for February to November 2009.

The average downscaled wind speeds can be seen in Figure 33. It can be noticed that wind speeds for the dynamical downscaling are significantly higher (see table 7) with some exceptions in the North Sea. The average wind speed for the dynamical downscaling is with 7.8 m/s roughly 20% higher than for COSMO-EU and the statistically downscaled model with 6.6 m/s each. Standard deviation of wind speeds in the whole domain are highest for the dynamical downscaling and lowest for the statistical downscaling with the COSMO-EU model being inbetween. Another measure that has been used to compare the simulated models is the root mean square difference (rmse), it is given in this context by

$$\text{rmse} = \sqrt{\frac{1}{T}\sum_t (v(t) - v'(t))^2}, \tag{7}$$

where v and v' are the model wind speeds to be compared and t runs over all time steps. Also the time series were compared by measuring the correlation coefficient, that is given by

$$r = \sum_t \frac{(v(t) - \bar{v})(v'(t) - \bar{v}')}{T\sigma\sigma'}, \tag{8}$$

with $(v(t), \bar{v}, \sigma)$ and $(v'(t), \bar{v}', \sigma')$ being the wind speed, the average wind speed and the standard deviation at a single grid point for two models respectively.

	Dyn. Downscaling	COSMO-EU	Stat. Downscaling
Average wind speed [m/s]	7.8	6.6	6.6
Stdev [m/s]	4.0	3.6	3.1

Table 7: Average wind speeds and standard deviations for the three compared wind speed models in the whole covered domain for February until November 2009 at 140 m height.

	Dyn & COSMO	Stat & Cosmo	Dyn & Stat
RMSE [m/s]	1.73	1.32	1.68
Correlation	0.79	0.92	0.80

Table 8: Root mean square differences and correlation coefficients for the three models pairwise computed for February until November 2009 as used for comparison and verification.

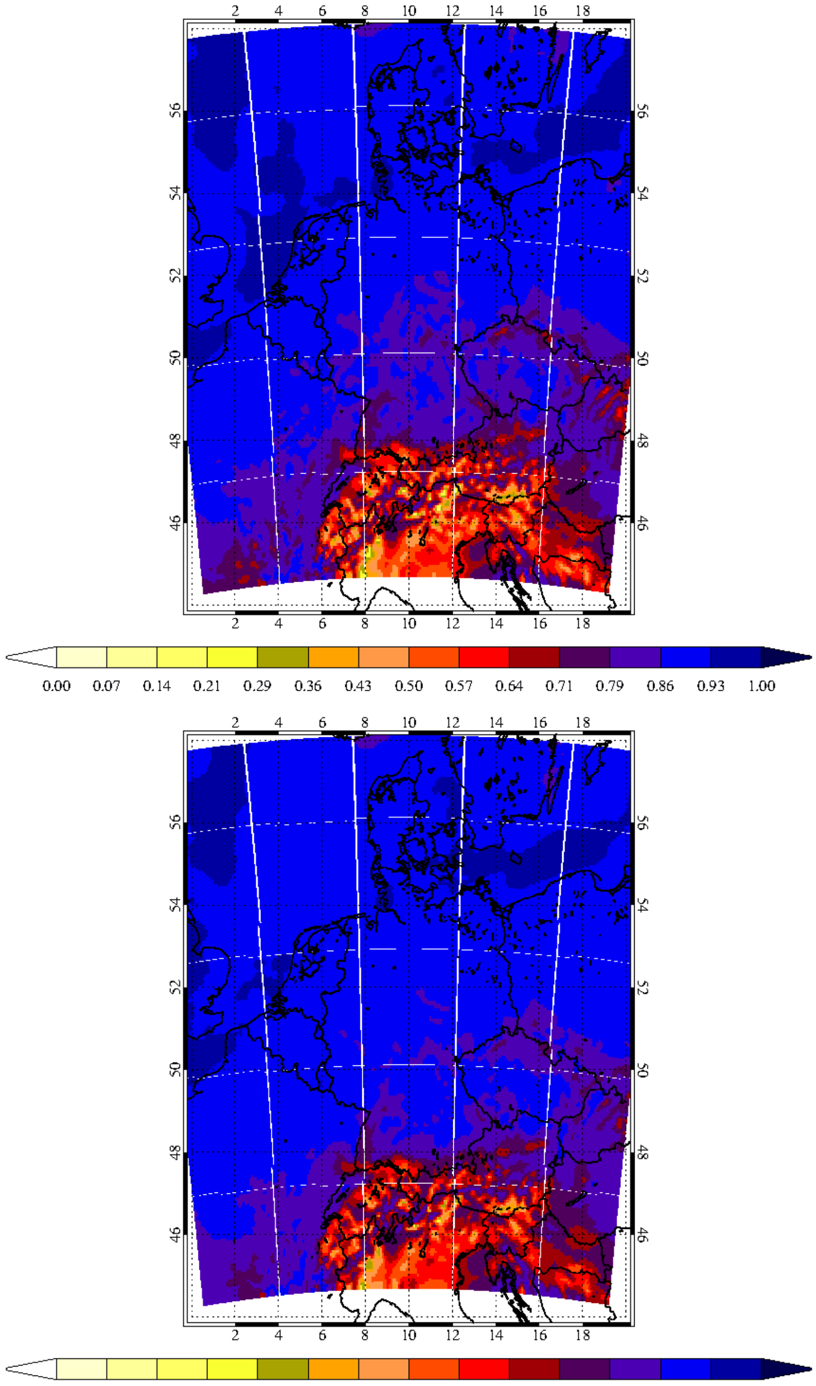


Figure 34: Correlation coefficients for the investigated domain per grid cell for February until November 2009 between COSMO-EU wind speeds and statistically downscaled wind speeds at 50 m height (top) and 140 m height (bottom).

The correlation coefficients between COSMO-EU wind speeds and the downscaled models can be seen in figures 34 and 35. The results for 140 and 50 m height for the comparison of the statisically downscaled wind speeds with COSMO-EU wind speeds look very similar. Correlation is very high at between 0.8 and 1.0 for for the offshore regions and almost all of Denmark, Germany, France, Czech Republic, Poland. In the mountaneous regions of the alps correlation factors shrink to values below 0.6. For the comparison of dynamically downscaled wind speeds with COSMO-EU wind speeds the results show a similar picture. Although the general correlation is lower, correlation factors in the offshore regions and the northern parts of the investigated regions are again high at values of 0.8 and above while in the mountaneous alpine regions correlation factors have values below 0.6.

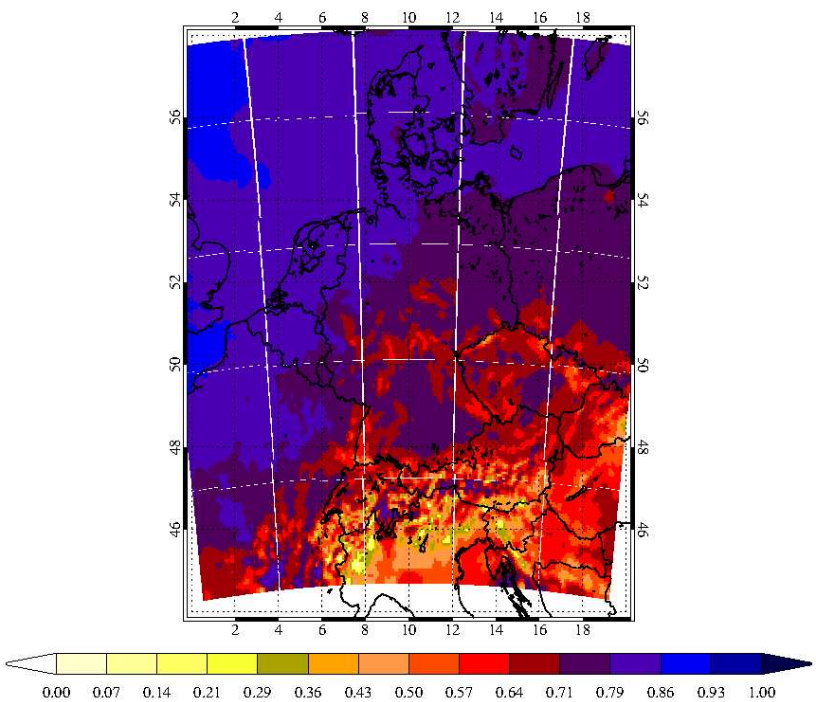


Figure 35: Correlation coefficients for the investigated domain per grid cell for February until November 2009 between COSMO-EU wind speeds and dynamically downscaled wind speeds at 140 m height.

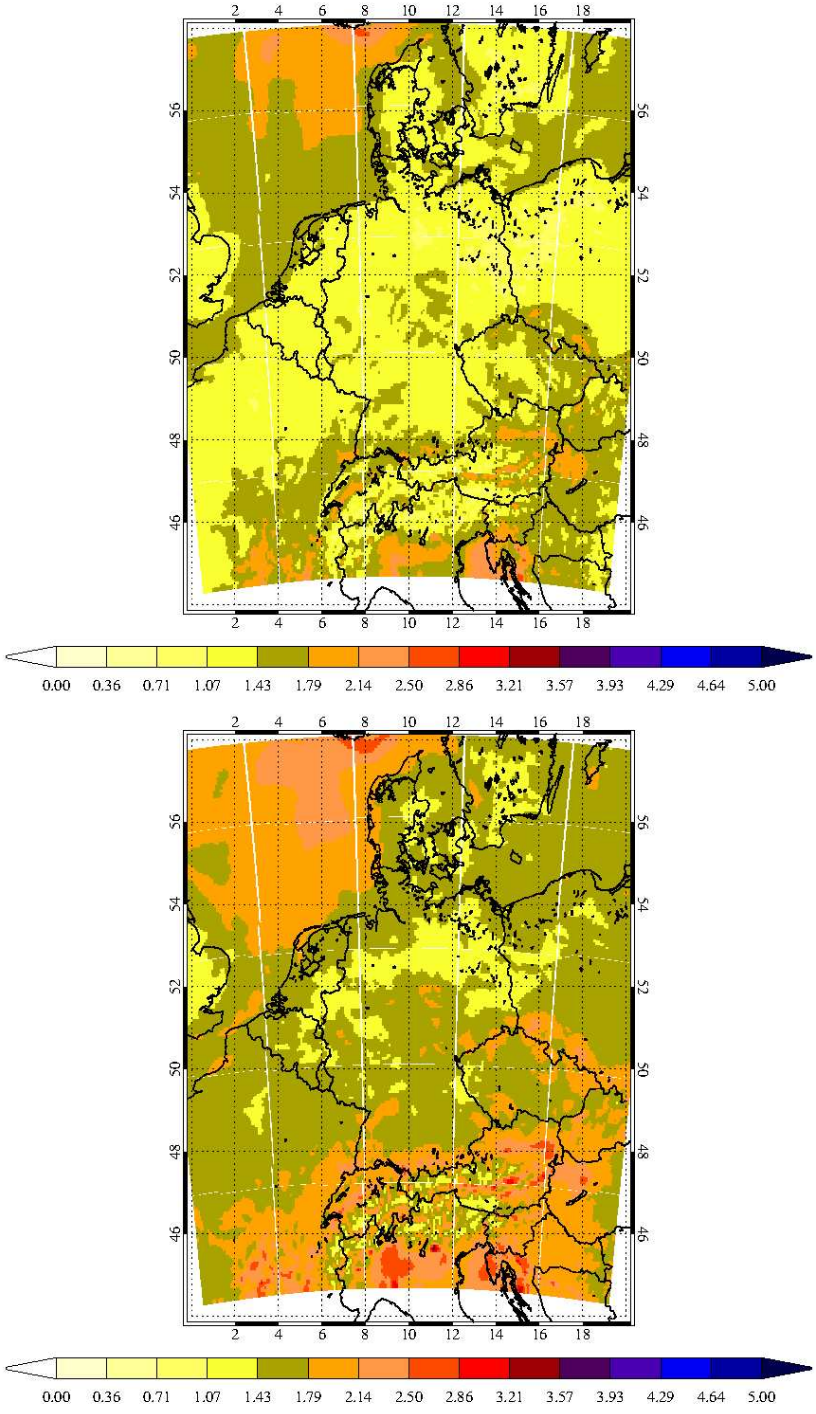


Figure 36: Rmse for the investigated domain per grid cell for February until November 2009 between COSMO-EU wind speeds and statistically downscaled wind speeds at 50 m height (top) and 140 m height (bottom).