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1 Evaluation of the meteorological forcing used for the Air  
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42 **Abstract**

43

44 Accurate regional air pollution simulation relies strongly on the accuracy of the mesoscale  
45 meteorological simulation used to drive the air quality model. The framework of the Air Quality  
46 Model Evaluation International Initiative (AQMEII), which involved a large international community  
47 of modeling groups in Europe and North America, offered a unique opportunity to evaluate the skill  
48 of mesoscale meteorological models for two continents for the same period. More than 20 groups  
49 worldwide participated in AQMEII, using several meteorological and chemical transport models with  
50 different configurations. The evaluation has been performed over a full year (2006) for both  
51 continents. The focus for this particular evaluation was meteorological parameters relevant to air  
52 quality processes such as transport and mixing, chemistry, and surface fluxes. The unprecedented  
53 scale of the exercise (one year, two continents) allowed us to examine the general characteristics of  
54 meteorological models' skill and uncertainty. In particular, we found that there was a large  
55 variability between models or even model versions in predicting key parameters such as surface  
56 shortwave radiation. We also found several systematic model biases such as wind speed  
57 overestimations, particularly during stable conditions. We conclude that major challenges still remain  
58 in the simulation of meteorology, such as nighttime meteorology and cloud/radiation processes, for  
59 air quality simulation.

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## 62 **1. Introduction**

63 Air quality (AQ) modeling has progressed significantly over the past decade. It has evolved from the  
64 investigation of limited case studies of a few days or weeks duration to operational use for decision  
65 makers. Models are now routinely used to produce operational AQ forecasts in several countries  
66 (Brandt et al., 2001; McHenry et al., 2004; McKeen et al., 2005; Otte et al., 2005; Tarasick et al., 2007;  
67 Honoré et al., 2008; Hogrefe et al., 2007; Balk et al., 2010; Menut et al., 2010; Kukkonen et al., 2011)  
68 and to provide a prospective evaluation of air pollutant emissions control scenarios for policy needs,  
69 as in the Clean Air For Europe program or the United States (U.S.) NO<sub>x</sub> State Implementation Plan  
70 Call (e.g., Amann et al., 2005; Gilliland et al., 2008; Gego et al., 2007). However, many uncertainties  
71 still remain and need to be reduced in order to improve the performance of such modeling systems  
72 so they would have high societal utility. Owing to the large number of interrelated processes in AQ  
73 models, biases in the representation of different processes are sometimes difficult to parse because  
74 of compensating errors, making it difficult to fully diagnose and attribute the different sources  
75 contributing to modeling uncertainty.

76 Uncertainties in AQ model simulations basically arise from three main classes of processes:  
77 (1) chemistry and aerosol physics; (2) fluxes (emissions, deposition, boundary fluxes); and  
78 (3) meteorological processes affecting transport and diffusion, chemistry, and surface fluxes (e.g.,  
79 Pielke and Uliasz, 1998; Seaman, 2000). This paper looks at the influence of the last class of  
80 processes. More precisely, it will focus on the meteorological processes and parameters known to  
81 have a strong influence on air pollutant concentrations and their variability. The evaluation of such  
82 parameters in meteorological models is particularly important because the requirements of weather  
83 forecasts are different from those of air quality forecasts. For instance, an accurate prediction of the  
84 height of the boundary layer is crucial for air quality prediction while it is not for weather prediction  
85 although it does have an indirect impact on weather in terms of triggering convection.

86 The three-dimensional wind fields transport primary pollutants or, if chemical reactions occur en  
87 route, secondary pollutants from emissions sources to receptor areas. Wind speed overestimation  
88 typically result in the underestimation of primary pollutant concentrations through increased  
89 ventilation and dilution, but they can also increase the concentrations of secondary pollutants near  
90 certain sources. For example, in areas close to nitric oxide (NO) emissions sources, an overestimated  
91 wind speed may induce a change in the photochemical regime since over-dilution of NO  
92 concentration will reduce ozone titration by NO, thereby resulting in an overestimation of ozone in  
93 the near-field. Wind direction errors will affect the path of pollutant trajectories and, hence, the  
94 source-receptor relationships. The concentration of pollutants in the lower troposphere, especially at  
95 the ground level, is also strongly sensitive to the rate of pollutant mixing by atmospheric turbulence,  
96 the height of the planetary boundary layer (PBL), the amount of venting to the free troposphere and  
97 transport from the upper-troposphere to the PBL for ozone. Atmospheric turbulence is, in turn,  
98 controlled by the magnitude of vertical temperature gradient and wind shear.

99 Meteorological parameters driving chemical processing are numerous. Radiation and its variability  
100 due to the presence of clouds, water vapor, aerosols and temperature are strong chemistry and  
101 aerosol thermodynamics drivers. For example, excessive cloud formation predicted at any altitude  
102 leads to the underestimation of below-cloud secondary pollutant formation from gas-phase  
103 processes and an overestimate in aerosol scavenging, inducing a low bias in secondary organic  
104 aerosol concentration. Many chemical reaction rates are temperature-dependent. And aerosol  
105 activation and aqueous-phase chemistry can occur in fog and clouds. Finally, meteorological  
106 processes also drive surface fluxes (emissions, deposition). Temperature and shortwave radiation  
107 control the emission of biogenic volatile organic compounds by vegetation, and wind speed and soil  
108 moisture control wind-blown dust or pollen emissions. Dry deposition is influenced by radiation,  
109 wind speed/turbulence, temperature, and surface wetness, and wet deposition is influenced by

110 precipitation intensity, vertical distribution (washout, rainout) and form (e.g., drizzle, rain, snow)  
111 (Gilliam et al., 2011).

112 Seaman (2000) provided an extensive overview of the influence of meteorology in regional AQ  
113 modeling in which he gave a number of examples of the sensitivity of AQ predictions to different  
114 meteorological variables. Hanna et al. (2001) employed a Monte Carlo approach to investigate the  
115 impact of uncertainties of 128 input variables, including a number of meteorological parameters, on  
116 ozone predictions made by a regional photochemical grid model (UAM-V). They found that the  
117 UAM-V predictions were sensitive to wind speed and direction, relative humidity, and cloud cover.  
118 Zhang et al. (2007) followed a meteorological ensemble approach in which they considered small  
119 initial perturbations in wind and temperature on MM5 meteorological forecasts and their  
120 subsequent impact on ozone levels in Houston, Texas predicted by the Community Multiscale Air  
121 Quality (CMAQ) model (Byun and Schere, 2006) for an episode in summer 2000. For this particular  
122 episode, they found high uncertainties in predicted ozone. Urban-scale sensitivities of air quality  
123 predictions to different meteorological variables were also studied within the EU project FUMAPEX  
124 and COST Action 715.

125 A number of studies have considered the impact of supplying meteorological fields for the same case  
126 from two or more different mesoscale meteorological models to the same regional AQ model (Sistla  
127 et al., 1996; Biswas and Rao, 2001; Hogrefe et al., 2001; Smyth et al., 2006; Pirovano et al., 2007; de  
128 Meij et al., 2009; Appel et al., 2010). Biswas and Rao (2001) used two different prognostic  
129 meteorological models (MM5 and RAMS) with the UAM-V AQ model and found an uncertainty of  
130 about 20% in simulating episodic 1-h ozone maxima. Hogrefe et al. (2001) evaluated temperature,  
131 water vapor mixing ratio, and wind speed predictions from two different prognostic meteorological  
132 models (MM5 and RAMS3b) and found that model predictions were best for temperature and worst  
133 for wind speed and that neither model showed skill in predicting intra-day variability (i.e., periods  
134 less than 12 hours). Smyth et al. (2006) examined predictions of temperature, relative humidity, and

135 wind speed from two different prognostic meteorological models (GEM and MM5) and found that  
136 differences in these fields resulted in a range of differences in  $O_3$ ,  $PM_{10}$ ,  $PM_{2.5}$ , and speciated  $PM_{2.5}$   
137 fields predicted by the CMAQ AQ model. de Meij et al. (2009) used two different prognostic  
138 meteorological models (MM5 and WRF) with the CHIMERE AQ model for winter and summer  
139 simulations of air quality in the Po Valley of Italy and found differences of 60% in  $PM_{10}$  predictions,  
140 particularly in the wintertime when predictions of PBL height made by the two meteorological  
141 models were significantly different. Finally, Appel et al. (2010) compared predictions made by CMAQ  
142 driven by two prognostic meteorological models (MM5 and WRF) and attributed differences in  
143 predicted AQ fields to differences in predicted wind speed, PBL height, cloud cover, and friction  
144 velocity.

145 Weather Services and research groups of more than 20 European countries investigated the  
146 influence of mesoscale meteorological models on regional AQ simulations in the framework of COST  
147 728 ([www.cost728.org](http://www.cost728.org)). Eleven different AQ modeling systems participated in an inter-comparison  
148 exercise. The task was to model concentrations of particulate matter (PM) during a complex high-  
149 pressure episode over Germany in winter 2003 (Stern et al., 2008). It was found that none of the  
150 chemical transport models (CTMs) was able to predict the observed high PM values in East Germany  
151 (Matthias et al., 2010). The largest meteorological influence on the simulated concentrations was  
152 connected with vertical mixing of the pollutants. However, it could not be concluded that the most  
153 accurate model results for meteorological quantities led to the most accurate CTM results since  
154 emission inventories that drive AQ models are uncertain. In some cases errors in the meteorological  
155 and AQ models cancelled out, resulting in reasonable pollutant concentration values. One of the  
156 conclusions of the COST 728 action was that extensive meteorological model testing on longer time  
157 scales is necessary to gain more insight into the meteorological effects that may cause errors in AQ  
158 modeling.

159 The framework of the Air Quality Model Evaluation International Initiative (AQMEII; Rao et al., 2011)  
160 offers a unique opportunity to evaluate AQ model strengths and weaknesses from a year-long AQ  
161 simulation for 2006 carried out by a large set of AQ models over two continents. This paper focuses  
162 on uncertainties associated with the meteorological inputs used by the AQMEII AQ modelers. It  
163 benefits immensely from the opportunity to inter-compare the performance of more than 10  
164 meteorological models or model configurations for the same meteorological parameters on the same  
165 analysis grids for the same extended period for two continental-scale regions.

166 The AQMEII project has collected both meteorological observations of several meteorological  
167 parameters and asked participating modeling groups to extract equivalent model values in a format  
168 that it would allow direct comparison. However, the limited number of parameters routinely  
169 observed does not allow a full and comprehensive evaluation. Thus, we focus our analysis on a few  
170 issues. The main questions we address here concerning transport and mixing are:

- 171 • Are boundary-layer wind speed and PBL height accurately simulated?
- 172 • Are boundary-layer temperature, relative humidity profiles, and surface radiation influencing  
173 atmospheric chemistry accurately simulated?
- 174 • Are meteorological processes influencing surface fluxes (surface temperature, wind speed,  
175 shortwave radiation, and precipitation) accurately simulated?
- 176 • What are the spatial and seasonal distribution of the biases in both mean and variability of  
177 the studied parameters?
- 178 • Are there any systematic differences in the prevailing meteorology over the two continents?

179 It must be noted that the questions addressed here relate strictly to the ability of models to *simulate*  
180 in retrospect and not *forecast* the meteorology of the lower troposphere. Because data assimilation  
181 is used, it is assumed that atmospheric model simulations are “best attempts” to reconstruct the



182 state of the atmosphere retrospectively at a scale relevant to simulated air quality. This is generally  
183 done in two steps: an analysis or a reanalysis is carried out by a weather centre by blending cycling  
184 forecasts with new observations, followed by a simulation using a limited-area model with increased  
185 resolution and detailed surface and boundary-layer processes that may be combined with some form  
186 of data assimilation like analysis nudging. Our conclusions thus do not necessarily apply to weather  
187 forecasts, for which the additional uncertainty due to the forecast itself must be taken into account.  
188 However, they do help to quantify current uncertainties in a number of important meteorological  
189 parameters required by AQ simulation models. Finally, it should be noted that this study only  
190 provides investigation and evaluation of multi-model performance in general terms, and specific in-  
191 depth performance evaluations are also being carried out of individual models (e.g. Gilliam et al.,  
192 2011).

193 In addition to the evaluation and inter-comparison of the predictions of 2006 meteorology for North  
194 America (NA) and Europe (EU) made by the different meteorological models applied in the AQMEII  
195 study, this paper also reviews the weather conditions experienced during 2006 over both continents  
196 and the climatological representativeness of that year. After a description of the meteorological  
197 observations for 2006 in Section 2 and the AQMEII 2006 meteorological simulations in Section 3, a  
198 summary of 2006 weather is given in Section 4. Section 5 contains a quantitative multi-parameter  
199 evaluation of the set of meteorological simulations, and the paper concludes with a discussion of  
200 results and conclusions in Section 6.

## 201 **2. Meteorological Observations**

202 Surface-based observations for the evaluation of the annual Weather Research and Forecasting  
203 (WRF) model NA simulations were extracted from the Meteorological Assimilation Data Ingest System  
204 (MADIS: <http://madis.noaa.gov/>) database. MADIS has both archived and real-time meteorological  
205 observations for North America including standard US and Canadian managed surface measurements

206 as well as mesonet, rawinsonde, wind profiler, aircraft, and satellite measurements. For the  
207 European domain, the surface observations were extracted from the National Center for  
208 Atmospheric Research (NCAR) global synoptic surface data archive  
209 (<http://dss.ucar.edu/datasets/ds464.0>). The extracted observations for 10-m wind (speed and  
210 direction), 2-m temperature, 2-m relative humidity and precipitation were ingested by the  
211 ENSEMBLE system of the European Commission Joint Research Centre at Ispra, Italy (Galmarini et al.  
212 2001, Bianconi et al. 2001, Galmarini et al. 2004), which allows matching in time and space with the  
213 various model datasets in order to carry out model performance evaluations. Some technical  
214 difficulties prevented the extraction of precipitation and relative humidity for the European domain,  
215 so the evaluation of these parameters is only for the North American domain. Since a robust, high  
216 resolution gridded precipitation dataset called the Parameter-elevation Regressions on Independent  
217 Slopes Model (PRISM) was available, the only direct evaluation of model precipitation is focused on  
218 the United States. The 4 km PRISM precipitation was aggregated up to the 12 km WRF grid so a direct  
219 comparison of seasonal precipitation could be made.

220 For upper-air analysis, meteorological variables observed from ozone soundings were downloaded  
221 from the WMO World Ozone and Ultraviolet Radiation Centre ([www.woudc.org](http://www.woudc.org)). Even though we do  
222 not investigate ozone in this article, this choice was made in order to have collocation with ozone  
223 measurements. Vertical profiles of pressure, temperature, relative humidity and wind speed were  
224 obtained from these soundings. In this study, a set of six stations was selected for each continent to  
225 serve as basis for model error statistics at the given altitudes of 0, 100, 250, 500, 750, 1000, 1500,  
226 2000, 3000, 4000, 5000, 6000, 7500 and 8500 m above ground level. These stations were selected in  
227 three ways:

- 228 • The data set should not be too small (i.e., it should contain 40 profiles or more)
- 229 • The station altitude should be close to the altitude of the respective model grid cell.
- 230 • The stations should cover different regions of the continent

### 231 **3. Meteorological Models**

232 AQMEII provided a 2006 meteorological reference simulation for each continent to all participants so  
233 as to encourage both maximum participation and model input harmonization, but the use of these  
234 simulations was not mandatory. The reference simulations for NA and EU were generated using the  
235 Weather Research and Forecasting (WRF) model version 3.1 (Skamarock et al., 2008) and MM5  
236 (Dudhia, 1993), respectively. The choice of these two models was ad hoc as one group on each side  
237 of the Atlantic volunteered to share their meteorological simulations. For the study conducted in this  
238 paper, groups used five different meteorological models or model configurations to drive NA AQ  
239 simulations and 11 different meteorological models or model configurations to drive EU AQ  
240 simulations. In this article, we emphasize the two reference simulations, as more than one group  
241 made use of each of these simulations, but we also describe and evaluate the other meteorological  
242 simulations that were employed.

243 For NA, the Advanced Research WRF (ARW) core was employed, which is a fully-compressible, non-  
244 hydrostatic, mass-conserving numerical solver. The modeling domain has a horizontal grid scale of  
245 12 km with 34 vertical levels extending from the surface to the 50 hPa pressure layer with 14 levels  
246 below 1 km and the first layer about 40 m thick. This 12-km domain aligns exactly with standard U.S.  
247 Environmental Protection Agency (EPA) modeling domains, including the 36-km modeling domain  
248 described in Otte (2008) and Gilliam et al. (2006) and the 12-km domain discussed in Gilliam and  
249 Pleim (2010) and Appel et al. (2010). The difference is that this AQMEII modeling domain was  
250 extended to the north and east in order to include some key emission sources in Canada. In addition  
251 to the domain used, most of the model physics and four-dimensional data assimilation (FDDA)  
252 techniques were adopted from previous U.S. EPA modeling research such as Otte (2008) and Gilliam  
253 and Pleim (2010), which provide guidance on using WRF and MM5 effectively for retrospective AQ

254 modeling applications although Gilliam et al. (2011) does suggests an updated technique that  
255 reduces transport errors in the lower troposphere.

256 Among the WRF physics options used were the Rapid Radiation Transfer Model Global (RRTMG) long-  
257 and short-wave radiation (Lacono et al., 2008), Morrison microphysics (Morrison et al., 2009), and  
258 the Kain-Fritsch 2 cumulus parameterization (Kain, 2004). For the land-surface model (LSM) and  
259 planetary boundary layer (PBL) model, the Pleim-Xiu LSM (Xiu and Pleim 2001; Pleim and Xiu 2003)  
260 and Asymmetric Convective Model version 2 (ACM2) (Pleim 2007a; Pleim 2007b) were used. These  
261 physics schemes, in particular, were developed explicitly for retrospective AQ modeling as the LSM  
262 employs an indirect soil moisture and temperature nudging scheme (Pleim and Gilliam, 2009). The  
263 soil nudging limits the error growth of critical near-surface fields such as temperature and moisture  
264 by adjusting surface energy fluxes to minimize the difference between the simulated 2-m  
265 temperature and moisture and that provided by an analysis. The ACM2 PBL scheme is also used in  
266 the CMAQ AQ model, so its use in WRF allows the mixing of pollutants to be consistent with the  
267 mixing of heat, moisture, and momentum within the PBL or other mixed layers in the atmosphere.  
268 Initialization and nudging follow the strategy described in Gilliam and Pleim (2010).

269 For EU, MM5 was run with lateral and surface (sea-surface temperature) boundary conditions  
270 obtained from the European Centre for Medium Range Weather Forecast (ECMWF) operational  
271 analyses, with a 6-hour sampling rate. Initial conditions (soil and atmospheric variables) were also  
272 taken from ECMWF analyses. The configuration used is Version 3.7, with most parameterizations as  
273 described in Chiriaco et al. (2006). Nudging to ECMWF analyses is applied with a relaxation time of  
274 about 3 hours for temperature and wind, and 15 hours for humidity. The 2006 simulation was split  
275 into twelve 1-month long simulations with new initializations 6 hours (spin-up time) before the first  
276 day of each month.

277 The vertical grid contains 32 sigma layers from surface to the top of the atmosphere, with 9 layers  
278 below the first kilometer. The top of the first layer was taken at  $s=0.996$  (about 40 m above the  
279 surface, thus the middle of the first layer is 20 m). The horizontal grid is taken along a Mercator  
280 projection, with grid spacing decreasing from south to north. It extends outside the chemical model  
281 grid imposed by the AQMEII coordinates ( $15^{\circ}\text{W} - 35^{\circ}\text{E}$ ;  $35^{\circ}\text{N} - 70^{\circ}\text{N}$ ). The exact domain boundaries  
282 for MM5 are  $18^{\circ}\text{W} - 38^{\circ}\text{W}$  and  $33.3^{\circ}\text{N} - 71.5^{\circ}\text{N}$ . At  $50^{\circ}\text{N}$ , the grid size is about 20 km while it is  
283 about 10 km at the northern boundary and 25 km at the southern boundary.

284 The planetary boundary layer (PBL) is described using the MRF PBL scheme (Hong and Pan, 1996).  
285 The microphysics scheme is the Reisner2 scheme, which considers five states of water: vapor, rain,  
286 cloud, ice, and graupel (Reisner et al., 1998). The cumulus scheme is taken from Grell and Devenyi  
287 (2002). The NOAH LSM scheme is used (Ek et al., 2003), with the default four layer depths changed  
288 to 7, 28, 100, and 289 cm to better match ECMWF model soil levels. The long-wave radiation scheme  
289 used is the Rapid Radiation Transfer Model (RRTM; Mlawer et al., 1997).

290 In addition to these two meteorological reference simulations offered to AQMEII participants, some  
291 of the groups performed their own meteorological simulations. A total of six different  
292 meteorological models were used: COSMO, ECMWF, GEM, MM5, PARLAM-PS, and WRF. A summary  
293 of some of the main characteristics of all of the models is given in Table 1. There is considerable  
294 overlap between the models in terms of physical parameterizations and run strategies employed, but  
295 five NA and 11 EU meteorological model configurations were distinct. The horizontal grid spacing  
296 used ranged from 12 to 50 km, and the number of vertical levels ranged from 23 to 58. Data  
297 assimilation techniques were employed by a minority of the models.

298 In Section 5, the five NA meteorological model configurations are denoted by the labels "M1NA" to  
299 "M5NA" and the 11 EU configurations by the labels "M1EU" to "M11EU". Three model  
300 configurations were applied for both 2006 NA and EU simulations and have been assigned the labels

301 “M1NA” and “M1EU”, “M2NA” and “M2EU”, and “M3NA” and “M3EU”. Note that the order in which  
302 the labels have been assigned is different from the order of the model configuration descriptions in  
303 Table 1 to keep anonymity.

#### 304 **4. 2006 Weather in North America and Europe**

305 For a number of years the U.S. National Climatic Data Center (NCDC) has led an effort to characterize  
306 the weather of recent years. Arguez et al. (2007) provides the summary of significant global weather  
307 events and anomalies in 2006. The highlights specifically for North America and Europe are covered  
308 here and will be used to provide context for the model evaluation where appropriate. One of the  
309 most significant characteristics of 2006 was its rank as the 5<sup>th</sup> warmest (global) in the last century.  
310 Regionally, parts of Europe (UK, Spain and the Netherlands) saw the warmest year on record and  
311 parts of the U.S. and Canada experienced the second warmest year on record. Figure 1 provides the  
312 850 hPa seasonal temperature anomaly, which clearly shows the warmer than normal weather. 500  
313 hPa geopotential height anomalies (Figure 2) correlated well with the 850 hPa temperature  
314 anomalies as the regions with warmer than normal temperatures almost always correlate to more  
315 ridging aloft. The averaged temperature in January over U.S. was 3.9 K above normal, which is a full 1  
316 K greater than the previous 100+ year record. Most of the central and western US was warmer than  
317 normal in the summer as well. Areas in the central and southwestern U.S. that saw the higher  
318 temperatures (Figure 1) and anomalous ridging aloft (Figure 2) also experienced very little rainfall  
319 and, as a result, severe drought conditions. A record-breaking heat wave that reinforced the drought  
320 conditions began in the northern Plains and upper Midwest in mid-July and spread to the western  
321 U.S. in late July then back to the east, all the way to the East Coast for the first half of August (Arguez  
322 et al., 2007).

323 The eastern U.S. and southern Ontario and Quebec experienced average to above average rainfall in  
324 the spring and summer. The 500 hPa height anomalies in Figure 2 indicate the east coast of North  
325 America did experience near to below normal 500 hPa height and temperature at 850 hPa (Figure 1)

326 in the spring and summer, which translates to above average rainfall. On the opposite side of the  
327 Continent, areas of the Pacific Northwest U.S. and British Columbia saw heavy rainfall the last few  
328 months of 2006 because of blocking ridge in the NW Pacific (Arguez et al., 2007).

329 For Europe, Arguez et al. (2007) showed annual near-surface temperature anomalies that were  
330 generally greater than 0.5-1.0 K for most of Europe. An examination of the seasonal 850 hPa  
331 temperature and 500 hPa geopotential height anomalies in Figure 1 and Figure 2, respectively, shows  
332 cooler than normal temperature and lower 500 hPa heights for the first part of 2006 across much of  
333 Europe. Arguez et al. (2007) identifies this large-scale weather pattern as common feature with the  
334 negative phase of the North Atlantic Oscillation (NAO) that was in place for the first few months of  
335 2006. Countries in the north and far western parts of Europe, like the British Isles and Scandinavia,  
336 saw temperatures at or slightly above normal and normal precipitation in the winter of 2006.

337 The large-scale weather pattern made a transition from cooler and drier over much of Europe in  
338 winter to warmer than normal, in general, for the rest of 2006. However, there was a substantial  
339 month-to-month variability from spring to summer that the seasonal anomalies do not capture well.  
340 For example, July 2006 was well above normal as an eastward extension of the Azores High  
341 developed over central Europe leading to an extreme heat wave (Arguez et al., 2007). Many of the  
342 central European countries, including Belgium, Netherlands, Germany, Czech Republic and Austria,  
343 set all-time records in terms of mean July temperatures. This heat wave was also accompanied by a  
344 large-scale pollution episode over Central Europe (Struzewska and Kaminski, 2008). In August  
345 however, this warm pattern transitioned to a cooler than normal pattern. Precipitation was generally  
346 lower than normal during the anomalously high temperatures and near or just above normal during  
347 the cooler periods like what occurred in August.

348 Autumn was the most anomalous season of the year over Europe. It broke the record of seasonal  
349 temperature by a large amount and was shown to have a temperature largely exceeding that

350 expected from analogue weather regimes in previous years (Yiou et al., 2007), presumably due to a  
351 concurrence of a large Atlantic sea surface temperature anomaly and a persistent southerly flow  
352 (Cattiaux et al., 2009). The 850 hPa temperature anomaly for autumn clearly shows that a large  
353 anomaly that had been centered in the Northern Hemisphere (+3.0 K) was now centered over the  
354 Denmark/Germany area and extended north to Scandinavia, west to the British Isles and south to  
355 France as well as much of southern Europe that borders the Mediterranean Sea. The 500 hPa height  
356 anomalies are in good agreement with the warm autumn temperatures as a persistent ridging is  
357 centered over Germany and Poland. Precipitation amounts under and around this ridge, as one  
358 would expect, were well below normal. Areas that did experience higher than normal autumn  
359 precipitation are those countries to the west and southwest periphery of the 500 hPa ridge anomaly,  
360 which includes Ireland, United Kingdom, western France and western Spain and Portugal. Much of  
361 Europe that borders the Mediterranean was dry as the axis of the 500 hPa ridge anomaly extended  
362 south into the Mediterranean Sea between Spain and Italy as shown by Figure 2 and describe in  
363 detail by Arguez et al. (2007).

## 364 **5. Quantitative Evaluation**

365 In this section, we quantitatively compare model simulations and observations of weather  
366 parameters that are most relevant to air quality. For the sake of synthesis, we have focused on three  
367 distinctive subregions on each continent that have qualitatively different climate and air quality  
368 characteristics. These subregions are shown in Figure 3, together with the locations of  
369 meteorological measurement sites.

370 For NA, subregion NA1, the southwestern U.S., was selected because of the combination of high  
371 solar radiation, low relative humidity, large cities with poor air quality (Los Angeles, Phoenix), and  
372 geographic location to the west of the Rocky Mountain barrier. Subregion NA2, the Texas area, was  
373 selected for its hot, humid climate, large cities with poor air quality (Houston, Dallas), and location to



374 the east of the Rocky Mountain barrier. Subregion NA3, northeastern NA including parts of Canada,  
375 has a marked seasonal cycle, three of the North American Great Lakes, the highest emissions areas in  
376 NA, and large cities (New York City, Philadelphia, Toronto, Montreal). For EU, subregion EU1, the  
377 British Isles and western France, was selected for its mid-latitude, mixed maritime-continental  
378 climate and large cities (London, Paris). Subregion EU2, Central Europe, has a rather continental  
379 climate with marked seasonality, many large cities, and large emissions areas. Subregion EU3, the Po  
380 Valley of Italy, has a Mediterranean climate, poor air quality, and belongs to a separate air shed from  
381 northern Europe due to the Alpine barrier.

### 382 **5.1 Transport and mixing**

383 The weather parameters that drive the transport and mixing of air pollutants are controlled by grid-  
384 scale winds and subgrid-scale turbulence, including shallow and deep convection. We use here the  
385 reduced set of available routine network observations described in Section 2. For resolving  
386 transport, the analysis uses the 10-m wind observations and vertical wind profiles obtained from  
387 ozonesonde launches.

388 Figure 4 shows the evolution of the 10-m wind speed averaged over all measurement station  
389 locations in each subregion for each calendar month for each model and for the observations. In  
390 general the seasonal cycle is well reproduced by all models in all subregions, but wind speed  
391 amplitude spread is rather large and overestimated for EU. Model values differ by rather constant  
392 multiplicative factors. This could be due to a combination of differences in the model resolution in  
393 the lowest layers and differences in the methodology of diagnosing the 10 m wind amongst models.  
394 A general overestimation is found in all regions but NA1 and NA2, and no obvious explanation was  
395 found for this feature.

396 The amplitudes of the diurnal cycle of wind speed are underestimated (Figure 5). In the stable  
397 nighttime boundary layer, wind speed is overestimated, probably as a result of the lack of vertical  
398 resolution (i.e., layer height is approximately 40m) and overly strong vertical diffusion. For the NA

399 subregions, the intensification of wind speed due to the stronger vertical momentum fluxes that are  
400 associated with the development of the convective boundary layer and associated increase in wind  
401 speed is not marked enough and daytime wind speeds are generally underestimated. However,  
402 biases are generally larger during the night, which indicates a general difficulty to simulate the stable  
403 boundary layer. A particular situation occurs for EU3 (the Po Valley) where even the shape of the  
404 diurnal cycle is not well simulated, probably due to the complex topography of the area and the land-  
405 sea interface that induces complex mesoscale circulations.

406 The skill of the models in simulating the day-to-day variability of daily mean wind speed is  
407 summarized in Figure 6, which shows Taylor diagrams (Taylor, 2001) for wind speeds in all subregions  
408 studied. In all subregions, simulations have a correlation exceeding 0.5, and often reaching 0.9. For  
409 NA, the amplitude of daily wind variability varies by a factor of two relative to the observed one, with  
410 no systematic bias, while the variability is overestimated by all models in the EU case, which is  
411 consistent with the general overestimation of wind speed. Over NA, there is a marked spread in  
412 model skill. Correlation is generally higher for NA2 and NA3, where three models have a correlation  
413 exceeding 0.9, than for NA1, where topographic and coastal effects dominate the meteorology. For  
414 EU, models' skill is higher in maritime areas (EU1) and Central Europe (EU2), but is poor over the Po  
415 Valley due to complex topography. The large spread in model skill leads to a skill of the ensemble  
416 mean or median that is not higher than that of any model.

417 The spatial distribution of surface wind speed is fairly well simulated by the models (Figure 7). Over  
418 NA, the differences between the windier mid-western areas and less windy eastern areas are  
419 correctly reproduced, even though the observed winds are somewhat weaker than the simulated  
420 winds. WRF also generally does well in simulating the strength of transport over the oceans. Over  
421 EU, MM5 reproduces the northwest – southeast wind speed gradient. Regional discrepancies are  
422 found, for example, in some mountainous areas (e.g., Scandinavia and Alpine regions), where poorly  
423 resolved effects of topography probably explain the simulated wind overestimation.

424 Vertical profiles (based on ozone soundings) of wind speed are compared to the results of several  
425 models over NA and EU (Fig. 8). The statistical measures (bias, RMSE, correlation), were calculated  
426 for each of the stations and then averaged. Wind speed is well simulated along the profiles but  
427 markedly overestimated at lower altitudes for EU, confirming the results for 10-m wind speed. For  
428 NA, more scatter occurs among models for wind, but agreement between model and observations in  
429 terms of the mean wind speed is stronger in the lowest 500 m for three of the models. The RMSE is  
430 between 2 and 4 m s<sup>-1</sup> (except for models M1NA and M2NA in North America) with slightly higher  
431 values in higher altitudes, which corresponds to higher wind speeds on average. The correlation is  
432 lowest close to ground, but may exhibit values exceeding 0.9 above 500 m in Europe and above 1500  
433 m in North America. Two models (M1NA, M2NA) show poor correlation of 0 – 0.25 in North America.  
434 For simulating North America, the results from the European groups show clearly less agreement  
435 with the observations compared to Canadian and U.S. groups. However it must be taken into account  
436 that different run schemes and nudging techniques are used (see Table 1). If a model run is restarted  
437 every few days with initial conditions that stem from reanalysis data, the results will stay close to the  
438 observations because they are typically considered in the reanalysis. A continuous model run on the  
439 other hand, that is only nudged to the wind fields above the PBL has much more freedom to develop  
440 differently than the driving reanalysis fields. This should lead to a larger variability of the simulated  
441 quantities and therefore larger RMSE and lower correlation.

442 In order to evaluate the skill of the model in representing turbulent mixing, PBL heights calculated by  
443 the different meteorological models are compared to observations at Lindenberg, Germany (14.3°E,  
444 52.1°N). The observational data has been derived from radiosondes using the bulk Richardson  
445 number method. The observational data has been derived from radiosondes using profiles of the  
446 bulk Richardson number  $Ri_b$ . The method is a standard and widely used approach  
447 to derive PBL height from the numerical weather prediction (NWP) models,

448 as well as from the radiosounding data (see e.g. the review by Seibert et al., 2000). Here, a critical  
449 Richardson number  $Ri_c = 0.2$  was chosen. The top of the PBL is the altitude where  $Ri_b > Ri_c$ .  
450 Each model has its own algorithm to diagnose the PBL height, many of them are based on similar  
451 approaches as the one applied to the observations. It was found that the models are able to simulate  
452 the PBL height at noon quite well (Fig. 9 and Table 2). This can be interpreted in a way that the PBL  
453 parameterizations are working reasonably well and the vertical mixing of pollutants under these  
454 conditions is likely represented adequately in the models. By contrast, particularly at 18 UTC and in  
455 the summer months, the modeled PBL height is much lower than observed (Fig. 9). This may be  
456 explained by the fact that this is a transition time to a stable PBL as static stability of the surface layer  
457 turns positive. In this transition phase the top of the PBL is not well defined and the models typically  
458 diagnose the top of the PBL to be one of the first few model layers while the radiosondes do not  
459 show this. Some of the models give very low PBL height around the top of the first model layer  
460 throughout the night which is clearly unrealistic, but default position of these non-TKE schemes. The  
461 morning ascent of the PBL, when strong mixing processes take place, could not, unfortunately, be  
462 investigated due to 6-hour observation sampling.

463 Table 2 gives the mean observed PBL heights at 0, 6, 12 and 18 UTC together with the bias, RMSE and  
464 the correlation of the model results when compared to the observations. Here, all observations  
465 including those when the PBL height was not well defined were taken into account. As mentioned  
466 above, the largest discrepancies between model results and observations occur at 18 UTC, at this  
467 time none of the models reproduce the observed values with reasonable accuracy. This is  
468 represented in poor correlation coefficients and a large negative bias. About 3-5 models show clear  
469 problems in representing the correct PBL height at all times except 12 UTC.

## 470 **5.2 Chemistry drivers**

471 Three of the meteorological parameters that drive atmospheric processing of emissions (chemistry  
472 and aerosol transformations, see Monks et al., 2009 for a full review) are evaluated here:

473 temperature, relative humidity and surface shortwave radiation. Biases of monthly means of 2-m  
474 temperature are generally small (Figure 10). Over NA only one model has a moderate positive  
475 temperature bias that occurs mainly in the winter season and is as large as 5 K. Otherwise, the  
476 remaining ensemble members have little spread and agree well with the observed temperature in a  
477 regional average sense. Likewise, in EU, biases remain small, with slightly more spread during winter  
478 months, but the model ensemble envelopes the observations well.

479 The diurnal cycles of 2-m temperature are also fairly well reproduced by the models (Figure 11).  
480 Unlike the 10-m wind speed, the amplitudes of the diurnal cycles for 2-m temperature are not  
481 underestimated except for one model over NA, which also had the systematic positive wind speed  
482 bias seen in Figure 5. Thus we expect that related temperature-dependent fields (clouds, longwave  
483 radiation and sensible heat fluxes, see e.g. Liu et al., 2003) are fairly well accounted for in the  
484 models.

485 The typical vertical temperature profile bias is between  $\pm 1$  K (Figure 12). On average the temperature  
486 is slightly underestimated by the models. The RMSE is between 1 and 2 K along the profile, best  
487 agreement being achieved between 1000 and 6000 m altitude. The correlation is above 0.9, and at  
488 many heights, even above 0.95.

489 For simulated ozone episodes to build up, it is essential that the highest diurnal temperatures are  
490 well predicted by the models, other parameters also being important. In order to focus on this issue,  
491 Figure 13 shows the 99.5<sup>th</sup> centiles of the models temperature distribution (hourly values) against the  
492 corresponding observed 99.5<sup>th</sup> centiles. In most cases, considering both continents, the extreme  
493 temperatures that were observed are greater than the model simulated temperatures. The  
494 differences, however, remain moderate and do not exceed 3 K. This small bias should have the  
495 effect of reducing gas-phase chemical reaction rates as well as slightly displacing the gas-particle  
496 equilibrium for volatile species.

497 Relative humidity (RH) influences photochemistry through reactions between water vapor and the  
498 oxygen radical, which forms the hydroxyl radical. Water vapor can be either an ozone sink or source,  
499 depending on the availability of nitrogen oxides. Relative humidity at 2 m is not as well simulated as  
500 temperature (Figure 14 vs. 10). Over NA, systematic biases are found for most models, and in  
501 general RH is overestimated. The bias is particularly marked over the southwestern U.S. (subregion  
502 NA1), the driest of the three NA subregions. This reveals model deficiencies in dry areas, with a  
503 possible consequence of overestimation of soil moisture. However, the amplitude of the diurnal cycle  
504 is simulated in a realistic manner (not shown).

505 Above the surface, relative humidity is overestimated by all models and in all regions (Figure 15), in  
506 agreement with surface analysis for NA. Biases and RMSE both increase with height. This is not  
507 surprising if one keeps in mind that the water vapor mixing ratio decreases rapidly with height and  
508 therefore RH is sensible to small deviations of the mixing ratio. The overestimation of RH might be  
509 connected with the underestimation of the temperature. The correlation of the time series, however,  
510 is relatively large, with values between 0.6 and 0.8.

511 Model predictions of hourly gridded surface shortwave radiation (SSWR) were submitted to AQMEII  
512 by most groups, but surface radiation components are not routinely measured at many stations in  
513 either NA or EU. Since shortwave radiation plays an important role in photochemistry, the surface  
514 energy budget, and biogenic emissions, it was still of interest to examine differences between  
515 models, especially because SSWR will be modulated by cloud shading, which may vary considerably  
516 between models due to the difficulties associated with predicting the presence and properties of  
517 clouds.

518 The lefthand column of Figure 16 shows the monthly variation of mean mid-day SSWR at the centers  
519 of the three NA subregions (see Fig. 3) predicted by four meteorological models. The highest  
520 summer values for the three subregions are predicted over the southwestern U.S. (NA1), and the  
521 largest differences between the models for this subregion occur in the spring ( $\sim 400 \text{ Wm}^{-2}$  or  $\sim 100\%$ ).

522 The lowest summer values are predicted for northeastern NA (NA3), and the largest differences  
523 between models for this subregion occur in June ( $\sim 400 \text{ Wm}^{-2}$  or  $\sim 100\%$ ). These summertime  
524 differences are surprisingly large and are likely due to differences in the predictions of clouds. The  
525 righthand column of Figure 16 shows the same analysis for the center points of the three EU  
526 subregions for nine meteorological models or model configurations. The largest actual difference  
527 between models occurs in June for EU3 ( $\sim 500 \text{ Wm}^{-2}$  or  $\sim 125\%$ ) but relative differences are even  
528 higher in the winter months. For the EU subregions the ranking between models is generally  
529 constant between subregions and across seasons. These systematic differences in SSWR between  
530 models may impact many other meteorological fields such as surface temperature and PBL height.

531 Figure 17 shows considerable variation in the model-simulated diurnal cycle of SSWR for the six  
532 subregions. For NA there are systematic differences of 15% to 50% between the four models at local  
533 noon and for EU there are differences of 30% to 60% between eight models (excluding one outlier).  
534 As expected, the maximum daytime value tends to decrease with increasing latitude, but cloud cover  
535 also plays a role; for example, the maximum daytime value is lower for subregion NA2 ( $31^\circ\text{N}$ ) than  
536 for NA1 ( $36.5^\circ\text{N}$ ). For the EU subregions there is also a suggestion that local noon differs between  
537 two clusters of models.

538 Figure 18 shows monthly variations in the standard deviation of mid-day hourly SSWR for each  
539 month of 2006 for the same six locations. This quantity provides another measure of the impact of  
540 differences in model predictions of hourly cloud fields on cloud shading. It is evident that there are  
541 considerable differences between the models throughout the year, but these differences vary from  
542 subregion to subregion. The differences are largest in spring and summer for the southwestern U.S.  
543 (NA1) but fairly even throughout the year for northeast NA (NA3). For the Texas subregion (NA2) and  
544 the three EU subregions, on the other hand, there is closer agreement between the models in the  
545 cold season and less agreement in the warm season. One possible explanation is a higher frequency

546 of stratiform cloud in the winter, a higher frequency of convective cloud in the summer, and closer  
547 agreement between model predictions of the former (see next section).

### 548 **5.3 Surface fluxes**

549 Biogenic emissions depend on a number of factors, including surface weather. Soil nitrogen oxides  
550 (NO<sub>x</sub>) and vegetation volatile organic compound (VOC) emissions increase nonlinearly with  
551 temperature, with sharp sensitivity at temperatures exceeding 30°C. The above analysis shows that  
552 these emissions should be fairly well represented in most models, but an underestimation may be  
553 expected due to moderate low temperature bias at highest temperatures. Biogenic VOC emissions  
554 also depend on radiation, but the model skill for radiation could not be properly evaluated against  
555 observations within this study.

556 A major driver of dry deposition fluxes is the stomatal resistance which also depends on temperature  
557 and radiation. Dry deposition, particularly for ozone, is also driven by turbulent mixing near the  
558 ground. Although we were not able to evaluate the model predictions of sensible heat fluxes, the  
559 weak differences between simulated and observed 2-m temperatures indicates that aerodynamic  
560 resistance should not undergo strong model biases.

561 For both aerosol particles and soluble gases, wet deposition fluxes depend on precipitation  
562 frequency, duration, intensity, and type (e.g., Wang et al., 2010). Model predictions of hourly  
563 precipitation for 2006 have been examined for the North American simulations. In terms of seasonal  
564 accumulation, Table 3 lists mean winter (Dec.-Feb.) and summer (June-Aug.) precipitation amounts  
565 for all measurement stations in each of the three NA analysis subregions and corresponding mean  
566 model-predicted precipitation amounts for these three groups of stations. In 2006, the NA1  
567 subregion received more precipitation in the winter than the summer while the opposite was true for  
568 the NA2 and NA3 subregions. Most of the models reproduced this geographically-varying seasonal  
569 cycle, but there is a wide variation in predicted amount and the models, including the ensemble  
570 mean, tend to overpredict seasonal precipitation. This is particularly true in the summer when



571 convective precipitation typically dominates (e.g., Tremblay, 2005), since the simulation of  
572 convective precipitation is challenging because of its small-scale and scattered nature.

573 Given that wintertime precipitation tends to be dominated by stratiform precipitation (Tremblay,  
574 2005), and given that stratiform precipitation tends to be longer-lived with more wide spread  
575 coverage than convective precipitation due to its synoptic forcing, it is useful to examine observed  
576 and predicted hourly precipitation intensity. Figure 19 shows winter- and summer-season  
577 histograms of observed and predicted occurrence frequencies for different hourly precipitation  
578 amounts for the three NA analysis subregions. Both observations and models exhibit more high-  
579 intensity precipitation events (i.e., a longer distributional “tail”) in the summer than winter for  
580 subregion NA3, about the same for subregion NA2, and fewer high-intensity events in subregion  
581 NA1. In meso- $\beta$ -scale models (i.e., horizontal grid spacing of 10-40 km) such as those considered  
582 here, transport by convective precipitation systems will be associated with subgrid-scale circulations  
583 and hence will not be resolvable. Figure 19, however, suggests that such high-intensity precipitation  
584 occurs infrequently (note the semi-log scale). In terms of low-intensity precipitation forecasts, on the  
585 other hand, most of the models underpredict non-precipitation events (i.e., the “< 0.5” bin includes  
586 dry conditions and “trace” precipitation) but overpredict the occurrence of low-intensity  
587 precipitation (i.e., 1-5 mm h<sup>-1</sup>). There is also considerable variability amongst the models. Note that  
588 it is likely that this difference between the measurements and models can be ascribed at least in part  
589 to the comparison here of point measurements to grid-scale predictions, which introduces the  
590 problem of representativeness error due to interpolation of model grid-cell values to station  
591 locations (e.g., Tustison et al., 2001). Nevertheless, the combination of higher accumulation, longer  
592 duration, and greater spatial coverage on average in the model predictions suggests that wet  
593 removal may be overemphasized by the models in areas of more frequent convection, leading to a  
594 tendency to underestimate ambient air concentrations of particles and water-soluble species such as  
595 SO<sub>2</sub>, HNO<sub>3</sub>, and NH<sub>3</sub>.

596  
597 Finally, Figure 20 compares the spatial distribution of seasonally observed precipitation (PRISM) for  
598 two seasons with the corresponding spatial distribution predicted by the U.S. EPA WRF simulation.  
599 WRF agrees with PRISM quite well in winter when grid-scale stratiform precipitation is likely  
600 dominant, whereas in summer, when diurnally-forced convective precipitation is most common, the  
601 PRISM and WRF differ significantly in total summer precipitation.

## 602 **6. Summary**

603 This study was devoted to a collective operational evaluation of regional meteorological models that  
604 forced the air quality simulations carried out in the AQMEII regional AQ modeling system inter-  
605 comparison. It was the first time that a multi-model evaluation of this scale has been performed,  
606 with five participating meteorological models or model versions over North America (NA) and 11  
607 models or model versions participating over Europe (EU). We emphasized model parameters that  
608 are major drivers of air quality variability. The focus was not to inter-compare the models and  
609 produce statistical metrics, but rather to discern general characteristics seen. This study produced a  
610 number of conclusions.

- 611 • There is considerable variability among model predictions, even for different configurations  
612 or post-processing of the same model. This is particularly clear for short wave radiation  
613 where noontime predicted values vary by a factor up to two. This scatter should contribute  
614 to variability in many other predicted fields, suggesting that prediction of the timing and  
615 location of clouds remains an ongoing challenge for both meteorological and AQ modeling.
- 616 • There are systematic positive model biases, particularly for EU, for surface and boundary-  
617 layer wind speed, which are confirmed both in 10-m wind and ozonesonde measurements.  
618 These biases should contribute to a tendency to underestimate surface concentrations of  
619 primary pollutants. The overestimation is particularly marked in stable wintertime or

620 nighttime conditions. The day-to-day variability of low-level wind speed is also systematically  
621 overestimated for EU.

622 • Developed planetary boundary layer (PBL) heights are, at one European site, well captured,  
623 but PBL height is poorly simulated at nighttime or transition times. Models generally  
624 underpredict PBL heights in these situations, which should lead to air pollutant concentration  
625 overestimation if this conclusion holds in other locations.

626 • Less clear conclusions hold for water vapor and precipitation, but we found large – albeit not  
627 systematic – differences for these parameters. These variables can significantly influence the  
628 predicted concentrations of fine particulate matter.

629 • The models have a tendency to underestimate the occurrence of non-precipitation  
630 conditions and extreme precipitation events but overpredict the occurrence of light to  
631 moderate precipitation conditions. This could lead to an overestimation of wet removal of  
632 particles and water-soluble gases.

633 • Not surprisingly, temperature is the best predicted of the variables that we analyzed in this  
634 study.

635 Our conclusions point to several systematic biases (e.g., overestimated wind speed, lack of long dry  
636 periods). These biases should induce significant and systematic concentration biases, in particular for  
637 primary pollutants. It is beyond the scope of this article to actually verify that concentrations  
638 undergo such biases. However, several of the conclusions of the AQMEII multi-model analysis of  
639 model skill in simulating particulate matter (PM) are consistent with our results (see Solazzo et al.,  
640 2011). In particular, model wind speed bias was found to be correlated with negative particulate  
641 matter biases. Overestimated rainfall frequency is also consistent with underestimated PM  
642 concentrations, but verification of this bias was not carried out.

643 Since the meteorological variables considered in this paper are known to have important influences  
644 on AQ predictions, the large variability in the predicted meteorological fields amongst the different

645 meteorological models and model versions will likely make an important contribution to the  
646 variability in the predicted AQ fields that has been quantified in companion AQMEII papers in this  
647 special issue. For primary pollutants and aerosols, dispersion (wind, boundary layer height) is the  
648 most important concentration driver. From our analysis, we conclude that model simulations of  
649 daytime meteorology have fewer deficiencies than simulations of nighttime meteorology. Nighttime  
650 concentrations undergo systematic overestimation of wind and underestimation of PBL height, which  
651 is a potential source of large error compensation for pollutant simulation. Therefore, nighttime  
652 meteorology remains a challenge for models. Finally, for photochemistry and secondary pollutants,  
653 shortwave radiation and its influence on cloud processes is probably the most critical process to  
654 improve as it is a major driver of ozone build up. We conclude that efforts must be made to reduce  
655 the uncertainty in the simulation of radiation and clouds.

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## 946 **Figure Captions**

947 **Figure 1:** Seasonal 850 hPa temperature anomalies (K) for 2006.

948 **Figure 2:** Seasonal 500 hPa geopotential height anomalies (dam) for 2006.

949 **Figure 3:** Six subregions selected for model and observation comparisons: (left panel) North America  
950 (24°N-54°N, 130°W-60°W); (right panel) Europe (30°N-70°N;15°W-30°E). The exact subregion  
951 boundaries are the following: (1) NA1, 31°N-42°N, 125°W-112°W; (2) NA2, 25°N-37°N, 104°W-90°W;  
952 (3) NA3, 36.5°N-48.5°N, 85°W-69°W; (4) EU1, 42°N-60°N, 10°W-5°E; (5) EU2, 46°N-56°N, 5°E-25°E;  
953 and (6) EU3, 43°N-46°N, 7°E-15°E. Dots indicate the location of the observation stations considered in  
954 this study. Sites used for profile calculations, where ozone soundings are launched are marked with a  
955 “+” sign.

956 **Figure 4:** Monthly averages of subregional mean wind speeds as observed (thick solid black lines)  
957 and as simulated from the various meteorological models used in AQMEII.

958 **Figure 5:** Mean annual diurnal cycle of wind speed by subregion as observed (thick solid black lines)  
959 and as simulated from the various meteorological models used in AQMEII.

960 **Figure 6:** Taylor plots for the simulation of daily wind speed over each continent (left panel: NA; right  
961 panel: EU). Each symbol type stands for a subregion. The amplitude of variability is the radial distance  
962 to origin. The amplitude of observation for a given subregion is shown by the symbol on the x axis.  
963 Larger symbols indicate the skill of the ensemble mean (open symbol) and the ensemble median  
964 (solid symbol).

965 **Figure 7:** Spatial distribution of the mean annual wind speed at 10 m as observed at measurement  
966 sites and simulated over the two continents by WRF for North America and MM5 for Europe.

967 **Figure 8:** Comparison of vertical profiles of wind speed for NA and EU soundings. The observations  
968 are based on irregular ozone soundings at six stations for EU and six stations for NA. The statistical

969 parameters bias, root mean square error and correlation were derived for time series in given  
970 altitudes.

971 **Figure 9:** Annual times series of PBL heights at Lindenberg, Germany, derived from radiosondes (obs)  
972 and from two selected models at 12UTC and 18 UTC.

973 **Figure 10:** Simulated and observed monthly mean 2-m temperature values for the six subregions.

974 **Figure 11:** Same as Figure 5 for the mean diurnal cycle of 2-m temperature.

975 **Figure 12:** same as Figure 8 but for temperature profiles

976 **Figure 13:** Simulated vs. observed 99.5<sup>th</sup> centiles of area-average hourly temperature distributions for  
977 each continental subregion of Figure 3. Each point represents a model and each color a different  
978 subregion. The area names are indicated on the figure.

979 **Figure 14:** Left panels: Seasonal cycle of relative humidity (%) at 2 m as averaged over observations  
980 (thick black line) or model simulations (other lines) for three NA subregions; Right panels: As in left  
981 panels for hourly precipitation rate (in mm).

982 **Figure 15:** Same as Figure 8 but for Relative humidity

983 **Figure 16:** Left panels: Mean monthly mid-day (hours 10-14 local time) surface shortwave radiation  
984 ( $W m^{-2}$ ) predicted by four meteorological models at center points of three NA subregions [NA1:  
985 36.5°N, 118.5°W; NA2: 31°N, 97°W; NA3: 42.5°N, 77°W]; Right panels: Same plots for nine models  
986 and center points of three EU subregions [EU1: 51°N, 2.5°W; EU2: 51°N, 15°E; EU3: 44.5°N, 11°E].

987 **Figure 17:** Left panels: Mean annual diurnal cycle (UTC) of surface shortwave radiation ( $W m^{-2}$ )  
988 predicted by four meteorological models at center points of three NA subregions [NA1: 36.5°N,  
989 118.5°W; NA2: 31°N, 97°W; NA3: 42.5°N, 77°W]; Right panels: Same but for nine models and center  
990 points of three EU subregions [EU1: 51°N, 2.5°W; EU2: 51°N, 15°E; EU3: 44.5°N, 11°E].

991 **Figure 18:** Same as Fig. 16 but for mean monthly standard deviation of hourly surface shortwave  
992 radiation ( $\text{W m}^{-2}$ ) for mid-day period (hours 10-14 LT).

993 **Figure 19:** Histograms of percentage occurrence of observed and predicted hourly precipitation  
994 amount ( $\text{mm h}^{-1}$ ) for the (a) winter and (b) summer season for the NA1 subregion, (c) winter and (d)  
995 summer season for the NA2 subregion, and (e) winter and (f) summer season for the NA3 subregion.

996 **Figure 20:** Spatial distribution of seasonal accumulated precipitation (mm) for the US1 WRF  
997 simulation and observations, which are represented by the Parameter-elevation Regressions on  
998 Independent Slopes Model (PRISM). Left panels represent winter (DJF) and right summer (JJA).

999

1000 **Tables**

Research Group that operated simulations and processing	Model	Appx. horiz. resol. (km)	# of vertical levels; # of levels < 1 km; model top;	Key parameterizations LSM = Land Surface Model; PBL = Planetary Boundary Layer Scheme; MP = Microphysics Scheme; CuP = Cumulus Parameterization; LWR = Long-Wave Radiation Scheme	Analysis and initialization (AI) , integration (IN), boundary conditions (BC), data assimilation (DA)
<b>North America</b>					
Environment Canada (CA)	GEM (Côté et al., 1998a,b)	15 (0.1375°)	58 8 10 hPa	LSM: ISBA (Noilhan and Planton, 1989; Belair et al., 2003) PBL: TKE scheme (Belair et al., 2003) MP: Sundqvist (Pudykiewicz et al., 1992) CuP: KFC (Kain and Fritsch, 1990, 1993) LWR: Li and Barker (2005)	AI: Global 0.33° analysis every 6 h IN: 1.25 d segments with 0.25 d overlap BC: None (global variable grid) DA: None
Helmholtz-Zentrum Geesthacht (DE)	COSMO-CLM (Steppeler et al., 2003; Schättler et al., 2009, Rockel et al., 2008)	24	40 11 20 hPa	LSM: multi-layer model TERRA-LM (Grasselt et al., 2008) PBL: TKE closure, Doms and Schaettler, 2004, Doms et al., 2008 MP: Seifert and Beheng, 2001 CuP: Tiedtke, 1989 LWR: Ritter and Geleyn, 1992	AI: 1.875° NCEP1 reanalysis IN: continuous run, 1 month spin up time BC: same as AI DA: Spectral nudging of wind in higher altitudes (von Storch et al., 2000)
Univ. Aarhus (DK)	MM5	50	29 11 100 hPa	LSM: NOAH (Ek et al., 2003) PBL: Eta MY (Janjic, 1990, 1994) MP: mixed phase Reisner 1 (Reisner et al. 1998) CuP: BM (Betts and Miller, 1993) LWR: CCM2 (Hack et al., 1993)	AI/IN/DA: One continuous simulation with grid nudging FDDA using 1° NCEP-FNL global analysis every 6 h. Relaxation/inflow-outflow lateral BCs.
Univ. Aveiro (PT)	MM5 Dudhia, 1993; Grell et al., 1994)	27	23 15 100 hPa	LSM: Five-Layer Soil model (Dudhia, 1996) PBL: MRF (Hong and Pan, 1996) MP: Reisner 2 (Reisner et al., 1998) CuP: Grell and Devenyi (2002) LWR: RRTM (Lacono et al 2008)	AI: 1° NCEP-FNL global analysis every 6 h IN: 5.25 d segments with 0.25 d overlap BC: same as AI DA: Not used
Environmental Protection Agency (US)	WRF (Skamarock et al., 2008)	12	34 14 50 hPa	LSM: PX LSM (Xiu and Pleim, 2001; Pleim and Xiu, 2003) PBL: ACM2 (Pleim, 2007a,b) MP: Morrison et al. (2009) CuS: Kain-Fritsch2 (Kain, 2004)	AI: 12-km NAM analysis + radiosondes every 6 h IN: 5.5 d segments with 0.5 d overlap BC: same as AI DA: V, T, q nudging in atmosphere; T, q

				LWR: RRTMG (Lacono et al 2008)	nudging in soil
<b>Europe</b>					
IFT (DE)	COSMO (Steppeler et al., 2003; Schättler et al., 2009)	24	40 total 9 below 1 km	LSM: multi-layer model TERRA-ML (Grasselt et al. 2008) PBL: prognostic TKE, 2.5 closure scheme (Doms et al. 2008) MP: Kessler type bulk scheme, ice phase, prognostic precipitation (Doms et al. 2007; Seifert and Crewell, 2008) CuP: mass flux scheme of Tiedke (1989) LWR: $\delta$ -two-stream (Ritter and Geleyn 1992)	Initialization and boundary conditions from the GME system (Majewski et al. 2002)
IMK-IFU (DE)	WRF/Chem	22.5	36 total 13 below 1 km	LSM: NOAH (Chen and Dudhia 2001, Ek et al, 2003) LWR: RRTM (Mlawer et al., 1997) CuP: Grell (Grell and Devenyi 2002) PBL : Hong et al. (2006)	Initialization and nudging from NCEP GFS 1° analyses. Nudging above PBL detailed in Gilliam and Pleim (2010). Note: the run was done with aerosol radiation effects (direct and indirect) and also included some aqueous chemical reactions (see Forkel et al., in preparation in this issue).
Helmholtz-Zentrum Geesthacht (DE)	COSMO-CLM (Steppeler et al., 2003; Doms and Schättler, 2004, Rockel et al., 2008 )	24	40 11 20 hPa	LSM: Multi-layer model TERRA-LM (Grasselt et al., 2008) PBL: TKE closure, Doms and Schaettler, 2004 MP: Seifert and Beheng, 2001 CuP: Tiedtke, 1989 LWR: Ritter and Geleyn, 1992	AI: 1.875° NCEP1 reanalysis IN: continuous multidecadal run BC: same as AI DA: Spectral nudging of wind in higher altitudes (von Storch et al., 2000)
Univ. Aarhus (DK)	MM5	50	29 11 100 hPa	LSM: NOAH (Ek et al., 2003) PBL: Eta MY (Janjic, 1990, 1994) MP: mixed phase Reisner 1 (Reisner et al. 1998) CuP: BM (Betts and Miller, 1993) LWR: CCM2 (Hack et al., 1993)	AI/IN/DA: One continuous simulation with grid nudging FDDA using 1° NCEP-FNL global analysis every 6 h. Relaxation/inflow-outflow lateral BCs.
FMI	ECMWF IFS	25	4 2 3.5 km	Physics from the IFS forecasting / assimilation system, interpolated to the grid (IFS, 2007)	ECMWF operational global forecasts
TNO	ECMWF IFS	25 (0.5°x0.25°)	4 2 3.5 km	Physics from the IFS forecasting / assimilation system, interpolated to the grid (IFS, 2007)	ECMWF operational global forecasts
IPSL	MM5 Dudhia, 1993; Grell et al., 1994)	20	32 9 100 hPa	LSM: NOAH (Ek et al., 2003) CuP: Grell and Devenyi (2002) LWR: RRTM (Mlawer et al., 1997) PBL: MRF PBL scheme	BC, initial conditions and nudging from ECMWF analyses

				MP: Reisner 2 (Reisner et al., 1998)	
Univ. Aveiro	MM5 Dudhia, 1993; Grell et al., 1994)	27	23 14 100 hPa	LSM: Five-Layer Soil model (Dudhia, 1996). CuP: Grell and Devenyi (2002) LWR: RRTM (Mlawer et al., 1997) PBL: MRF PBL scheme MP: Reisner 2 (Reisner et al., 1998)	
Univ. Hertfordshire (UK)	WRF (Skamarock et al., 2008)	18	<b>52</b> total <b>11</b> below 1 km	LSM: NOAH (Ek et al., 2003) PBL: Hong et al (2006) Microphysics Morrison et al (2009) CuP Grell and Devenyi (2002) LWR: RRTMG (Lacono et al 2008)	BC, initial conditions and nudging from ECMWF analyses
MSC (HR)	PARLAM-PS Tsyro and Støren 1999	50	<b>20</b> total <b>2</b> below 1 km	Most parameterizations from the HIRLAM model, see description in Sass et al (1994)	BC from ECMWF analyses, then forecasts 4x a day
NOAA	WRF/Chem	22.5	<b>36</b> total <b>13</b> below 1 km	LWR: RRTM (Mlawer et al., 1997) CuP: Grell (Grell and Devenyi 2002) LSM: NOAH (Chen and Dudhia 2001, Ek et al, 2003) PBL : Hong et al. (2006)	Initialization and nudging from NCEP GFS 1° analyses. Nudging above PBL detailed in Gilliam and Pleim (2010)

1001

1002 **Table 1:** Summary of some key characteristics of the meteorological models or model configurations participating in AQMEII.

1003

1004

Hour (UTC)	Mean Obs	M1EU	M2EU	M3EU	M4EU	M5EU	M7EU	M8EU	M9EU	M10EU
Bias (m)										
All hours	628	30	39	-476	-210	-3	-139	-361	-288	-55
0	363	11	34	-326	-246	22	-113	-317	-293	54
6	366	8	76	-326	-132	32	-126	-313	-276	29
12	1078	167	237	-612	72	33	-264	-280	-150	-170
18	705	-68	-193	-638	-538	-99	-52	-532	-434	-134
RMSE (m)										
All hours		542	464	645	481	358	386	538	471	433
0		443	223	403	310	208	215	394	343	281
6		547	253	412	271	206	209	400	343	253
12		550	589	797	410	402	504	527	478	536
18		615	631	836	768	514	503	750	650	565
Correlation										
All hours		0,66	0,70	0,56	0,70	0,78	0,77	0,69	0,76	0,62
0		0,41	0,78	0,03	0,59	0,85	0,73	0,09	0,73	0,56
6		0,27	0,69	-0,02	0,45	0,80	0,76	0,02	0,61	0,57
12		0,72	0,73	0,53	0,81	0,79	0,72	0,75	0,78	0,58
18		0,51	0,25	0,19	0,25	0,49	0,67	0,39	0,50	0,35

1005

1006 **Table 2:** Comparison of simulated PBL heights with observations at Lindenberg, at 0, 6, 12 and 18 UTC, and for all hours. On total, 1457 values were taken  
 1007 into account.

1008



1009

Region	Season	N	Obs	M1NA	M2NA	M3NA	M4NA	M5NA	Ensemble
NA1	DJF	115	93	130	66	158	135	206	139
NA1	JJA	115	16	9	2	37	22	30	20
NA2	DJF	203	106	137	143	123	132	195	146
NA2	JJA	203	125	283	99	274	290	258	241
NA3	DJF	291	152	186	207	194	184	235	201
NA3	JJA	291	208	431	418	314	351	440	391

1010

1011 **Table 3:** Observed and model-predicted 2006 mean seasonal precipitation accumulations at available measurement stations (mm) in three North American  
1012 analysis subregions. The “Ensemble” column corresponds to mean of model values.

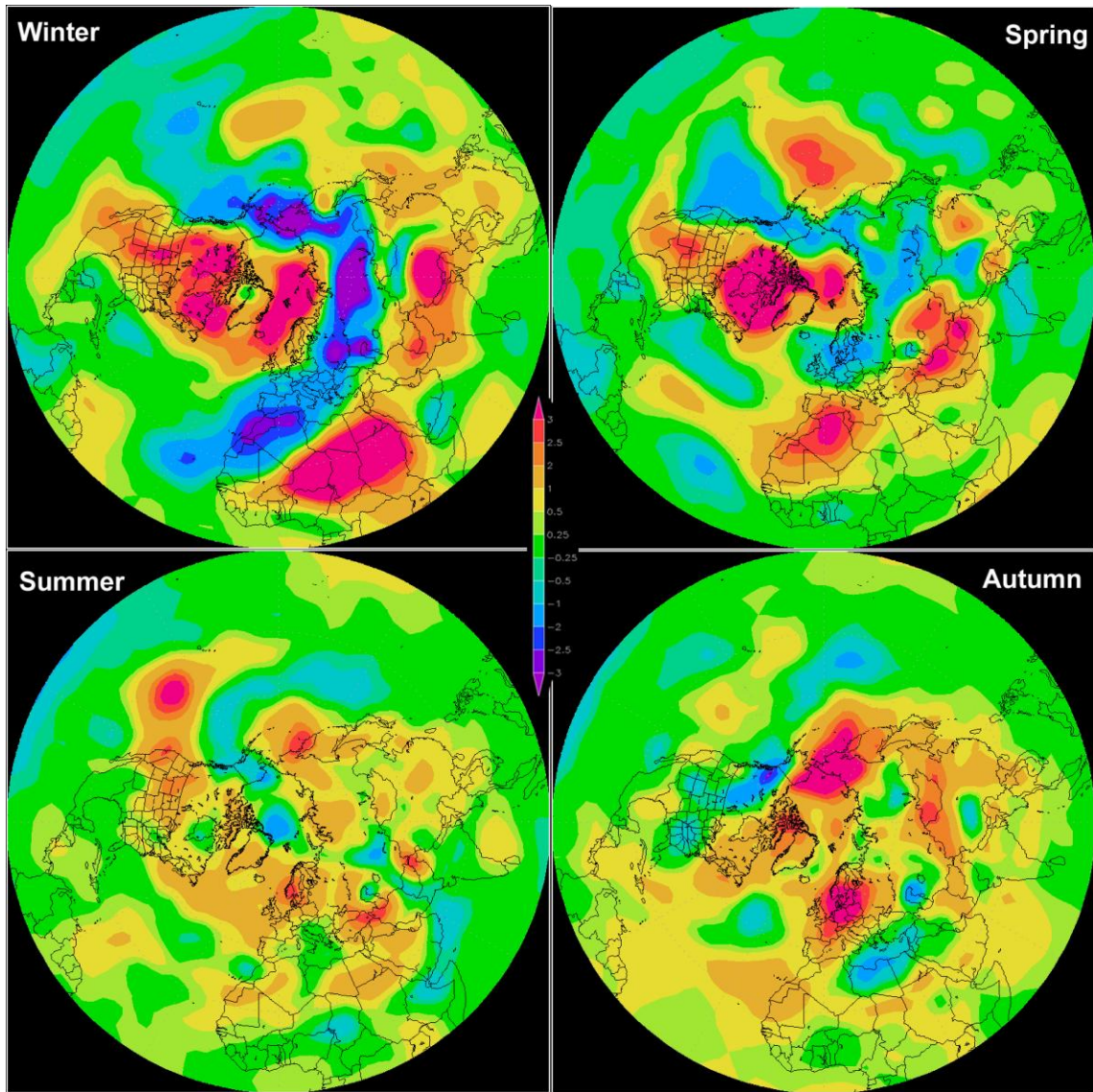


Figure 1

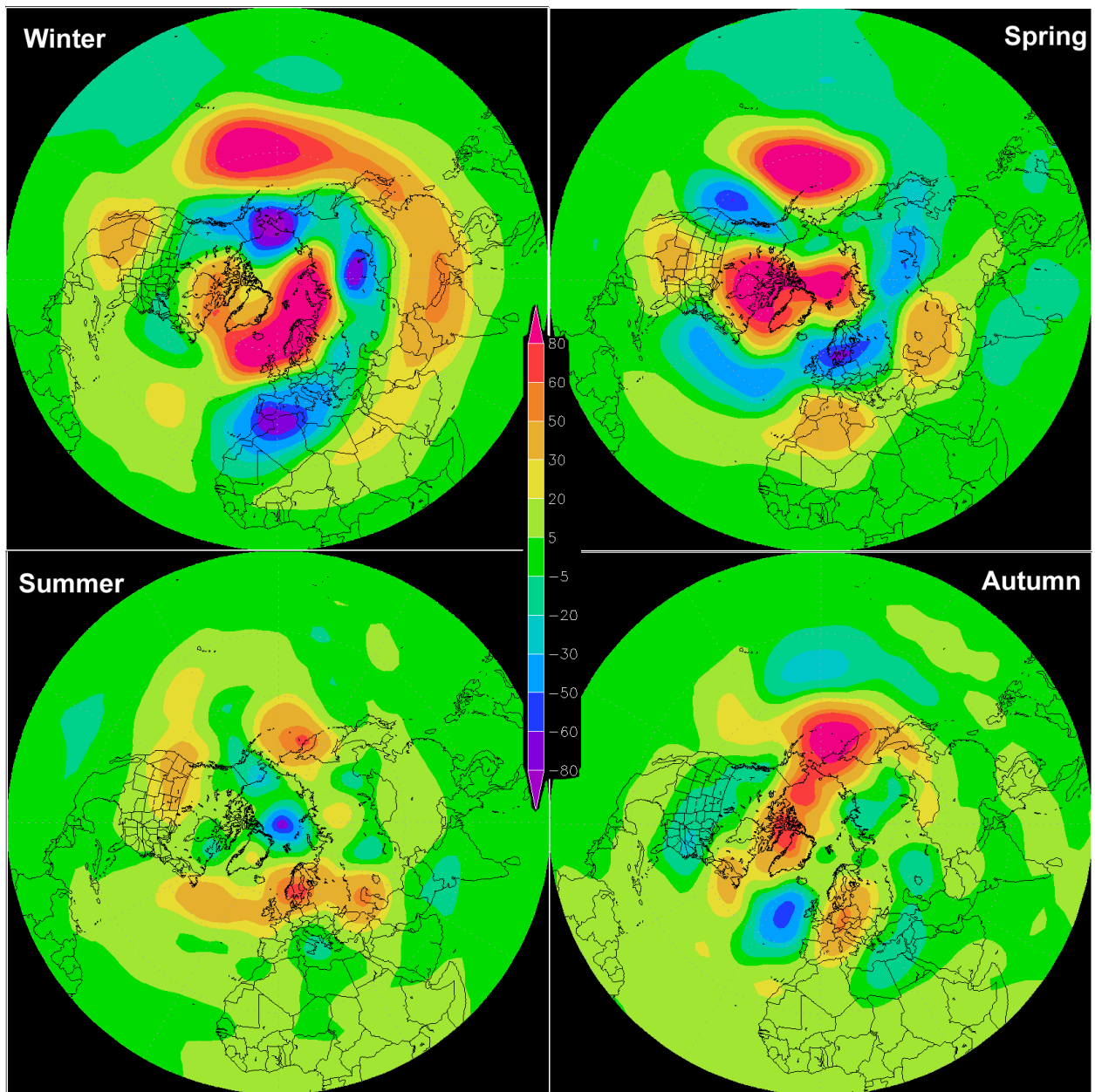


Figure 2

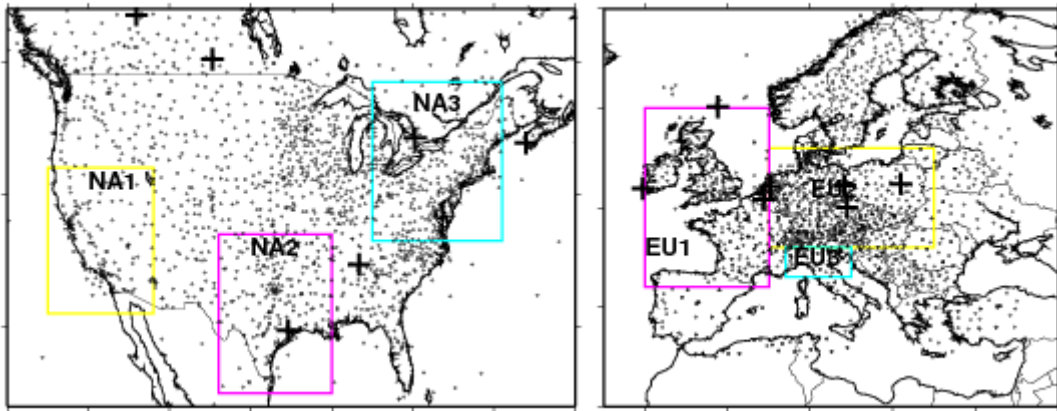


Figure 3

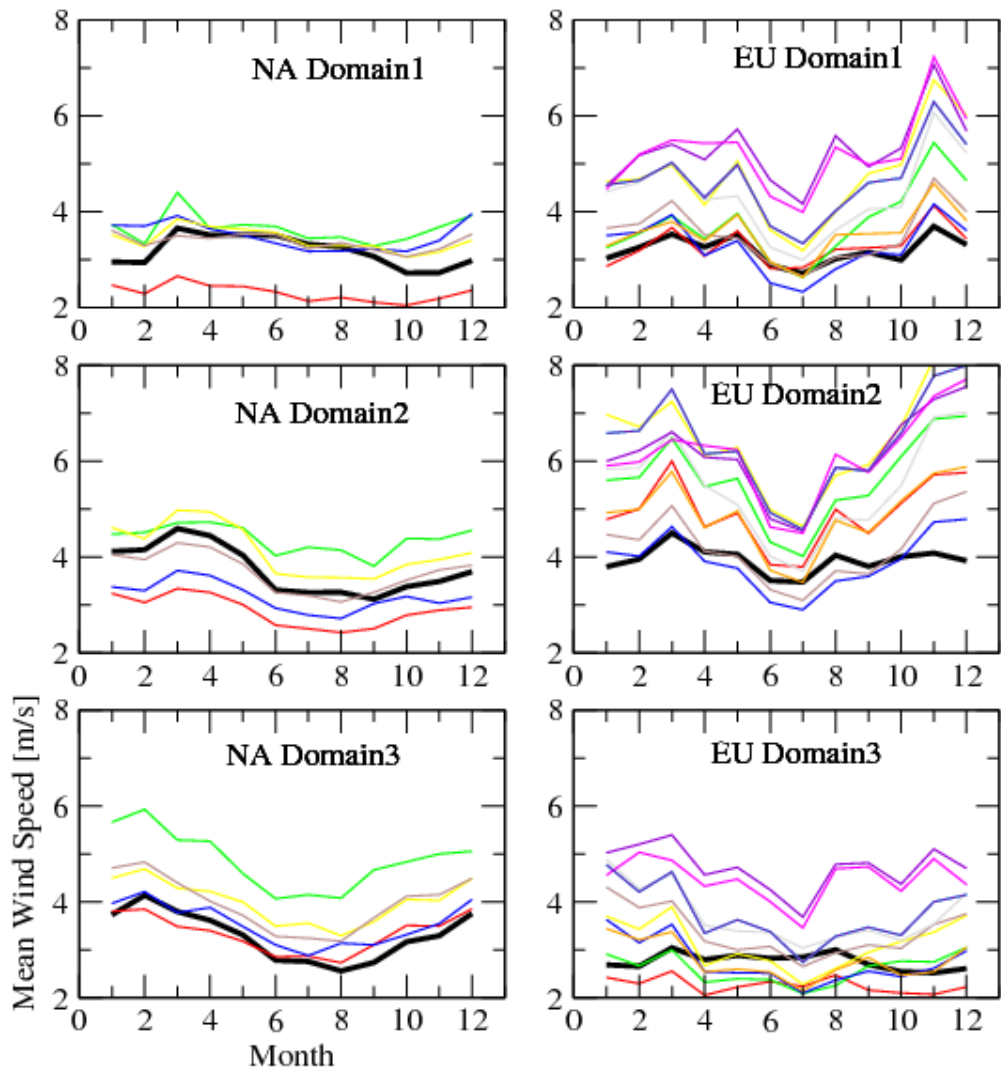


Figure 4

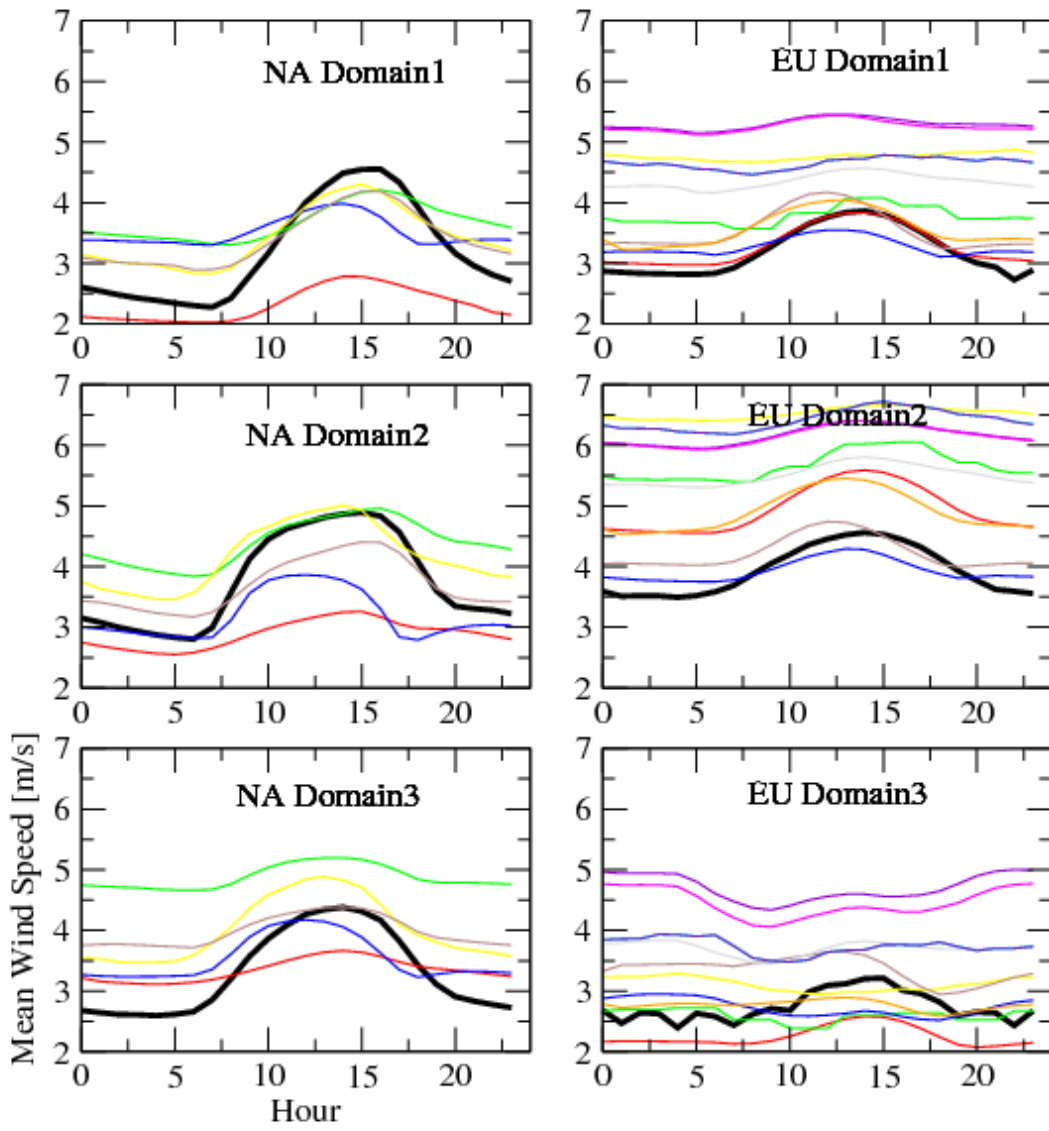


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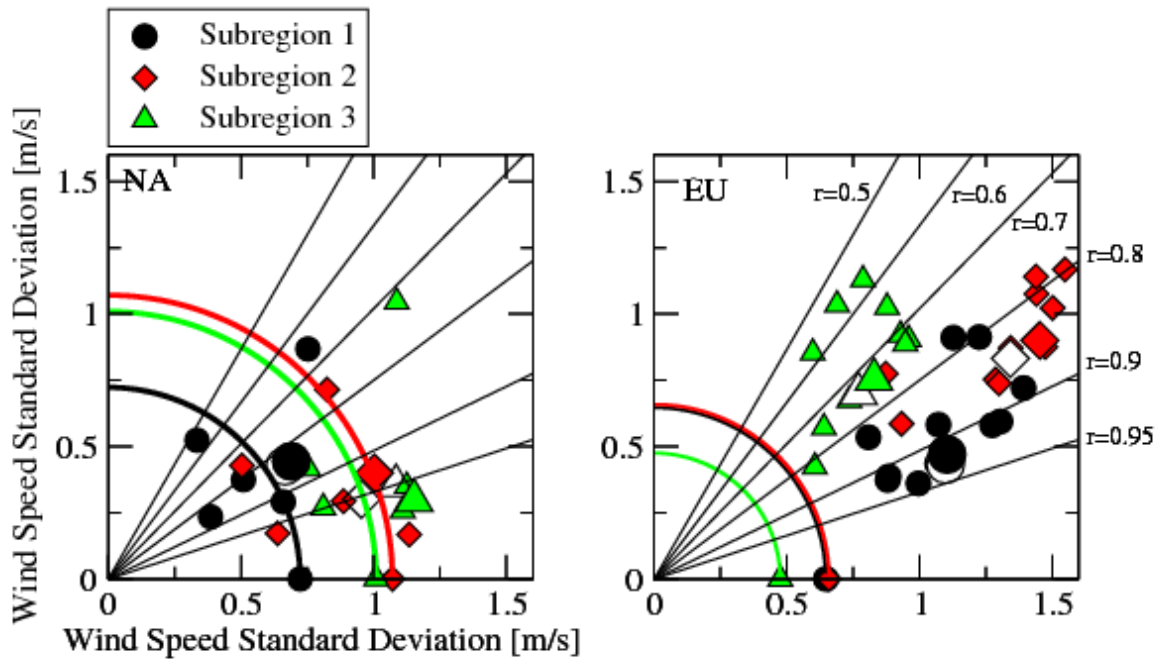


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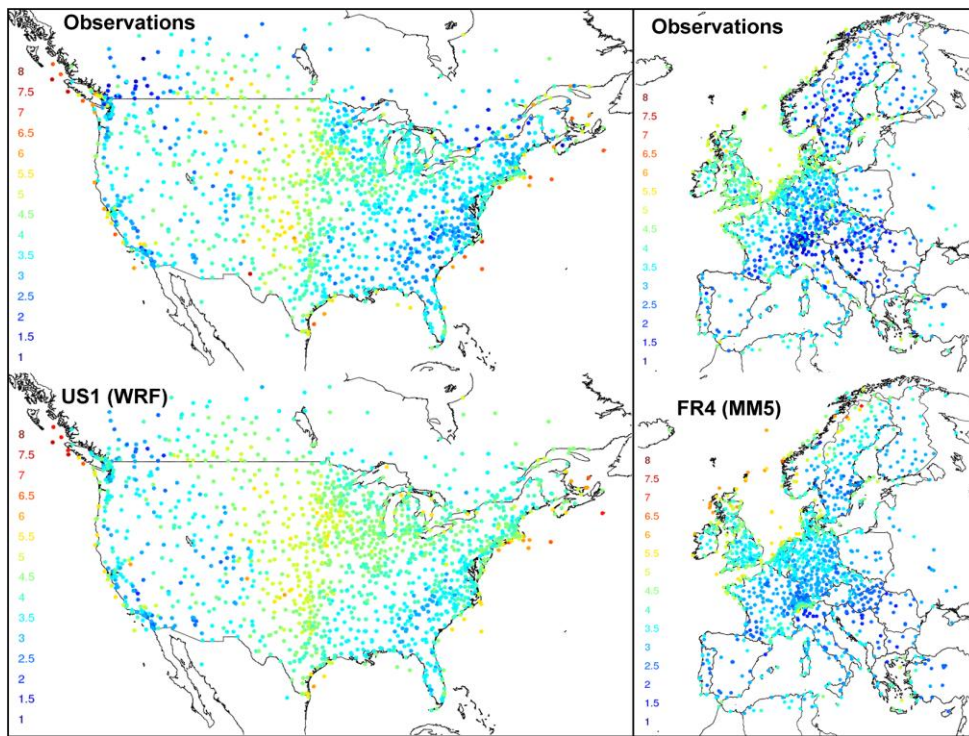


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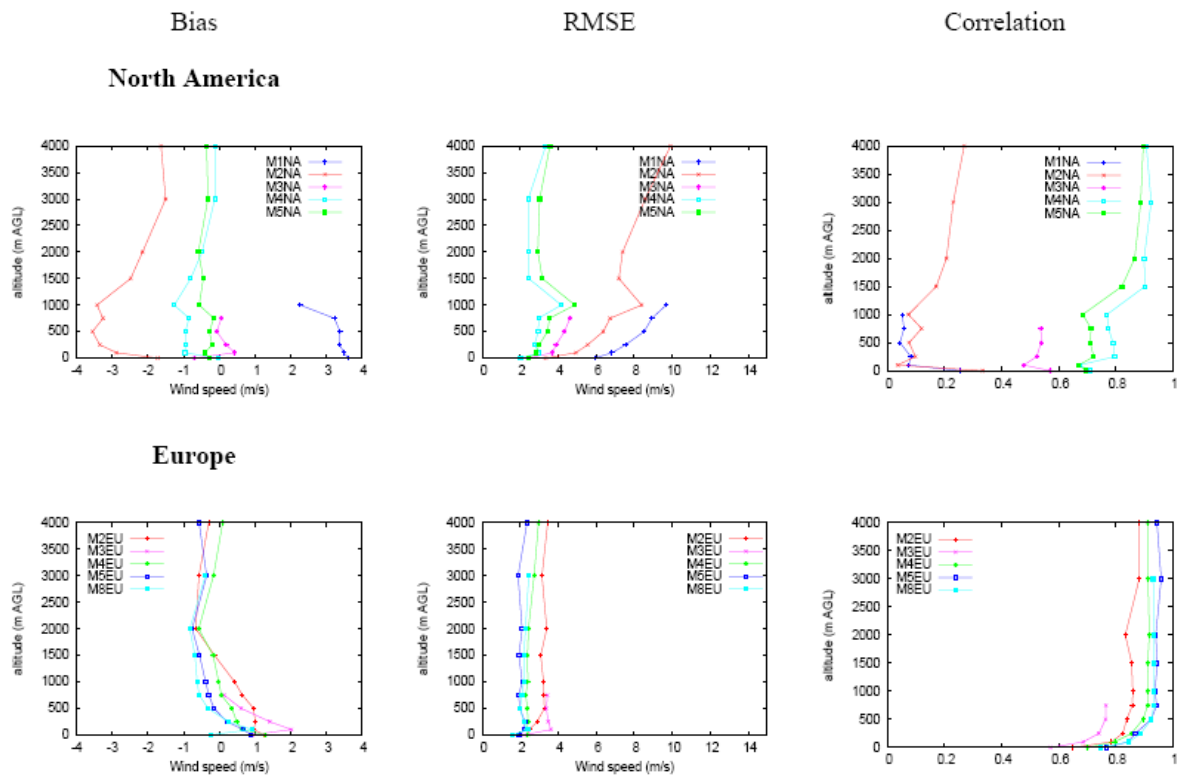


Figure 8

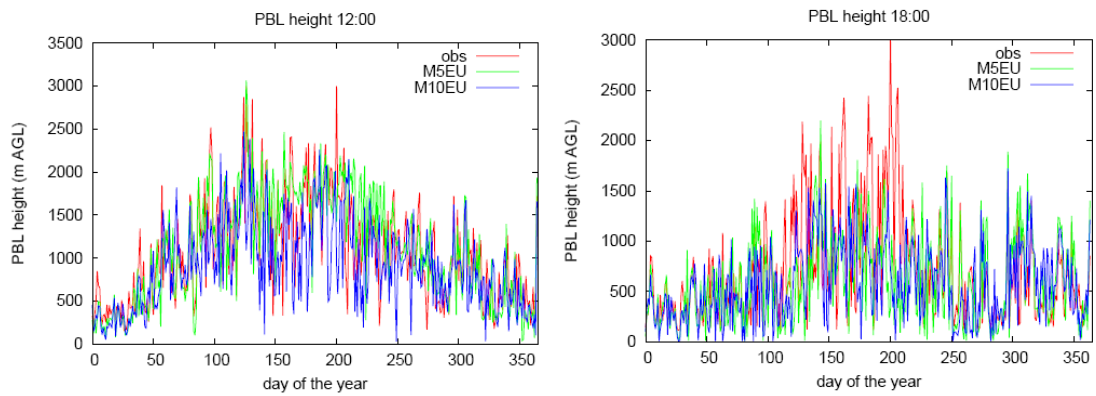


Figure 9



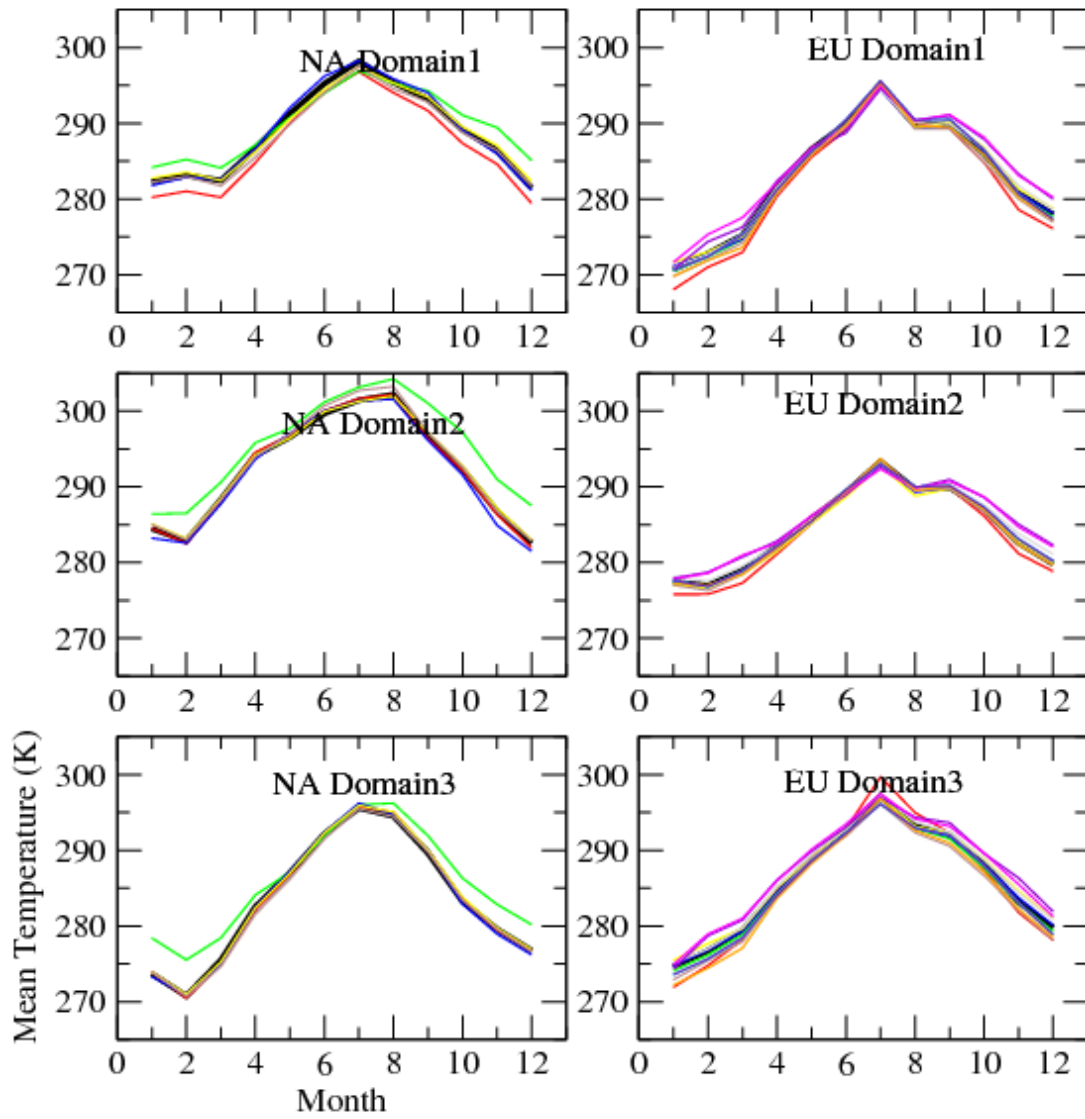


Figure 10

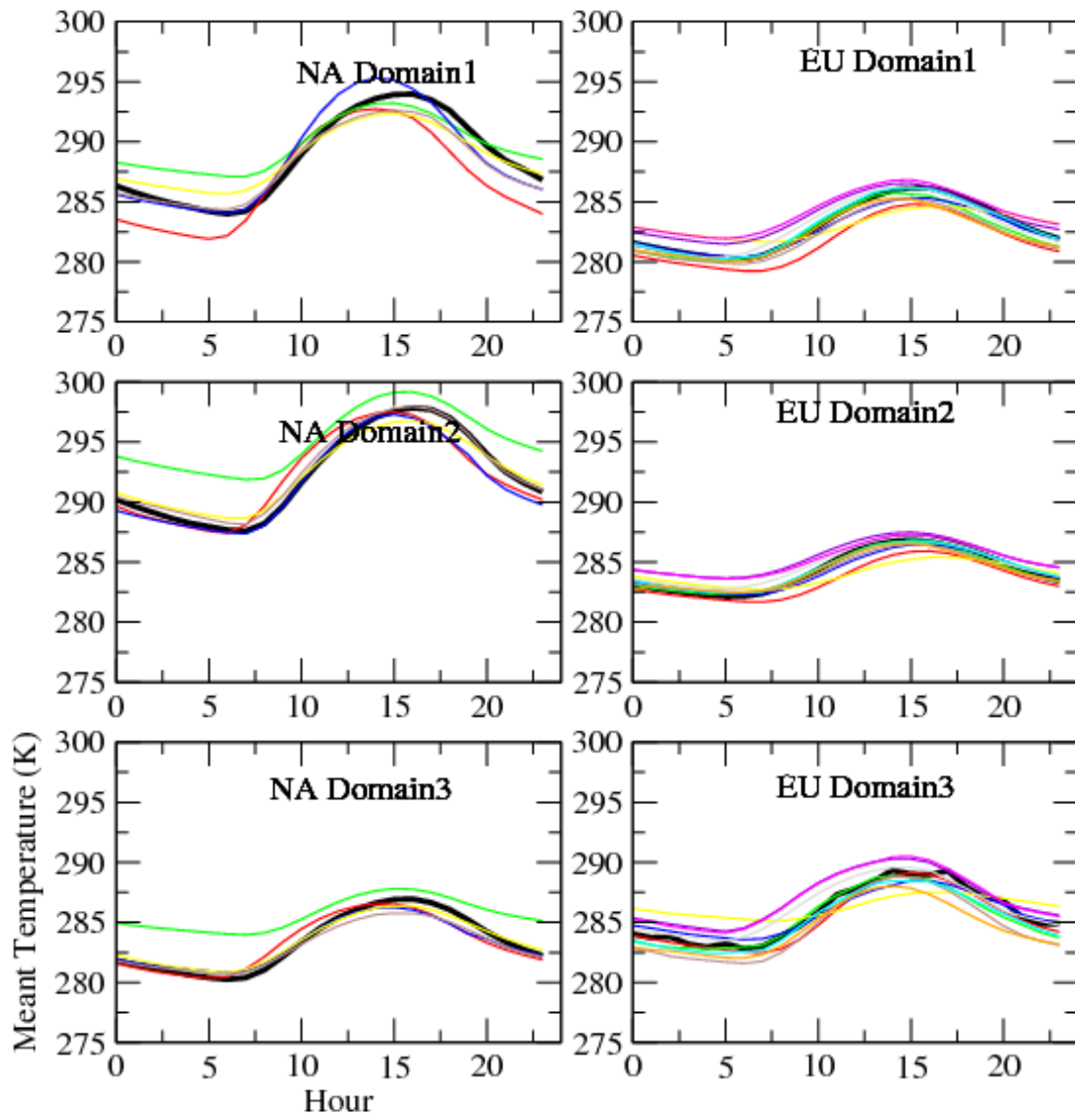


Figure 11

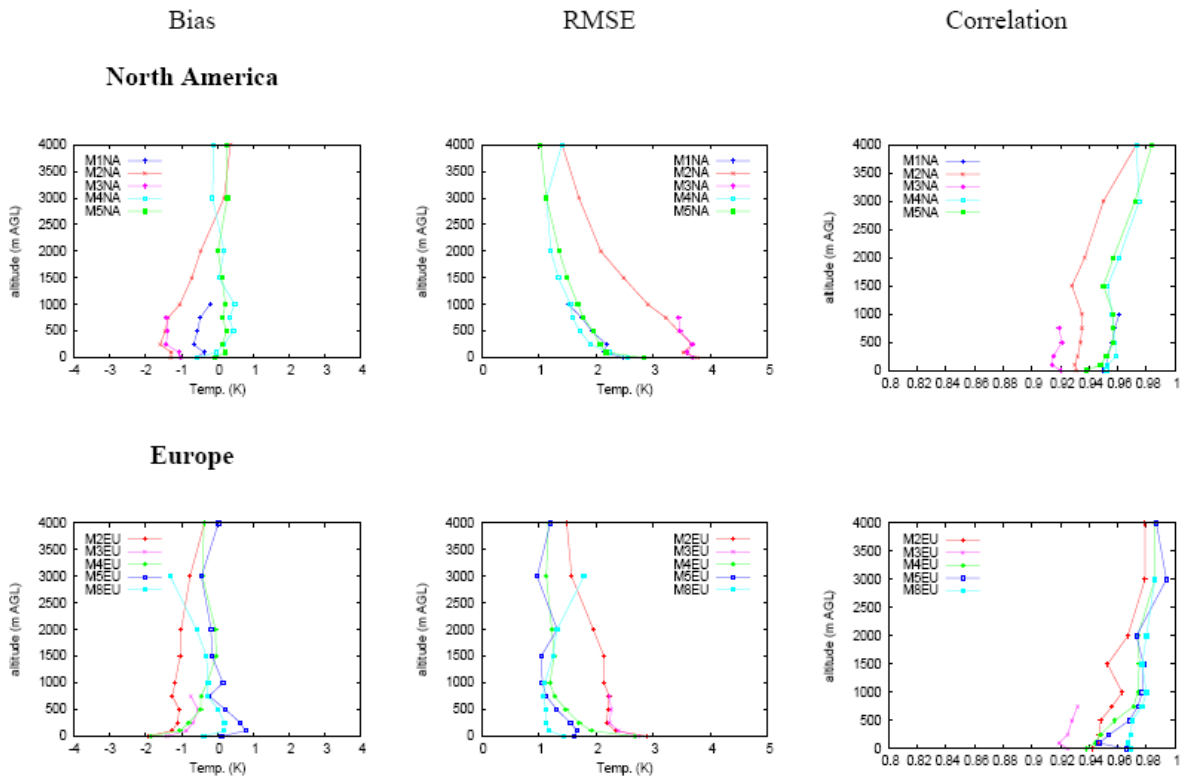


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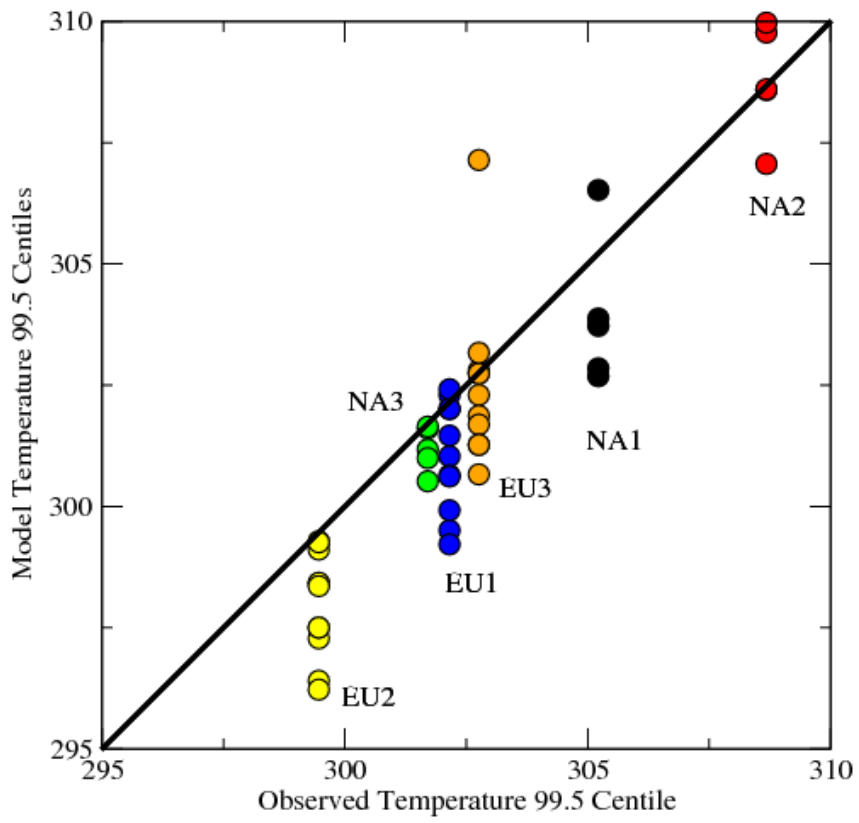


Figure 13

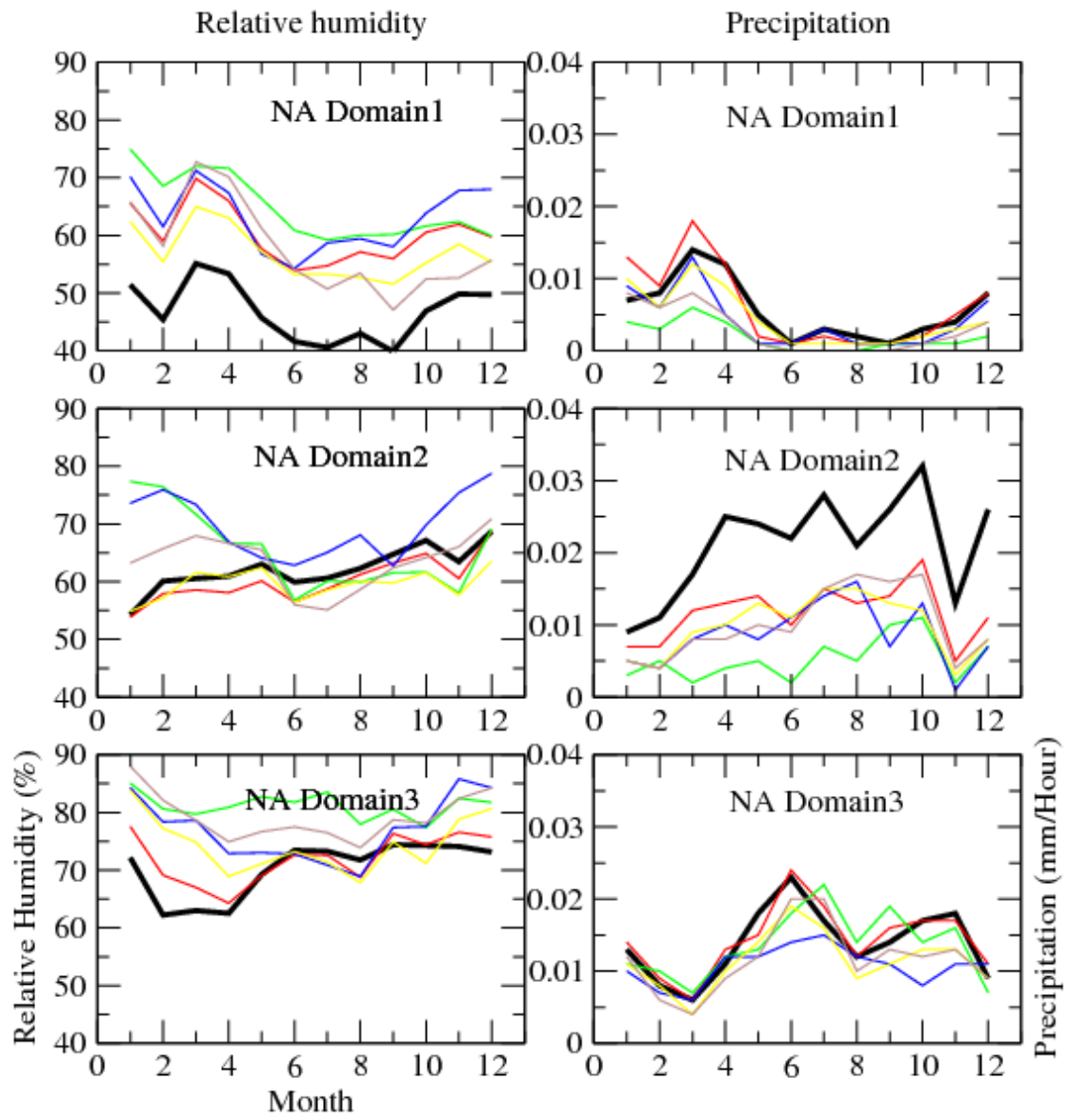


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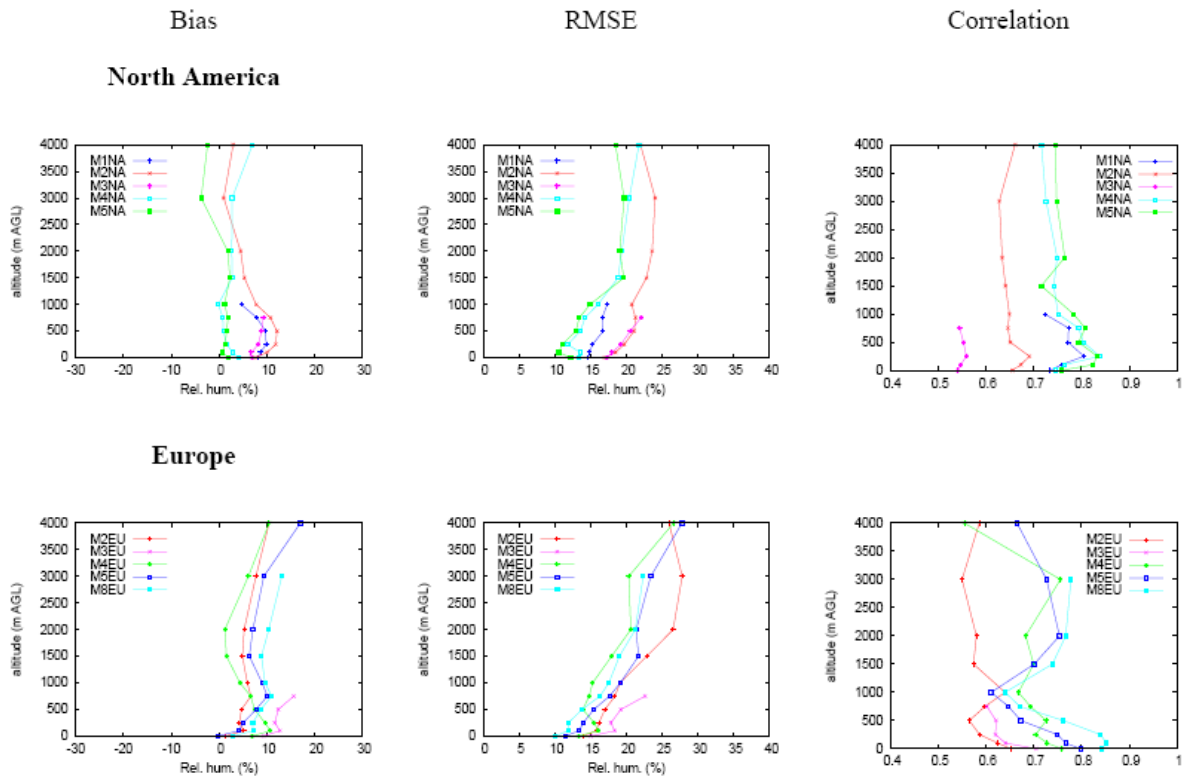


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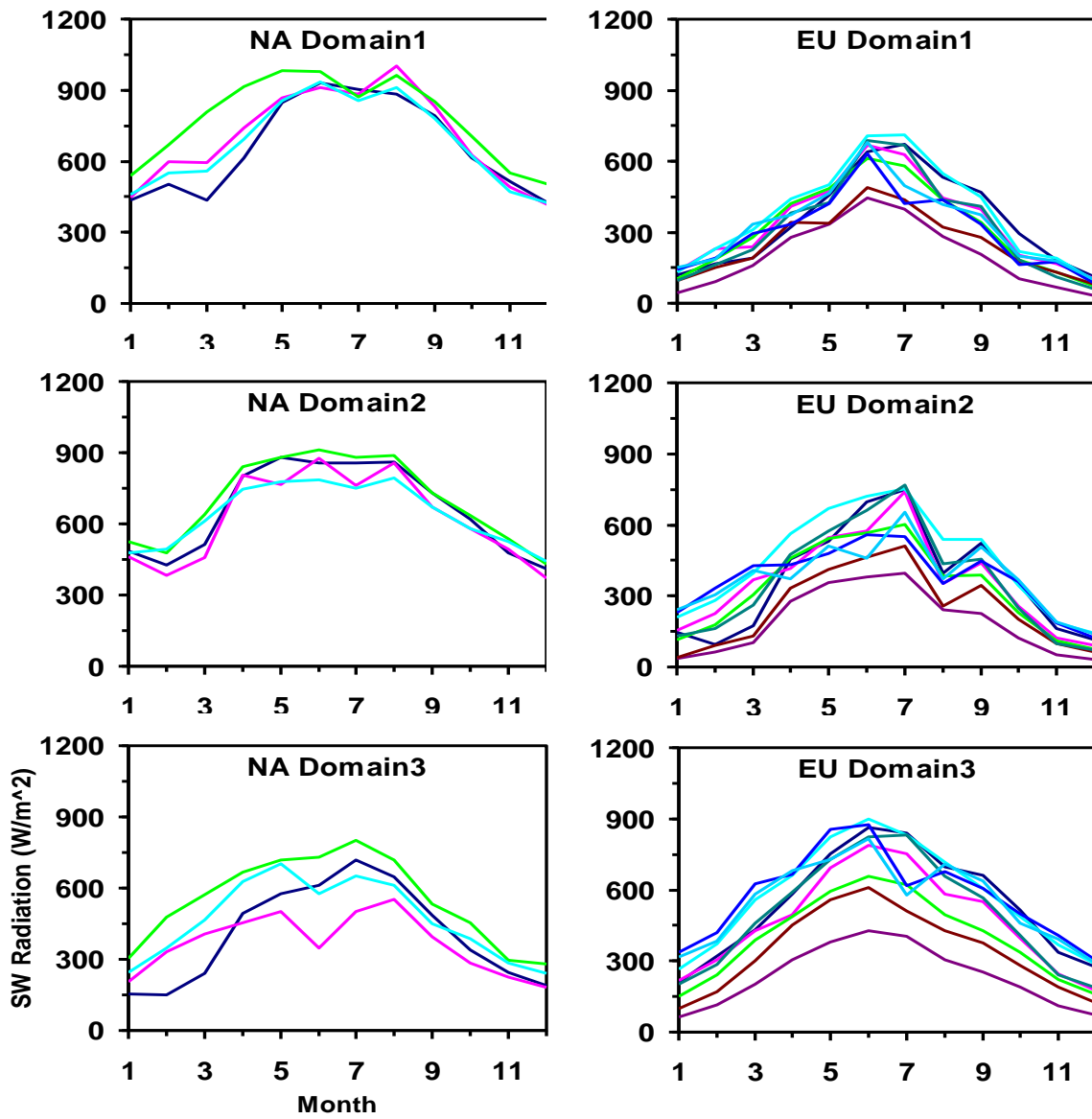


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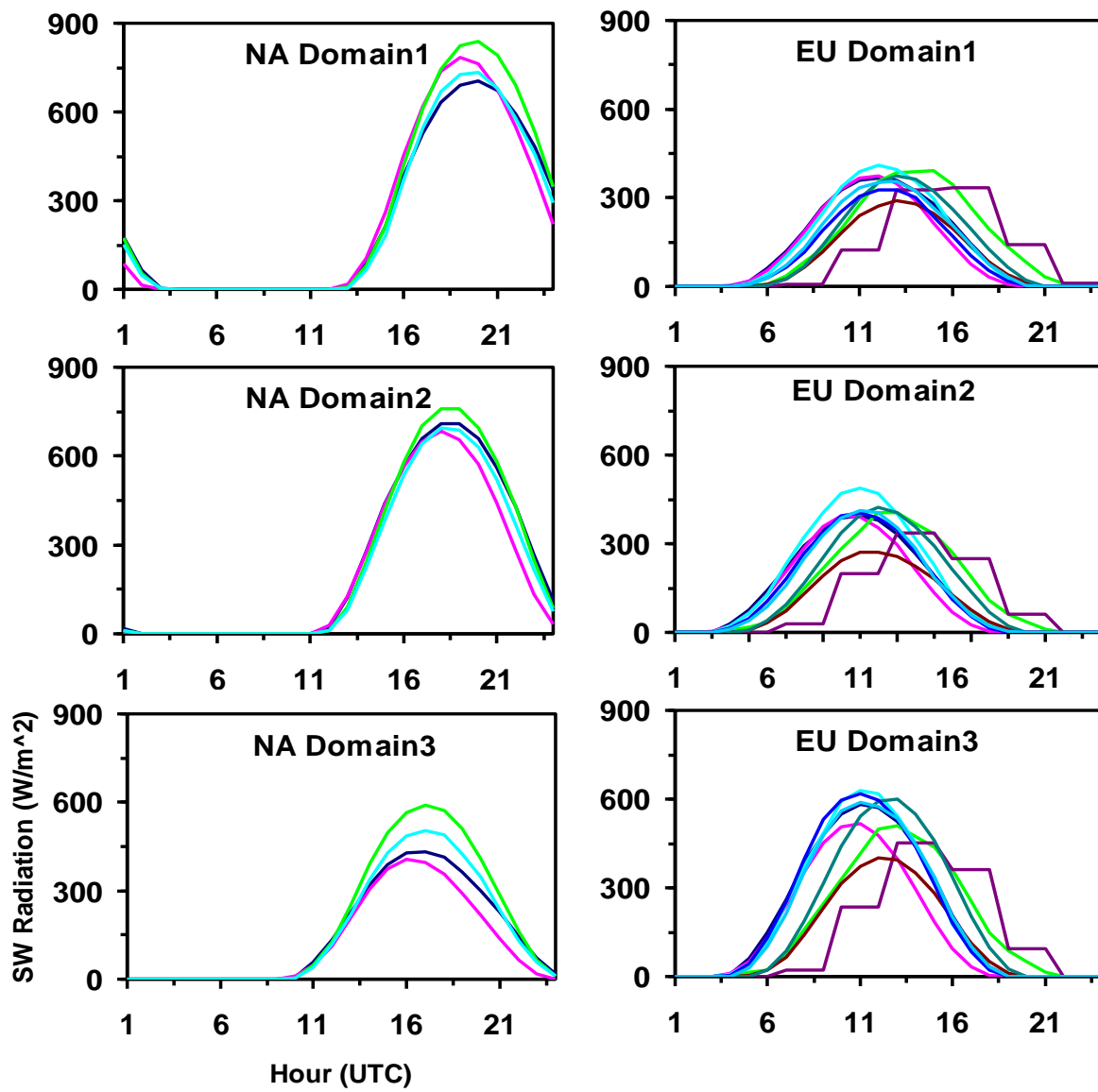


Figure 17



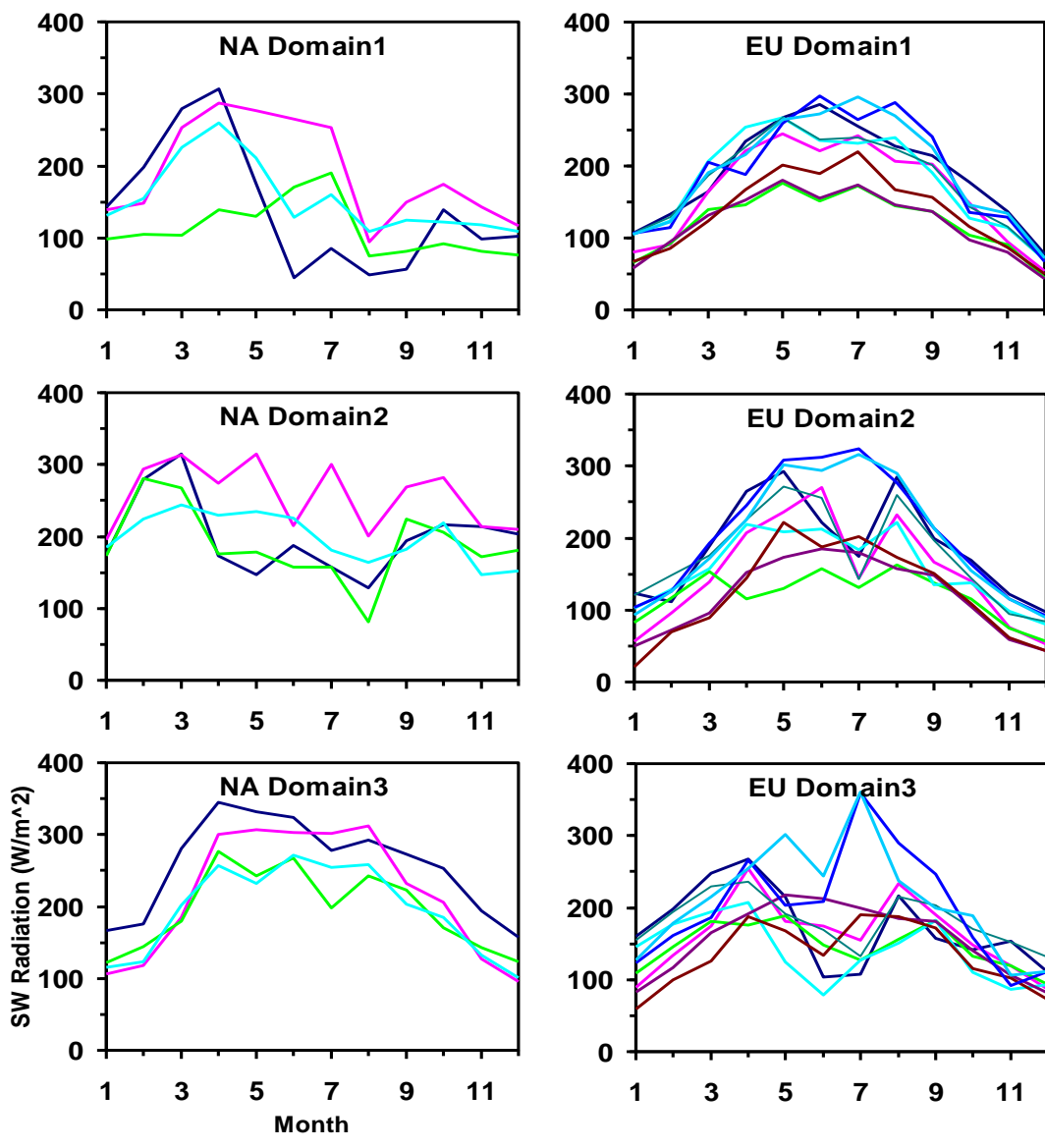


Figure 18

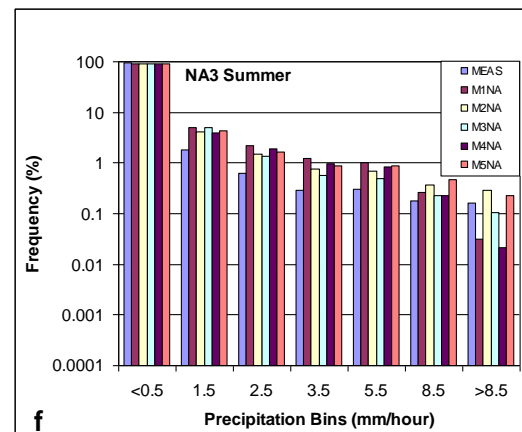
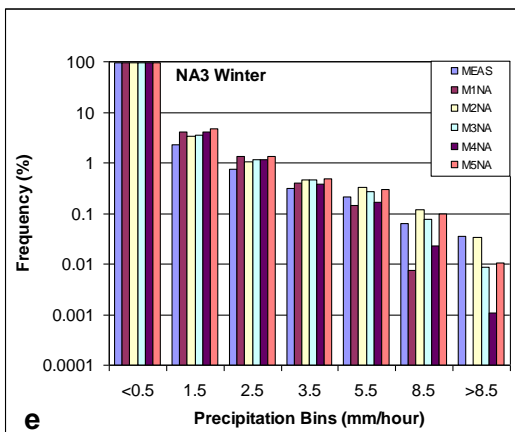
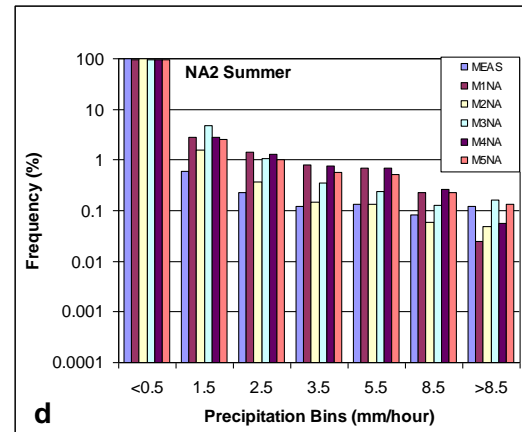
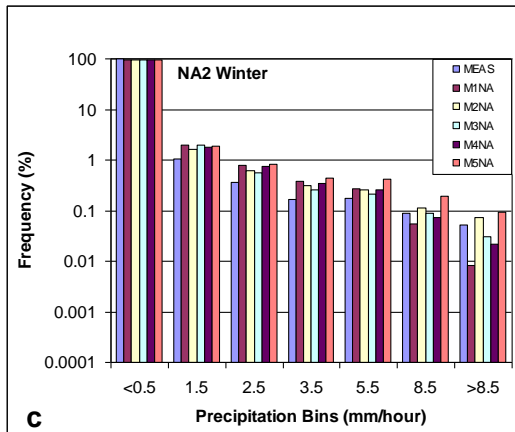
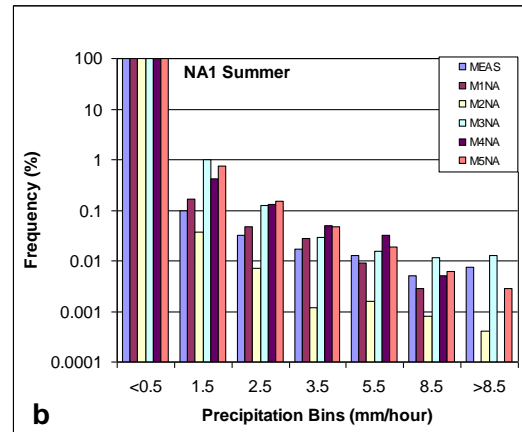
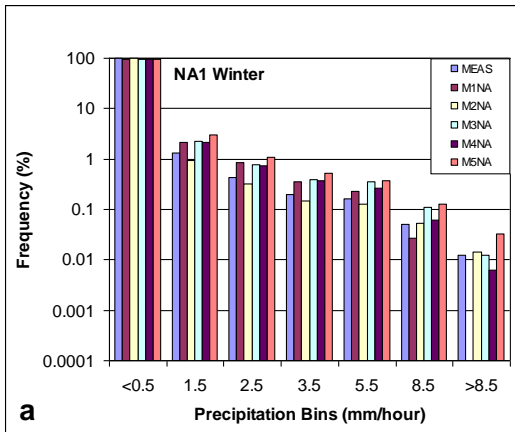


Figure 19

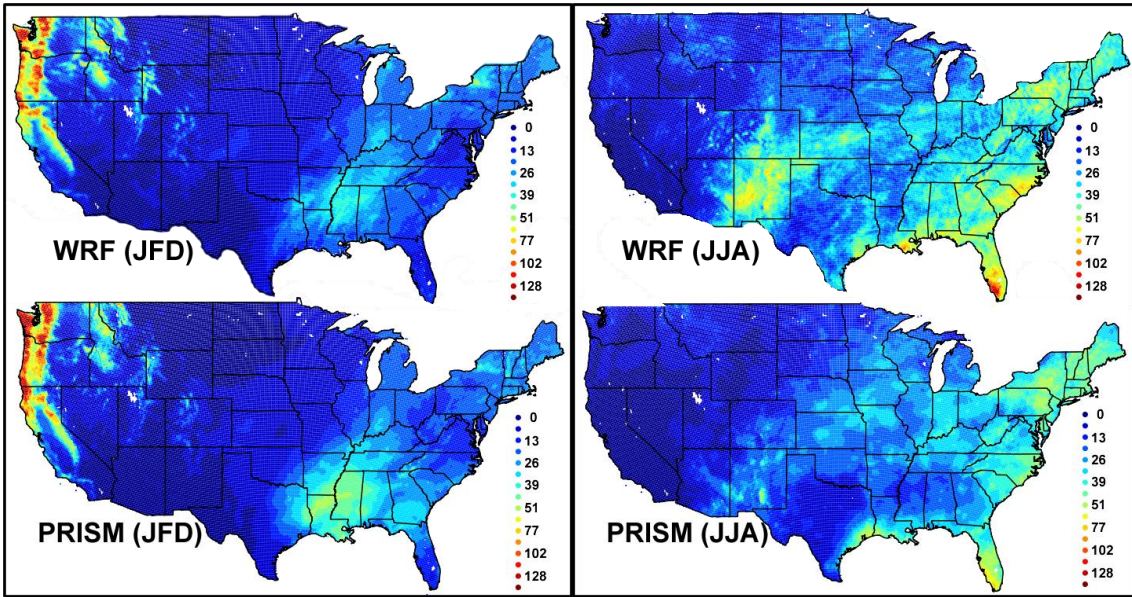


Figure 20