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Implementing Subgrid-Scale Cloudiness into the Model for Prediction Across Scales – Atmosphere (MPAS-A) for Next Generation Global Air Quality Modeling

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1. Objective and Background

The U.S. EPA is developing a next generation air quality modeling system (see J. Pleim talk) utilizing the Model for Prediction Across Scales – Atmosphere (MPAS-A) as its meteorological foundation. Several preferred EPA physics schemes & options were implemented into MPAS-A: the Pleim-Xiu land surface model with fractional land use for a 40-class National Land Cover Database, the Pleim surface layer, the Asymmetric Convective Model 2 planetary boundary layer scheme, and analysis nudging four-dimensional data assimilation (FDDA). This study discusses the effects on air quality-relevant meteorological parameters due to implementing an updated Kain-Fritsch (KF) convection parameterization into MPAS-A that adds subgrid-scale cloud feedback to the radiation schemes and a scale-aware convective time scale.

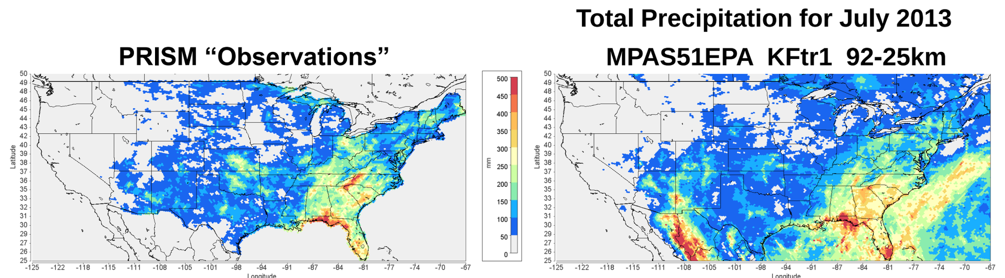
2. Approach

Simulations of July 2013 were conducted on global variable resolution meshes with the higher resolution cells centered over the contiguous United States (CONUS). Driving fields for the FDDA and soil nudging were provided by NOAA/NCEP's GDAS/FNL, GFS, and RUC analyses. Results from MPAS-A simulations utilizing the added EPA physics schemes were evaluated against observations available from NCEP's Meteorological Assimilation Data Ingest System (MADIS) and PRISM data. Simulations presented here are labeled according to:

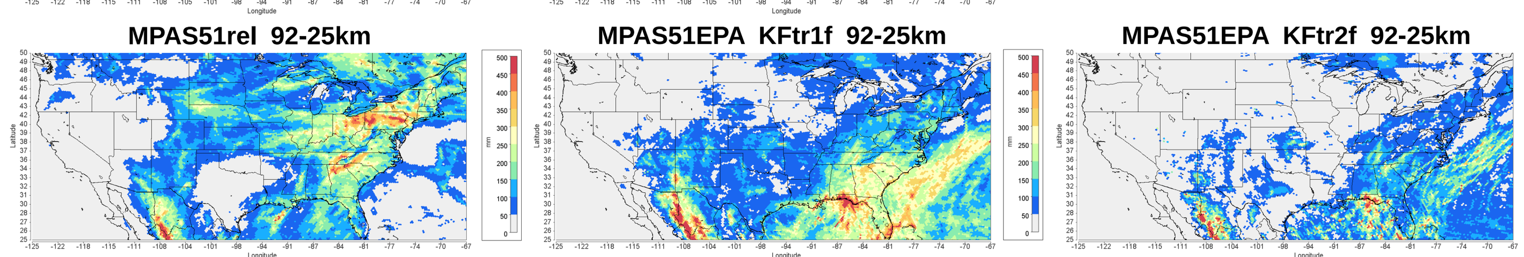
- **MPAS51rel** = unmodified released code version of MPAS-A v5.1 using Noah LSM, M-O sfc. layer, YSU PBL, and KF CPS (based on the default module from WRF v3.2.1);
- **MPAS51EPA** = EPA-modified MPAS-A v5.1 code using all added EPA enhancements and recent KF convection parameterization scheme (based on WRF v3.8.1);
- **KFtr1** or **KFtr1f** = KF using trigger 1 without or with feedback to radiation, respectively;
- **KFtr2** or **KFtr2f** = KF using trigger 2 without or with feedback to radiation, respectively;
- **92-25km** or **46-12km** = two different resolution global variable meshes used in these simulations with seamless mesh refinement to finest resolution over CONUS.

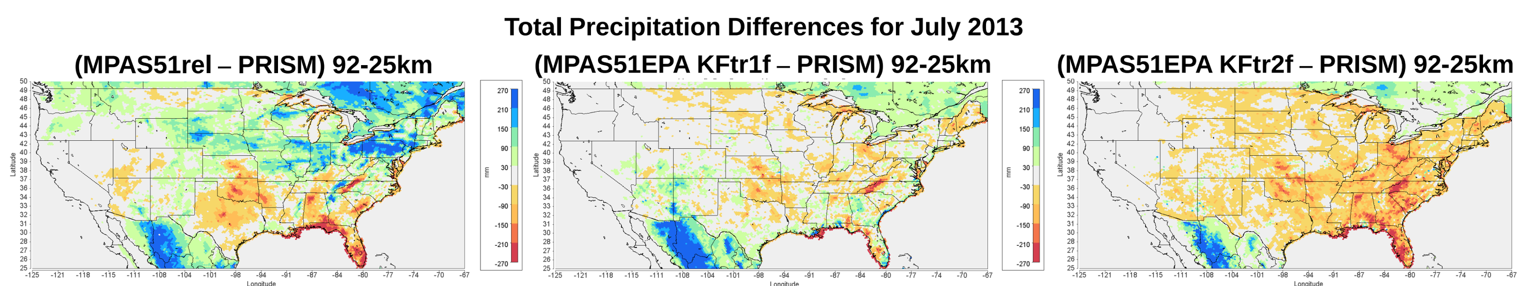
Other options used by all simulations included RRTMG SW and LW radiation schemes (without O_3 climatology), WSM6 microphysics, grid-scale cloud fraction based on relative humidity, SST updates without fractional sea-ice, and no gravity wave drag over orography.

3.1. Results: Precipitation



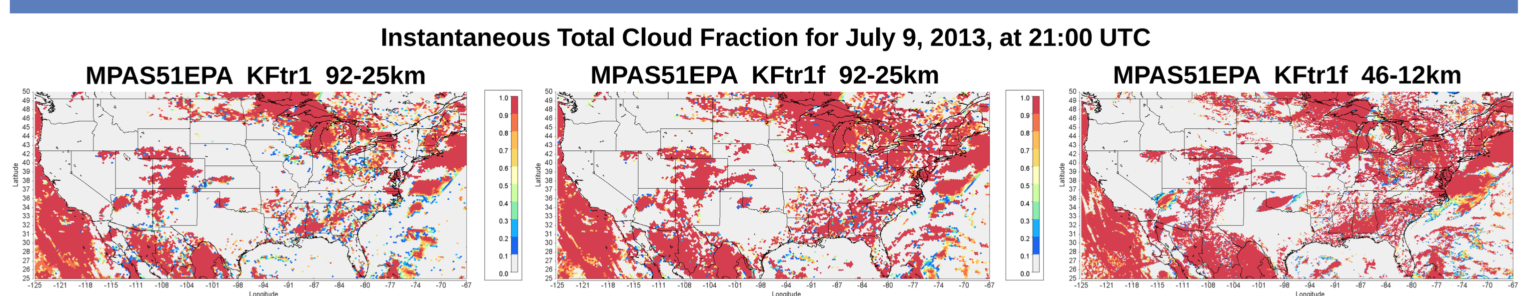
Default KF typically overestimates rainfall due to a lack of cumulus-radiation interactions.



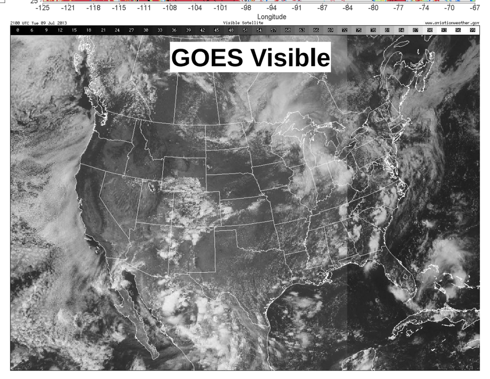


MPAS51rel lacks FDDA, so the general precipitation pattern differs significantly from observations. With FDDA, the other simulations produce patterns similar to PRISM, though selecting KF trigger 2 tends to underestimate the monthly precipitation. Using KF trigger 1 with feedback to radiation (KFtr1f) produces the best match to PRISM.

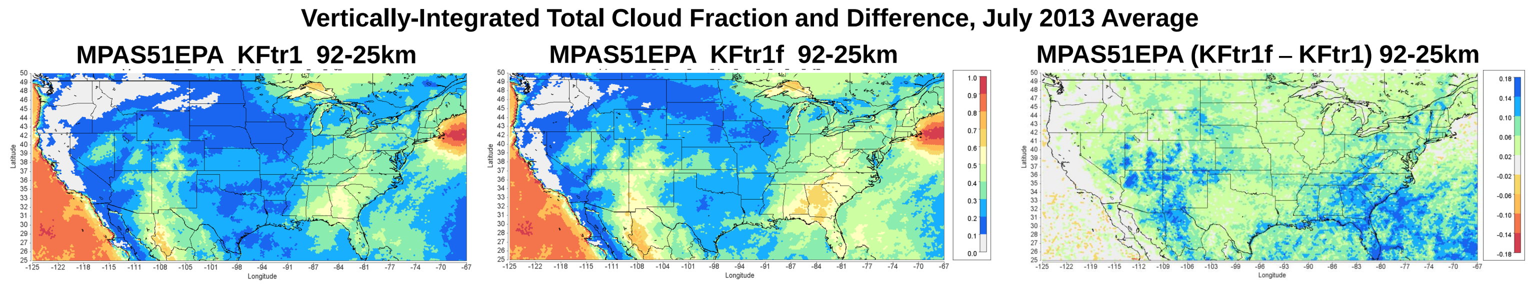
3.2. Results: Cloudiness



Total cloudiness when cumulus-radiation interactions are enabled in MPAS-A (i.e., KFtr1f) shows better agreement with satellite observations in some areas. Note that the vertically-integrated cloud fraction from MPAS-A only denotes the presence of cloud fraction in any layer and does not indicate cloud optical depth.

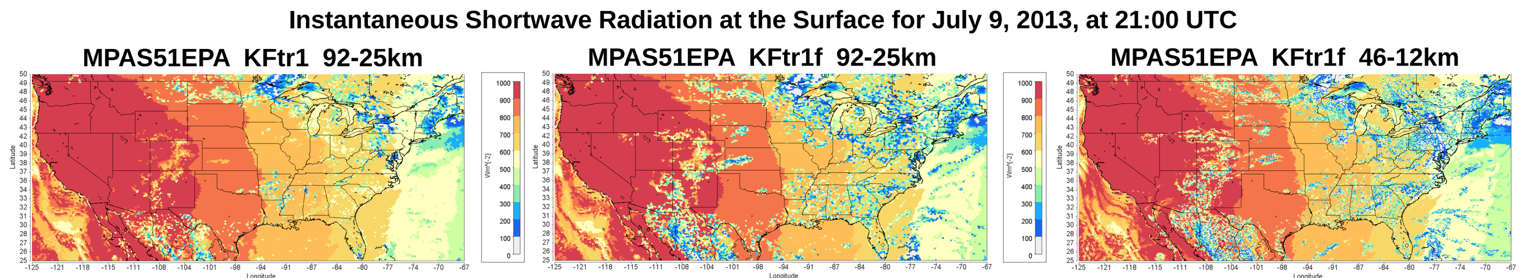


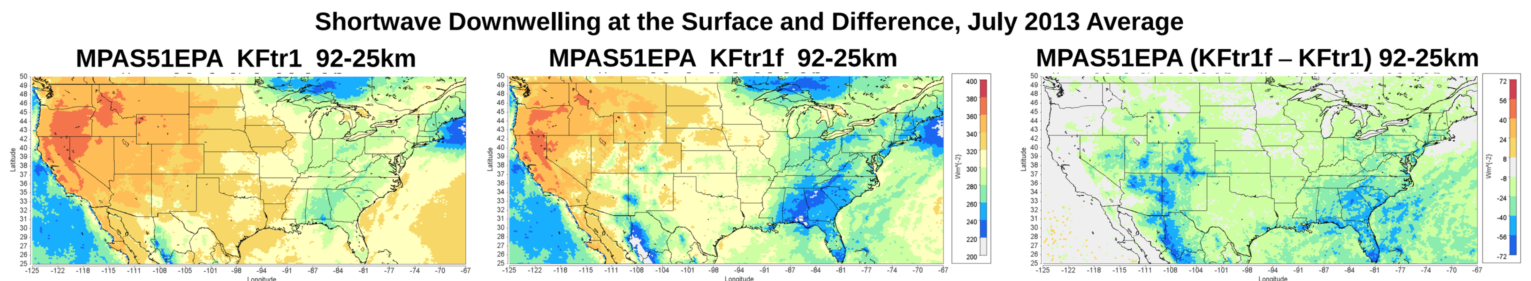
3.2. Results: Cloudiness (cont'd)



Resolved cloud fraction is based on relative humidity (see KFtr1 above). The increase in mean monthly cloudiness when including subgrid-scale cumulus clouds is shown in the KFtr1f and difference figures. For July 2013, average total cloudiness increased nearly everywhere and up to 18% in the Southwest and Southeast U.S. where convection dominated.

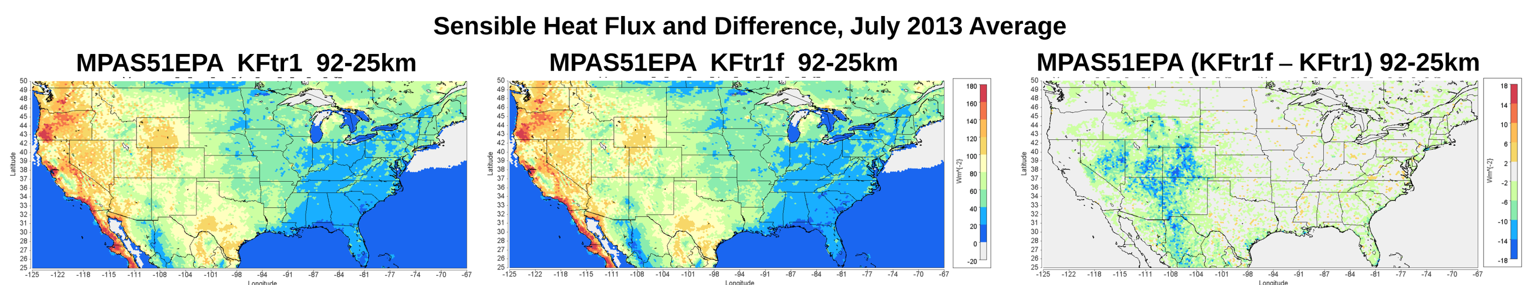
3.3. Results: Shortwave Radiation

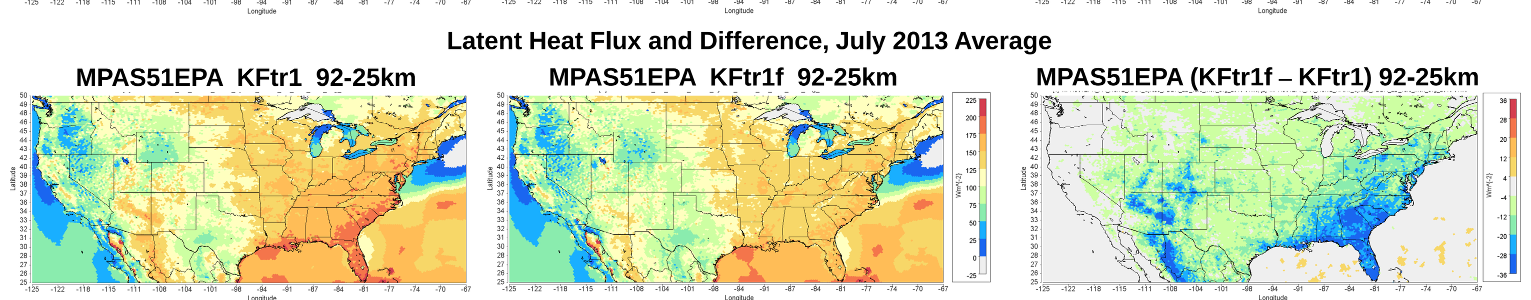




Accounting for the subgrid-scale cumulus cloudiness in addition to the grid-scale resolved cloudiness reduced the average July 2013 shortwave radiation reaching the surface by nearly 20% in the Southwest and Southeast U.S., with a general reduction of at least 8 W m^{-2} over most of the U.S. Note that all temporal averages presented here were calculated over all hours (day and night), somewhat obscuring the effect of the KF feedback compared to restricting the analysis to afternoon hours only, for example. As can be seen here, especially when comparing the instantaneous shortwave figures to the GOES image in Section 3.2, shortwave radiation reaching the surface provides an indication of the simulated cloud optical depth.

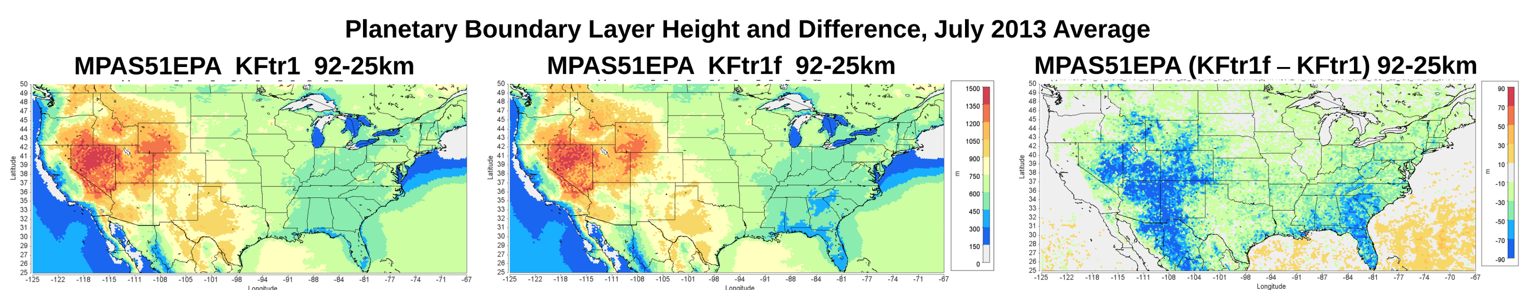
3.4. Results: Sensible & Latent Heat Fluxes





Impacts from enabling KF feedback were also significant for the surface energy budget. The relatively dry ground of the Intermountain West was a factor for the largest reduction in sensible heat flux (HFX) when cumulus clouds were added to the July 2013 simulation, with smaller mixed effects on HFX in the more moist eastern U.S. Areas with more precipitation in the Southwest and Southeast saw average latent heat flux reductions of nearly 25%, along with general reductions of at least 4 W m^{-2} elsewhere in the U.S.

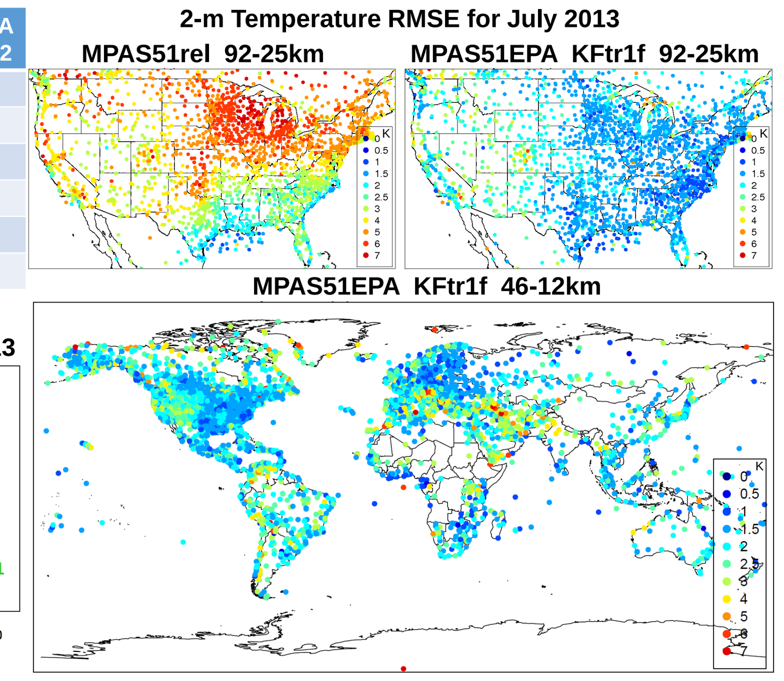
3.5. Results: Planetary Boundary Layer Height

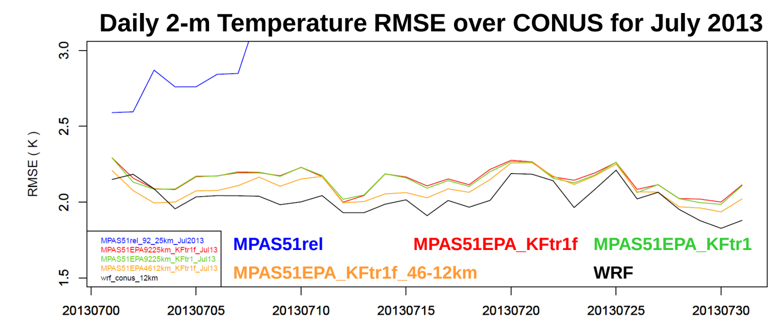


Enabling KF feedback to the radiation schemes also reduced the average planetary boundary layer height (PBLH), which could lead to greater simulated pollutant concentrations due to less dilution of near-surface primary emissions and secondary pollutants. The KFtr1f – KFtr1 PBLH difference plot shows small reductions generally everywhere, but with 10% to nearly 20% reductions over the southern Intermountain West and the Southeast.

3.6. Results: 2-m Temperature

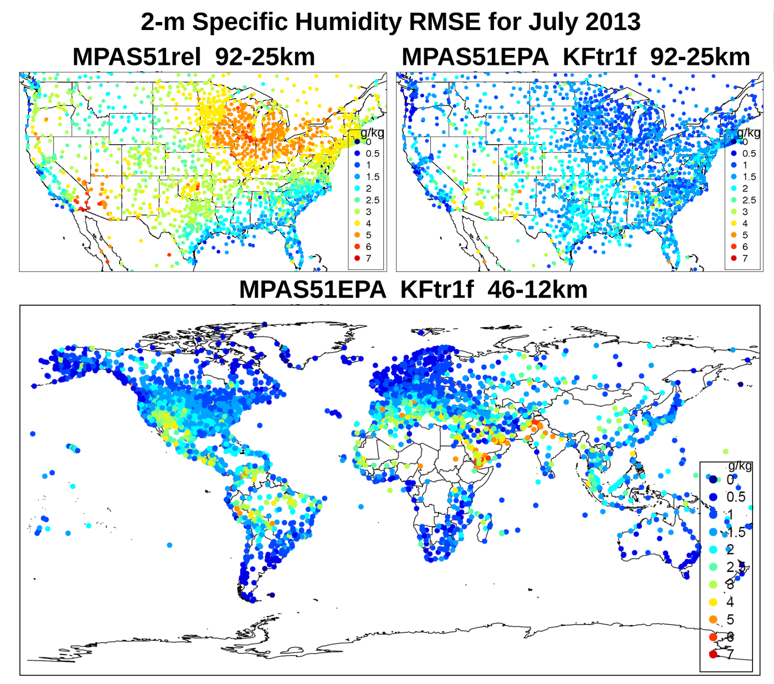
Statistic for CONUS T_{2m}	MPAS51rel 92-25km	MPAS51EPA KFtr1 92-25	MPAS51EPA KFtr1f 92-25	MPAS51EPA KFtr1f 46-12
RMSE (K)	4.692	2.145	2.150	2.095
MAE (K)	3.517	1.588	1.599	1.554
NME (%)	6.952	3.177	3.197	3.109
MB (K)	0.632	0.069	0.002	0.066
NMB (%)	1.249	0.138	0.004	0.132
Corr.	0.694	0.932	0.932	0.935



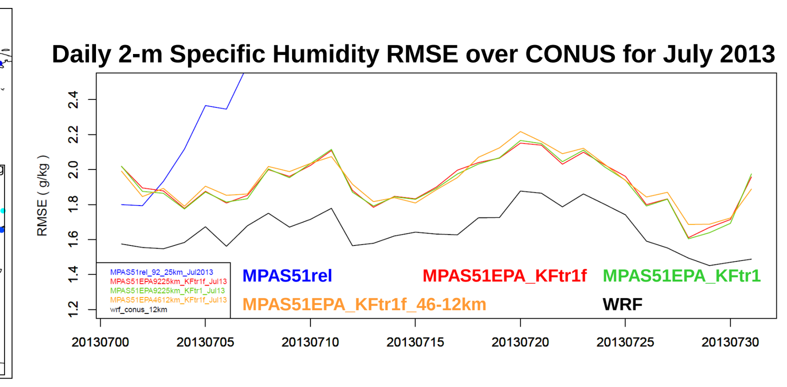


Analyses in Sections 3.6-3.8 utilized AMET v1.3. Here, T_{2m} statistics are much improved when using all of the EPA enhancements compared to the release version of MPAS v5.1.

3.7. Results: 2-m Specific Humidity



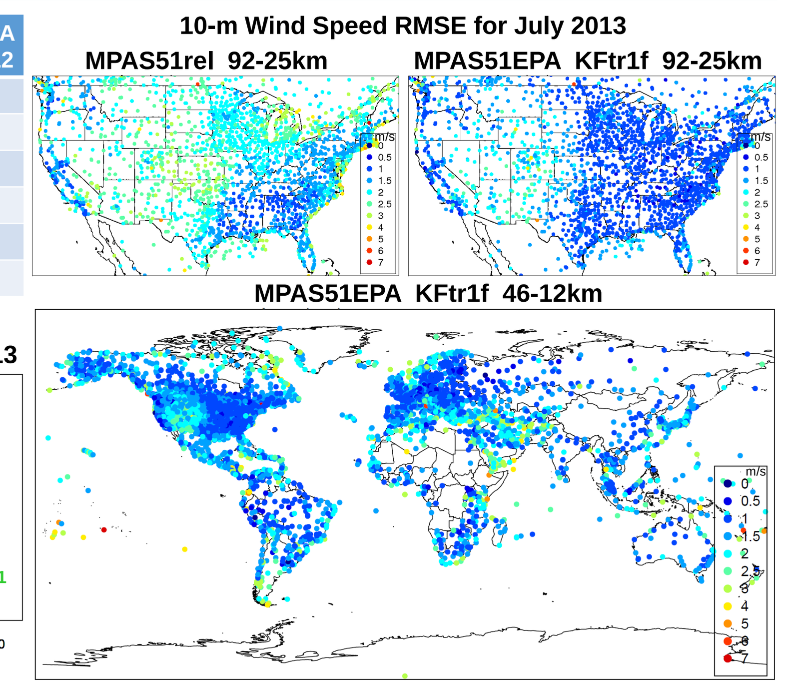
Statistic for CONUS Q_{2m}	MPAS51rel 92-25km	MPAS51EPA KFtr1 92-25	MPAS51EPA KFtr1f 92-25	MPAS51EPA KFtr1f 46-12
RMSE (g/kg)	3.525	1.920	1.924	1.939
MAE (g/kg)	2.690	1.423	1.427	1.447
NME (%)	9.509	4.971	4.986	5.038
MB (g/kg)	0.355	0.229	0.219	0.154
NMB (%)	1.255	0.801	0.764	0.536
Corr.	0.640	0.896	0.900	0.892

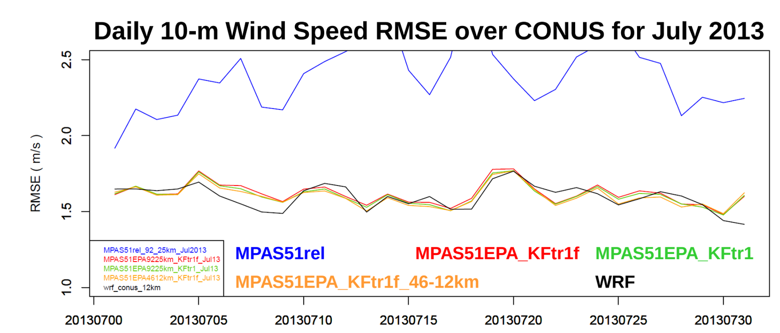


Like T_{2m}, Q_{2m} has a much lower RMSE with the EPA modifications than the default MPAS-A simulation. MPAS51rel would benefit most from FDDA. (WRF was simulated on a 12-km grid.)

3.8. Results: 10-m Wind Speed

Statistic for CONUS WS_{10m}	MPAS51rel 92-25km	MPAS51EPA KFtr1 92-25	MPAS51EPA KFtr1f 92-25	MPAS51EPA KFtr1f 46-12
RMSE (m/s)	2.412	1.612	1.622	1.604
MAE (m/s)	1.823	1.160	1.164	1.157
NME (%)	2.060	1.312	1.316	1.308
MB (m/s)	0.300	-0.089	-0.137	-0.108
NMB (%)	0.339	-0.101	-0.154	-0.122
Corr.	0.242	0.583	0.578	0.590





WS_{10m} also improved using the EPA enhancements. As with Q_{2m}, the MPAS51EPA runs generally agree with each other in the RMSE time series, even with 12-km WRF in this case.

4. Conclusions

- The following EPA physics enhancements and options were successfully implemented into MPAS-A v5.1: PX LSM with NLCD40 fractional land use and MODIS-based initialization of deep soil moisture; PSL; ACM2 PBL; KF v3.8.1 with feedback to radiation, scale-aware convective time scale, extended lookup table; FDDA analysis nudging; a custom vertical grid.
- These EPA enhancements improved statistical agreement with observations.
- KF trigger 1 with feedback to radiation reproduced July 2013 PRISM precipitation best.
- Enabling KF feedback to radiation exhibited the expected impacts to air quality-relevant MPAS-A model variables, mainly by reducing the solar radiation shining on wet ground under simulated precipitating convective clouds.
- All EPA enhancements (including KF v3.9.1) have now been implemented into MPAS-A v5.2.

U.S. Environmental Protection Agency
Office of Research and Development