Evaluation of Cumulus Cloud – Radiation Interaction Effects on Air Quality-Relevant Meteorological Variables from WRF, from a Regional Climate Perspective

Jerold Herwehe, Kiran Alapaty, Tanya Otte, Chris Nolte, and Russ Bullock

National Exposure Research Laboratory, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina

www.epa.gov

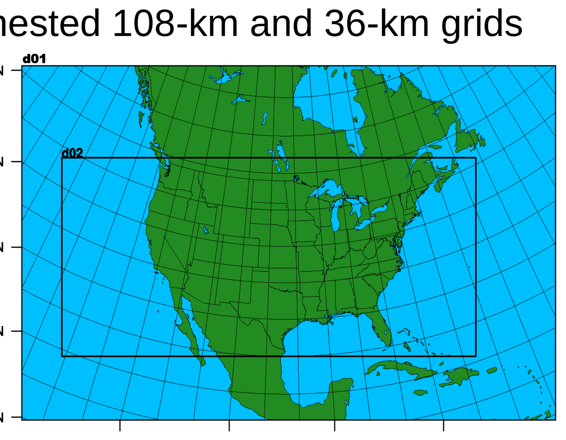
Jerold A. Herwehe | herwehe.jerry@epa.gov | 919-541-0166

1. Background

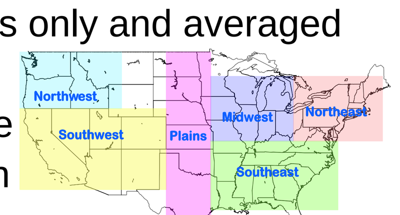
Although the Weather Research and Forecasting model (WRF) accounts for resolved clouds, WRF does not consider interactions between subgrid-scale convective clouds and radiation. This omission is one reason WRF overestimates surface precipitation during summer. To address this problem, WRF has been modified to provide cloudiness and condensate feedbacks from the Kain-Fritsch (KF) convection parameterization to the Rapid Radiative Transfer Model – Global (RRTMG) radiation schemes to allow the subgrid cumulus clouds, along with the resolved clouds, to affect shortwave (SW) and longwave (LW) radiative processes (Alapaty et al., *Geophys. Res. Lett.*, 2012; Herwehe et al., in preparation). The addition of subgrid cloud – radiation interactions to WRF has implications for the meteorological parameters used to drive air quality models.

2. Approach

Three-year (1988-1990) regional climate simulations were conducted using WRF v3.5 without (**Base** case) and with the subgrid cloud – radiation interactions (**Modified** case). All simulations used KF convection, WSM6 microphysics, RRTMG SW and LW radiation, Noah land-surface model, YSU planetary boundary layer (PBL) scheme, 34 layers, 50 hPa domain top, and two-way nested 108-km and 36-km grids (**d01** and **d02** domains, respectively→).



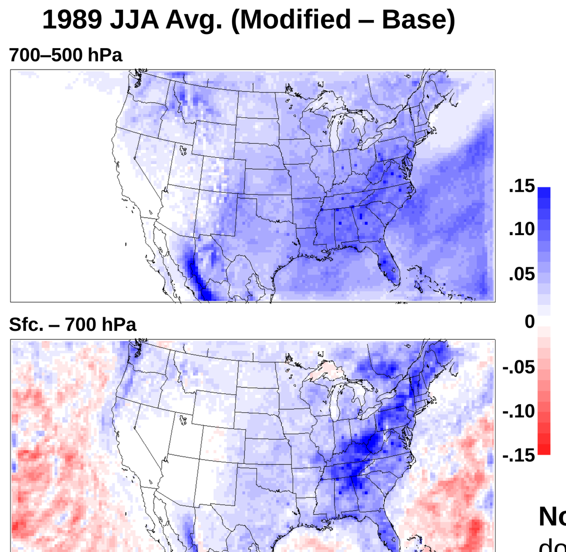
Initial and boundary conditions came from NCEP-DOE AMIP-II Reanalysis (R-2) data, which also provided fields for FDDA analysis nudging of wind, temperature, and moisture above the PBL. Temporal averages shown in this study include all hours (day and night). Time series were computed for land points only and averaged over each of the six regions shown (→); time series for only the **Southeast** U.S. (SE) region are shown in this study. Evaluation was conducted on results from the 36-km grid (**d02**) via comparison with reanalysis data, such as the North American Regional Reanalysis (NARR) and the Climate Forecast System Reanalysis (CFSR), and with observations, such as the Clouds and the Earth's Radiant Energy System (CERES) and the Surface Radiation network (SURFRAD) data sets.



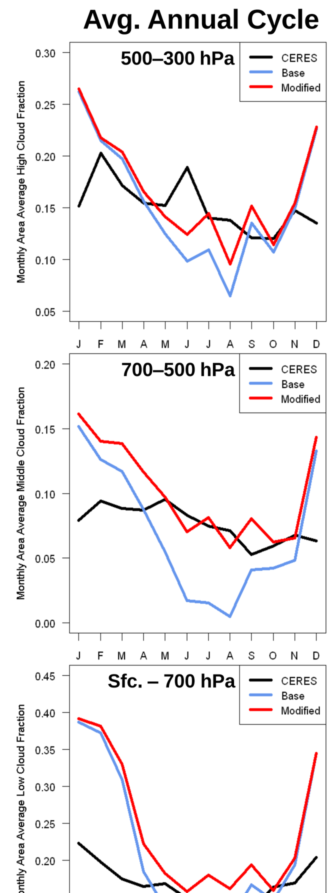
3.1. Results: Cloudiness

The Modified case shows increased cloudiness during the warm months when convection is active, in better agreement with CERES observations in the SE, and improves afternoon cloudiness. WRF overestimates cloudiness in winter.

Cloud Fraction Differences 1989 JJA Avg. (Modified – Base)

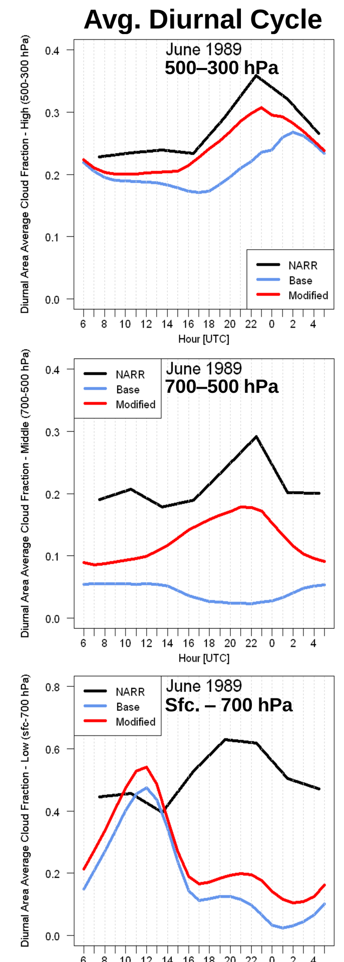


Cloud Fraction Avg. Annual Cycle



Note: CERES data time period does not match the simulations; for qualitative comparison only.

Cloud Fraction Avg. Diurnal Cycle

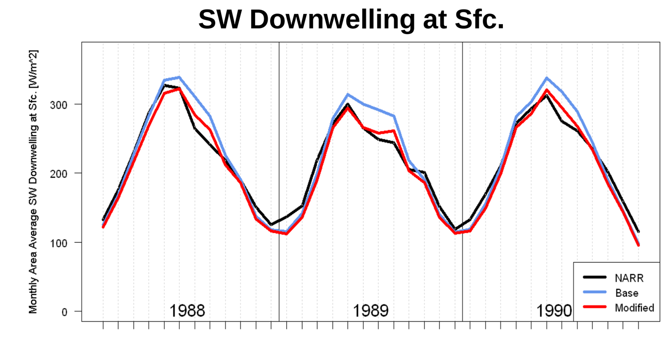


Note: NARR low, middle and high cloud layers are defined differently than in our analysis, but are still useful for temporal study.

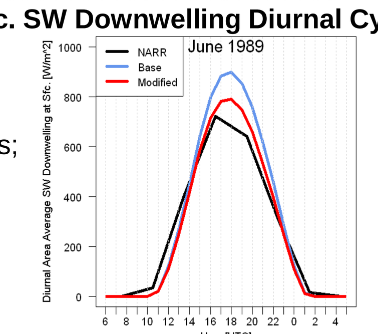
3.2. Results: Shortwave Radiation

The addition of subgrid cloudiness in the Modified case reduces the bias of the SW radiation during the warm months in the SE. More clouds and less SW radiation means reduced photolysis.

SW Downwelling at Sfc.

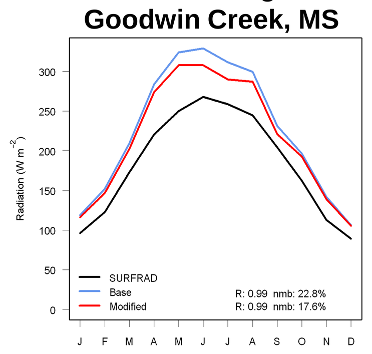


Sfc. SW Downwelling Diurnal Cycle



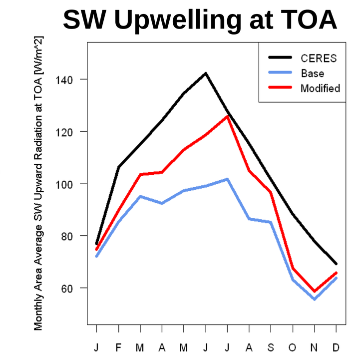
Note: NARR data are available at 3-h intervals; NARR radiation values are 3-h averages.

SW Downwelling at Sfc. Goodwin Creek, MS

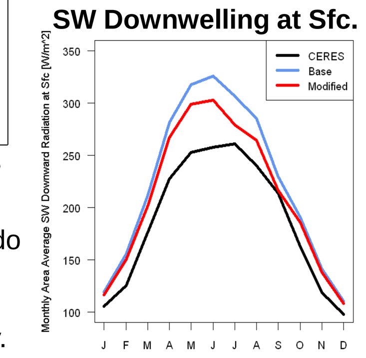


Note: SURFRAD and CERES data time periods do not match the simulations; annual cycles are for qualitative comparison only.

SW Upwelling at TOA



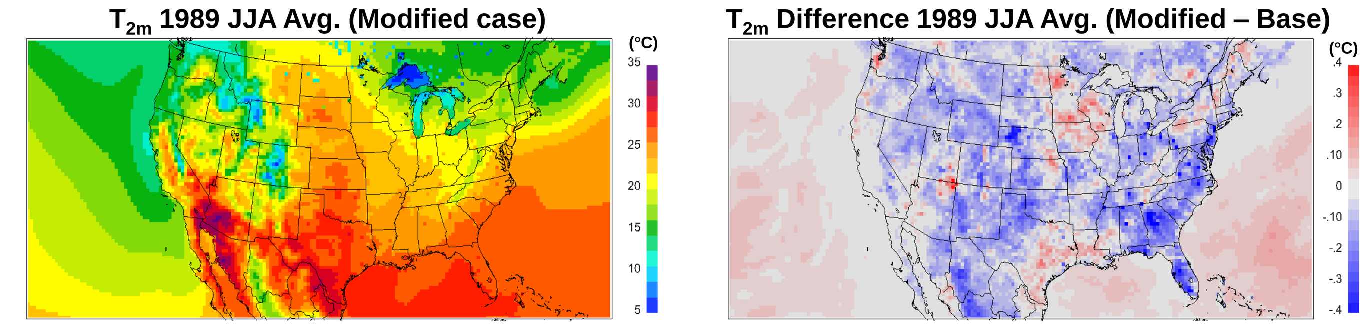
SW Downwelling at Sfc.



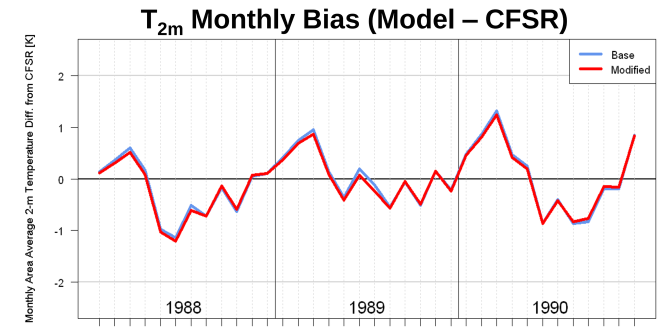
3.3. Results: 2-m Temperature

As expected, the addition of cumulus cloudiness in the Modified case also reduces T_{2m} in the SE (and other areas) during summer, as shown below. By averaging over all hours, the T_{2m} differences (Modified – Base) are quite small, but cooler midday and slightly warmer nocturnal temperatures result.

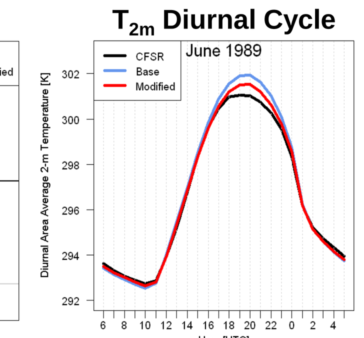
T_{2m} 1989 JJA Avg. (Modified case) / **T_{2m} Difference 1989 JJA Avg. (Modified – Base)**



T_{2m} Monthly Bias (Model – CFSR)



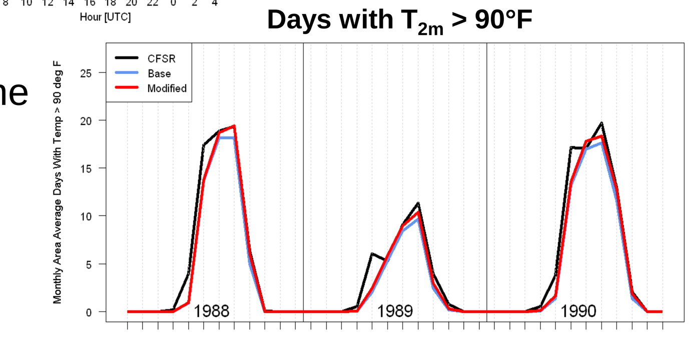
T_{2m} Diurnal Cycle



For the SE, the Modified case shows little change in bias, but cooler afternoons could reduce biogenic emissions.

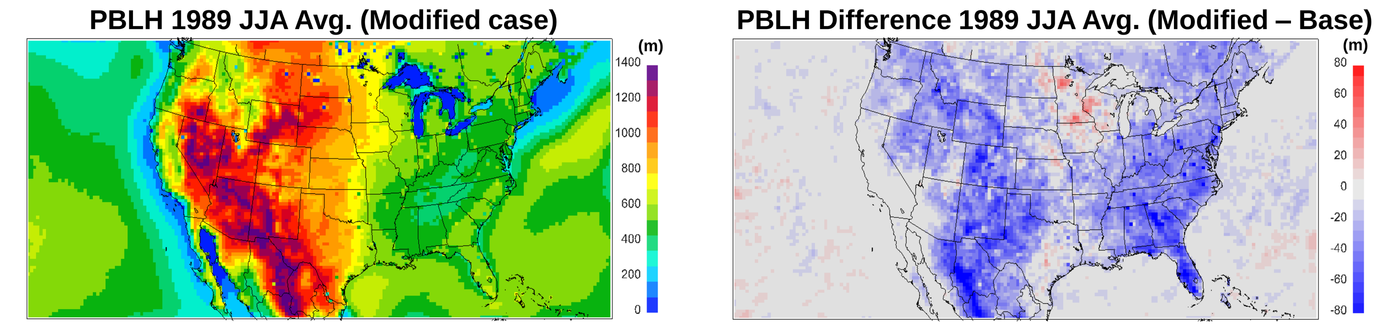
As heat waves are correlated with high ozone (O_3) episodes, the improvement in extreme heat days simulated by the Modified case may produce more exceedance days when driving subsequent air quality simulations.

Days with T_{2m} > 90°F



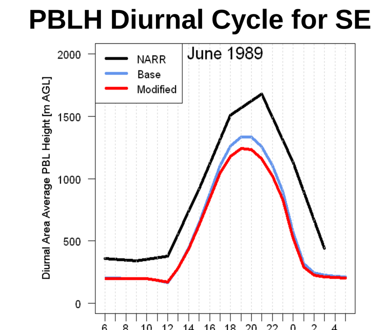
3.4. Results: Planetary Boundary Layer Height

PBLH 1989 JJA Avg. (Modified case) / **PBLH Difference 1989 JJA Avg. (Modified – Base)**



As much as a 10% reduction in seasonally-averaged PBL height is evident in the SE for the Modified case, as a consequence of accounting for the addition of subgrid cloudiness and its concurrent reduction in surface insolation and surface layer instability. A shallower PBL would mean less dilution of surface emissions and precursors, potentially yielding greater concentrations of pollutant reaction products (like O_3).

PBLH Diurnal Cycle for SE

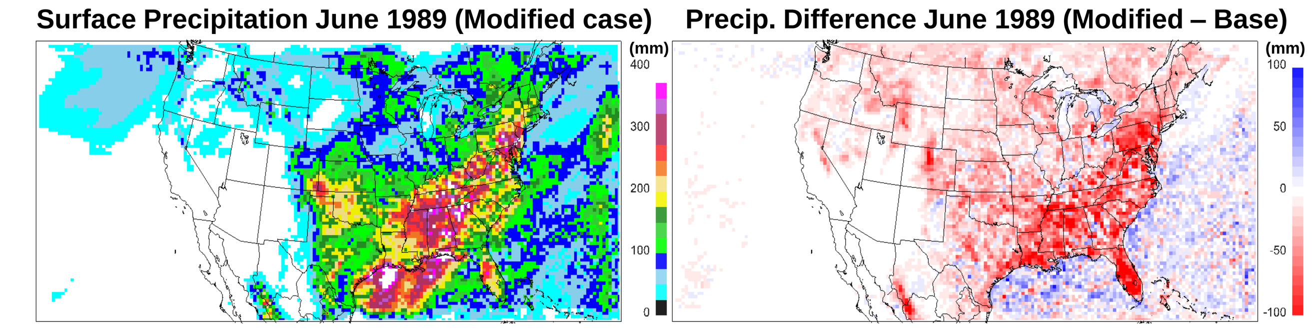


Note: NARR uses a different formulation to diagnose PBL height than that provided by the YSU PBL scheme in WRF.

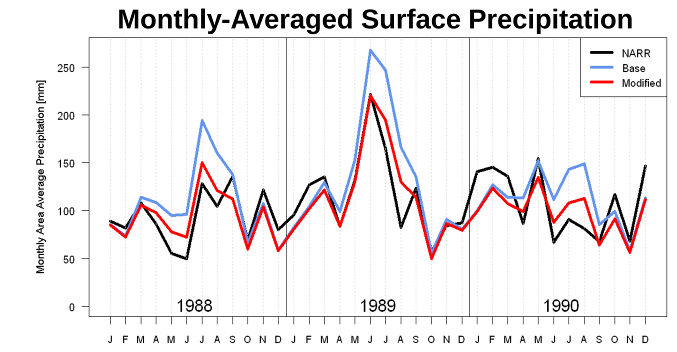
3.5. Results: Precipitation

The Modified case reduces the total precipitation in the SE and eastern U.S. during summer, represented by this June 1989 example.

Surface Precipitation June 1989 (Modified case) / **Precip. Difference June 1989 (Modified – Base)**

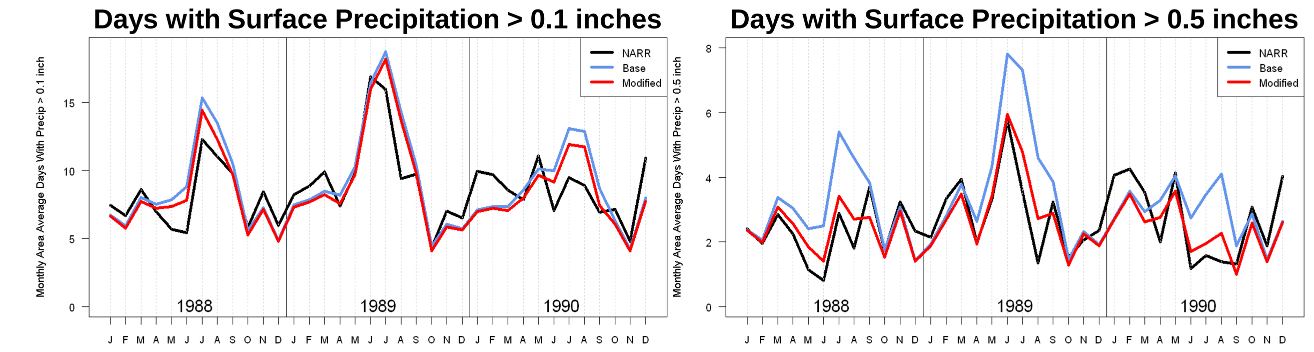


Monthly-Averaged Surface Precipitation



The Modified case improves summer precipitation totals compared with NARR (as seen here for the SE), having the greatest effect on heavier rainfall events when convective precipitation dominates.

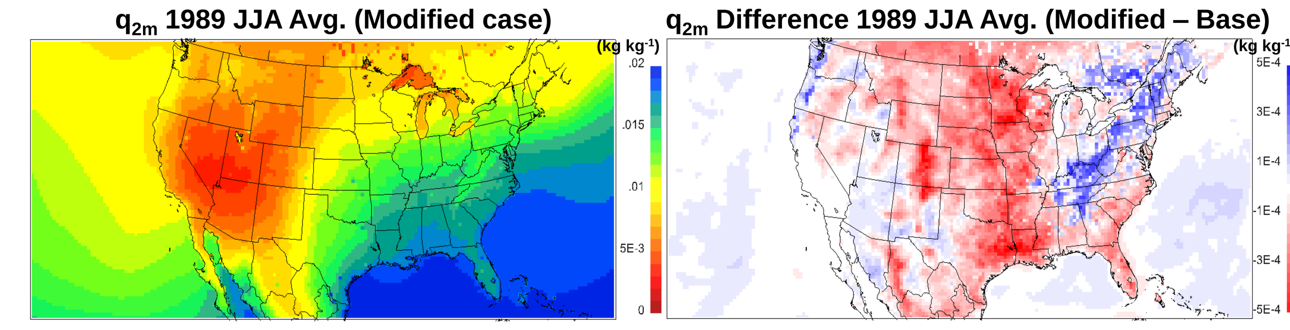
Days with Surface Precipitation > 0.1 inches / **Days with Surface Precipitation > 0.5 inches**



3.6. Results: 2-m Water Vapor Mixing Ratio

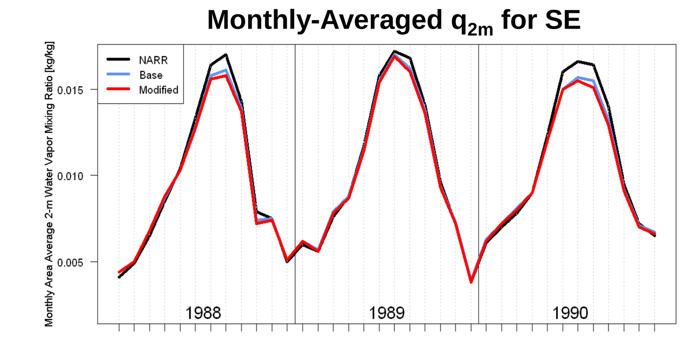
Like temperature, humidity is an important factor for O_3 and for the exchange between gas and particle phases for PM. For summer 1989, the Modified case produced slightly drier conditions over the Great Plains and coastal SE, slightly more humidity along the western Appalachians.

q_{2m} 1989 JJA Avg. (Modified case) / **q_{2m} Difference 1989 JJA Avg. (Modified – Base)**



A small decrease in 2-m water vapor can be seen for the Modified case during summer in the SE, largely due to the reduction of convective precipitation and latent heat fluxes.

Monthly-Averaged q_{2m} for SE



4. Conclusions

Implementing cumulus-radiation interactions in WRF yields these findings:

- Better simulation of summer from increased cloudiness below 300 hPa;
- Improved the SW radiation budget (and LW budget, to a lesser extent);
- Mitigated the overestimation of summer precipitation in the SE, while improving the prediction of extreme rainfall events;
- Improved prediction of heat extremes, despite small avg. T_{2m} changes;
- Reduced boundary layer heights, and;
- Minor changes to near-surface humidity.

♦ Findings have implications for biogenic emissions, photolysis, dilution of precursors and reaction products, reaction rates, O_3 episodes, particle/gas partitioning, secondary organic aerosol formation, aqueous chemistry, wet scavenging, transport, and regional air quality.

♦ Cumulus – radiation interactions currently being tested on 12 km grids for regional climate applications and to drive the Community Multiscale Air Quality (CMAQ) model in simulations of future air quality.

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