United States Environmental Protection Agency

Adding Four-Dimensional Data Assimilation (a.k.a. grid nudging) to MPAS

Russell Bullock

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

WRF User's Workshop
June 29, 2016

United States Environmental Protection Agency

Acknowledgements

- Rob Gilliam (EPA) – Atmospheric Model Evaluation Tool (AMET), used for evaluation of modeling results against observations in NCEP's Meteorological Assimilation Data Ingest System (MADIS)
- Hosein Foroutan (NRC Post Doc at EPA) – Provided code for mass balance checking in MPAS-Atmosphere

Introduction

- The U.S. Environmental Protection Agency is considering the Model for Prediction Across Scales (MPAS) as the basis for its “next-generation” air-quality modeling system.
- MM4, MM5, and WRF have previously been used to provide meteorological information for the Community Multi-scale Air Quality (CMAQ) model.
- Nearly all of our applications are done in a retrospective mode where the simulation can be “nudged” towards known past conditions using Four-Dimensional Data Assimilation (FDDA).
- Data assimilation methods using 4D-VAR/EnKF tend to be much more computationally expensive.

FDDA in MPAS - Atmosphere

- The concept of “analysis nudging” from Stauffer and Seaman (1990) has been applied in MPAS-Atmosphere just as it was to MM4, MM5 and WRF.
- MPAS has no rectangular grid like WRF. However, once the necessary “target” values are define to match the MPAS prognostic variable array, the nudging process is much the same.
- One FDDA option that WRF does have that we cannot apply in MPAS is “spectral nudging” where finer-scale model features are selectively conserved.
- To provide a similar capability for MPAS when Voronoi mesh refinement is applied, the nudging strength can be reduced for smaller cells. Stauffer and Seaman (1994) recommended weaker nudging for fine-scale modeling.

FDDA in the MPAS code structure

- Working from MPAS version 4.0 (code dated 22 May 2015)
- Special FORTRAN modules for FDDA are all contained in ~/src/core_atmosphere/physics
- Modified:
    - mpas_atmphys_driver.F
    - mpas_atmphys_manager.F
    - mpas_atmphys_todynamics.F
- New:
    - mpas_atmphys_fdda.F
- ~/src/core_atmosphere/registry.xml is modified for new arrays and to add the FDDA input stream
- ~/src/core_atmosphere/physics/Makefile is augmented to build with the new FDDA module

Creating the FDDA Targets

- FDDA nudging is applied for temperature (ϴ), humidity (q_v) and wind (U). Wind involves some extra complications.
- MPAS system already provides model initialization software
- Simply apply that software for each time where FDDA targets are desired. (typically 00, 06, 12, 18 UTC)
- Scripts have been developed to automate the process of running init_atmosphere_model for each FDDA time, extracting the nudged prognostic variables, and composing the FDDA input file.
- Variable extraction and FDDA file composition is done using NetCDF Operators (NCO) software.

FDDA Tendencies

- Prognostic variables for temperature, water vapor and wind are "nudged" towards target values which represent the best estimate for actual values.
- The nudging tendency for prognostic variable *α* is obtained from:

$$(\partial\alpha/\partial t)_{FDDA} = G_{\alpha}\, W_{layer}\, W_{PBL}\, (\alpha_{target} - \alpha)$$

where: G_{α} is a nudging inverse time scale or "nudging coefficient"
W_{layer} is a layer-dependent weighting function (1 or 0)
W_{PBL} is a PBL weighting function (1 or 0)

- W_{layer} = 1 in layers ≥ a namelist-specified layer number,
= 0 otherwise
- W_{PBL} = 1 in layers above the PBL height (k > kpbl),
= 1 if namelist control variable is set to .true.,
= 0 otherwise

FDDA Tendencies

- Nudging of Θ and q_v is from direct comparison of model and target values at cell centers.
- *U*-nudging is based on FDDA tendencies for variables *UReconstructZonal* and *UReconstructMeridional* at cell centers.
  - PBL and convection schemes already operate on wind components at cell centers and use subroutine “tend_toEdges”
  - Could nudge wind across cell edges (*U*), but this presents 1.5 times as many values to nudge and would require complex logic separate from Θ and q_v nudging
  - Would also make future addition of obs-nudging more difficult
- Coupled tendencies for Θ, q_v and U are calculated with the new FDDA terms in “physics/mpas_atmphys_todynamics.F”

FDDA Namelist Options

- Additional physics options

  config_fdda_scheme = ‘off’ (default)
  = ‘no_scaling’
  = ‘length_scaled’

- With ‘no_scaling’, the nudging coefficient is always applied at the value specified for each variable
- With ‘length_scaled’, the nudging coefficient is scaled down for cells with mean distance to its neighboring cells (*dcEdge_m*) < 100000 m. Scaling factor for cell (k) is dcEdge_m(k)/100000.
- I’m just now starting to test model sensitivity to other scaling functions and thresholds.

FDDA Namelist Options

- Additional physics options

config_fdda_t = .true. or .false. (default is .false.)
config_fdda_t_in_pbl = .true. or .false. (default is .true.)
config_fdda_t_min_layer = INTEGER (default is 0)
config_fdda_t_coef = REAL (default is 3.0E-4.)

config_fdda_q = .true. or .false. (default is .false.)
config_fdda_q_in_pbl = .true. or .false. (default is .true.)
config_fdda_q_min_layer = INTEGER (default is 0)
config_fdda_q_coef = REAL (default is 3.0E-4) *[may reduce this]*

config_fdda_uv = .true. or .false. (default is .false.)
config_fdda_uv_in_pbl = .true. or .false. (default is .true.)
config_fdda_uv_min_layer = INTEGER (default is 0)
config_fdda_uv_coef = REAL (default is 3.0E-4)

FDDA Test Application

- MPAS-Atmosphere was applied on the published 92-25km mesh (x4.163842.grid.nc) with the origin repositioned to 40N, 95W
- Model initialization and FDDA data were produced from 1 x 1° NCEP FNL Operational Model Global Tropospheric Analyses (ds083.2)
- USGS land use data were used here (now testing with MODIS)
- Model top: 30 km W-damping height: 27 km
- Model layers: 50 (custom vertical distribution)
- Simulation period: 00 UTC 1 July 2013 – 00 UTC 1 August 2013
- Time step length: 150 s Number of acoustic sub-steps: 6
- Horizontal diffusion length: 25 km
- Other non-physics options: default

FDDA Test Application

- Physics options for standard MPAS

config_sst_update = .true. and .false.   (*tested using both options*)
config_sstdiurn_update = .false.
config_deepsoiltemp_update = .false.
config_radt_lw_scheme = 'rrtmg_lw'
config_radt_sw_scheme = 'rrtmg_sw'
config_radtlw_interval = '00:10:00'
config_radtsw_interval = '00:10:00'
config_bucket_update = 'none'
config_microp_scheme = 'wsm6'
config_convection_scheme = 'kain_fritsch'
config_lsm_scheme = 'noah'
config_pbl_scheme = 'ysu'
config_gwdo_scheme = 'off'
config_radt_cld_scheme = 'cld_fraction'
config_sfclayer_scheme = 'monin_obukhov'

FDDA Test Application

- Physics options for FDDA

config_fdda_scheme = ‘off’, ‘no_scaling’ and ‘length_scaled’

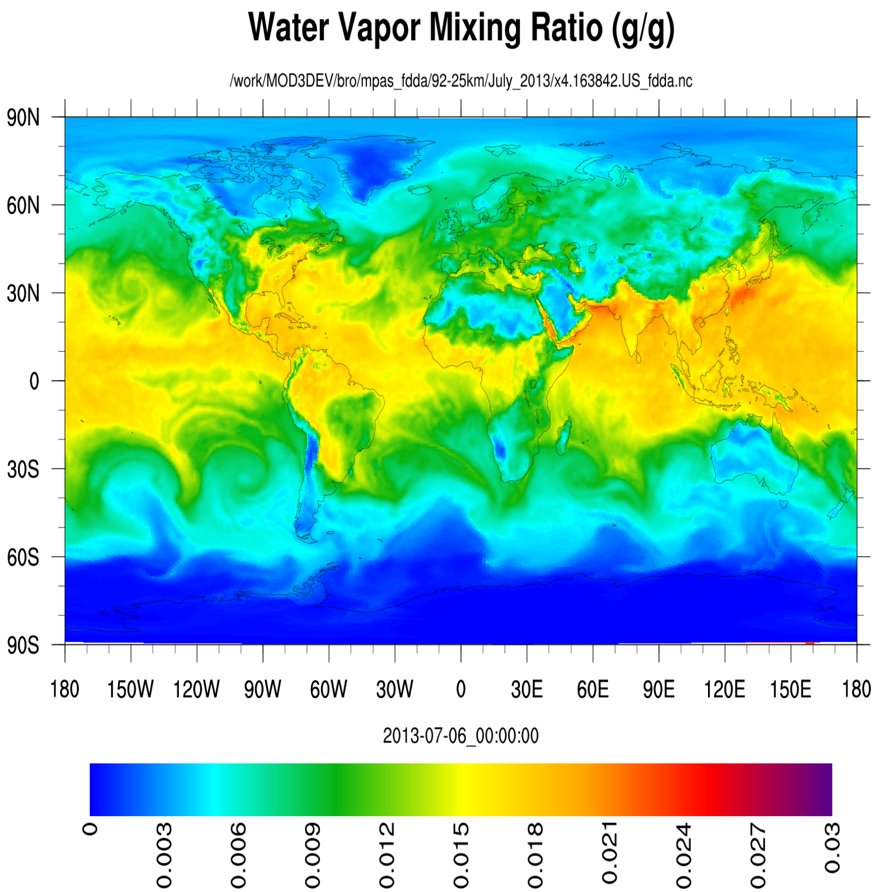
config_fdda_t = .true.
config_fdda_t_in_pbl =.false.
config_fdda_t_min_layer = 0
config_fdda_t_coef = 3.0E-4.

config_fdda_q = .true.
config_fdda_q_in_pbl =.false.
config_fdda_q_min_layer = 0
config_fdda_q_coef = 3.0E-5

config_fdda_uv = .true.
config_fdda_uv_in_pbl =.false.
config_fdda_uv_min_layer = 0
config_fdda_uv_coef = 3.0E-4

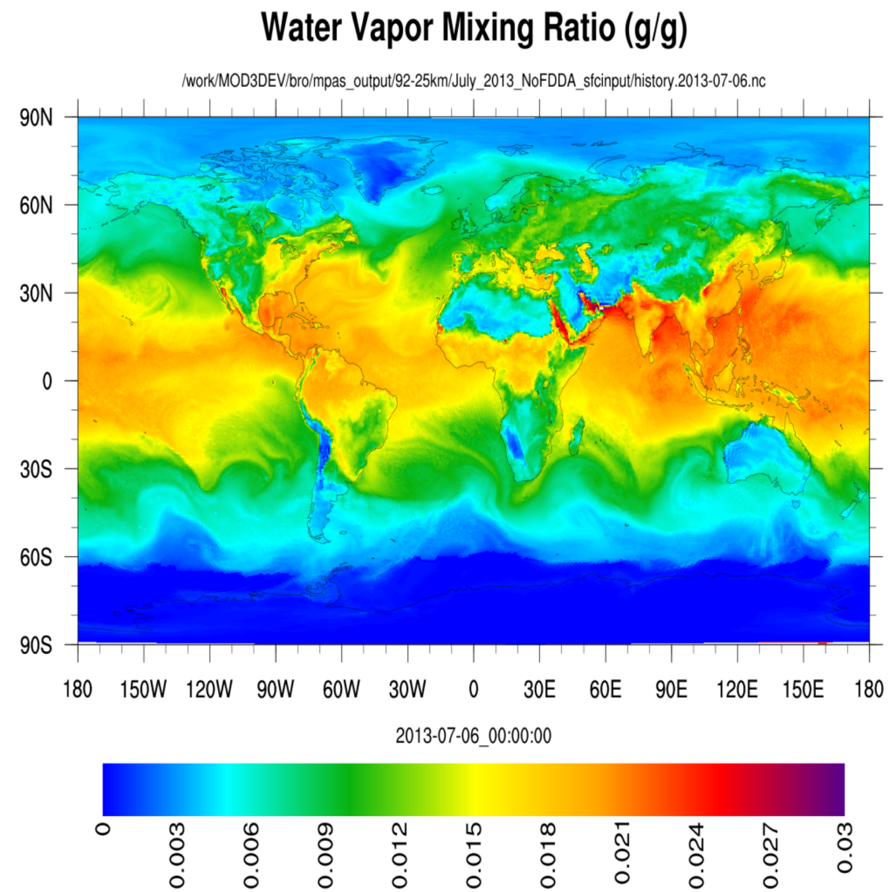
Without FDDA

FDDA Target (FNL)



Layer 1

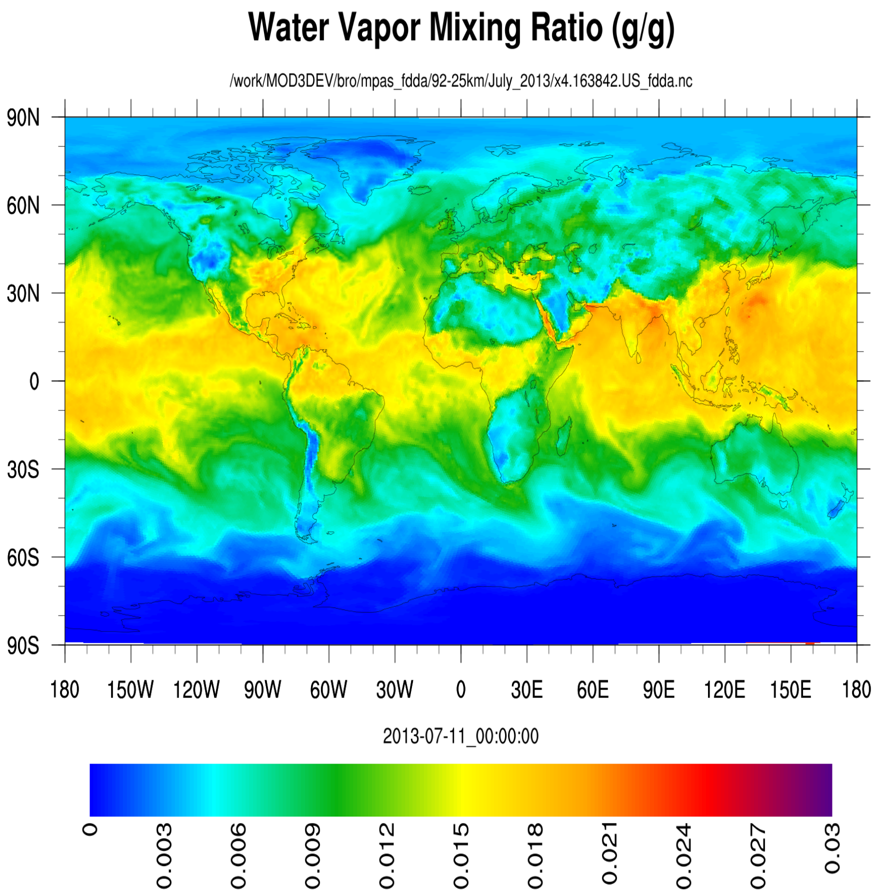
Simulation (+5 days)



Layer 1

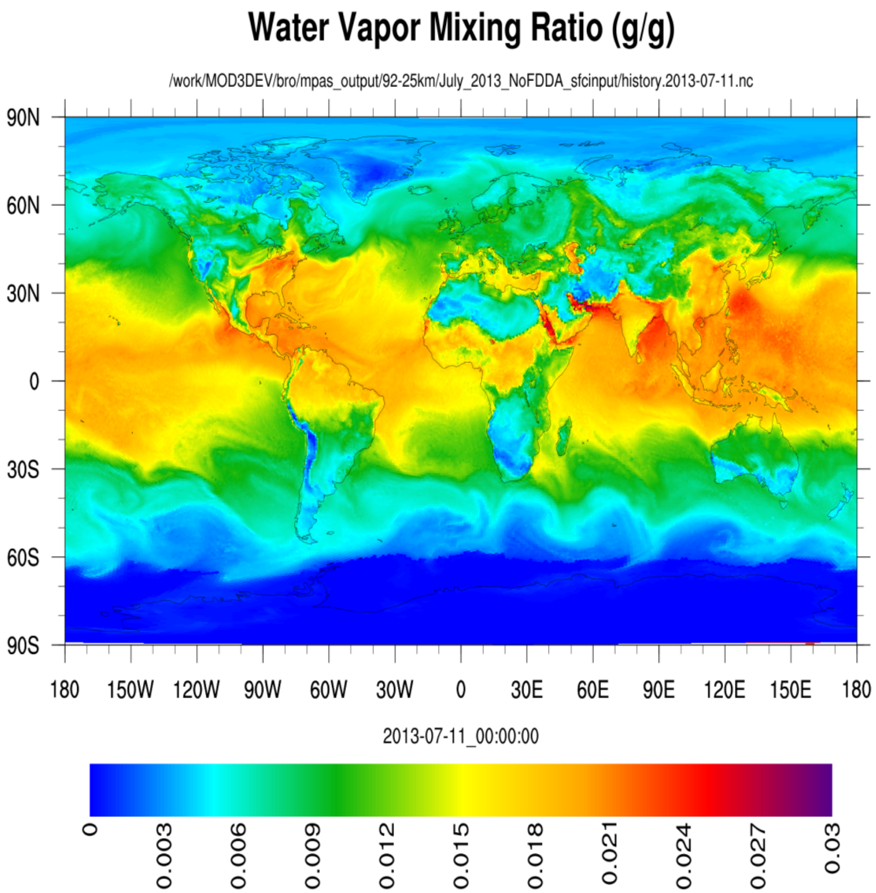
Without FDDA

FDDA Target (FNL)



Layer 1

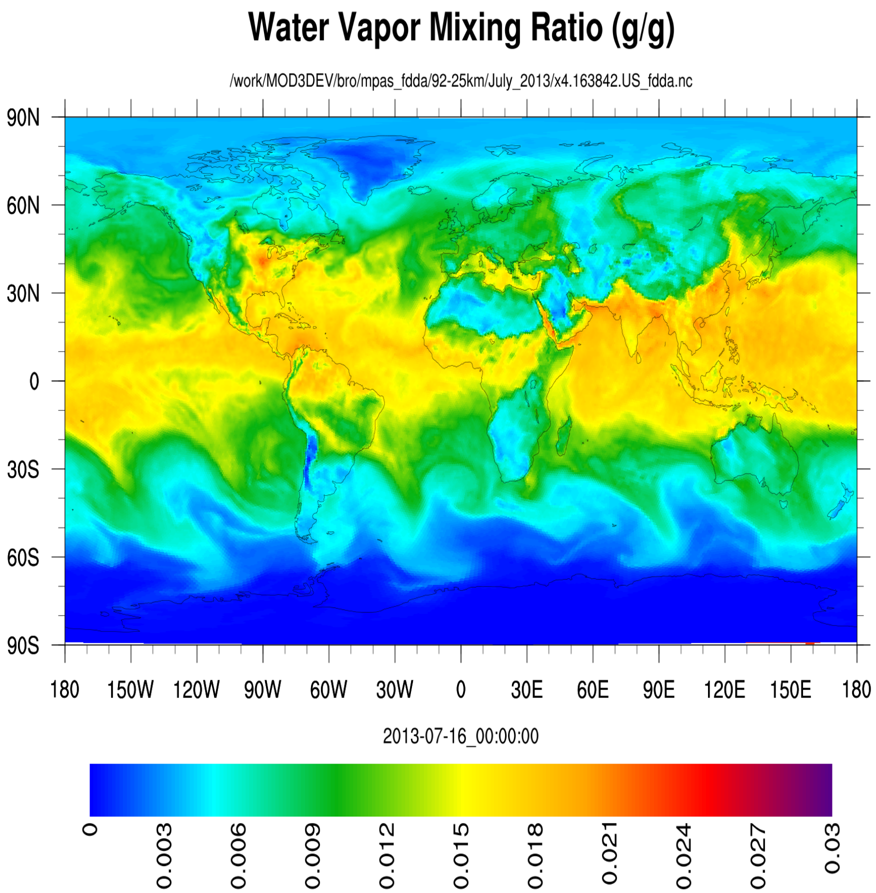
Simulation (+10 days)



Layer 1

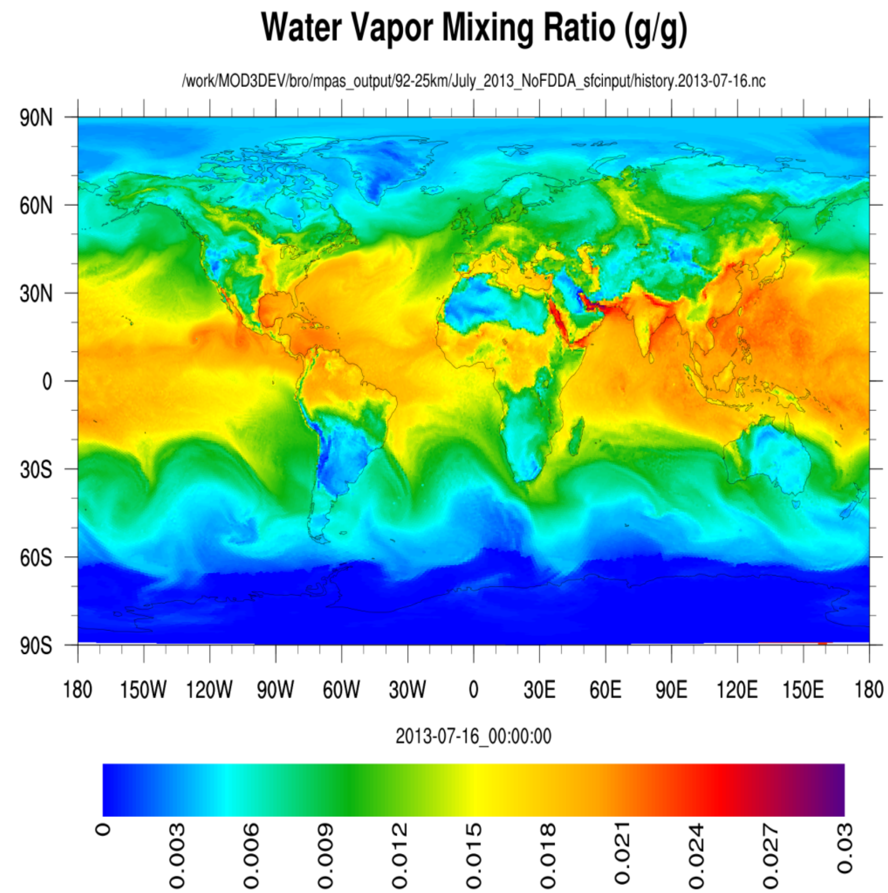
Without FDDA

FDDA Target (FNL)



Layer 1

Simulation (+15 days)

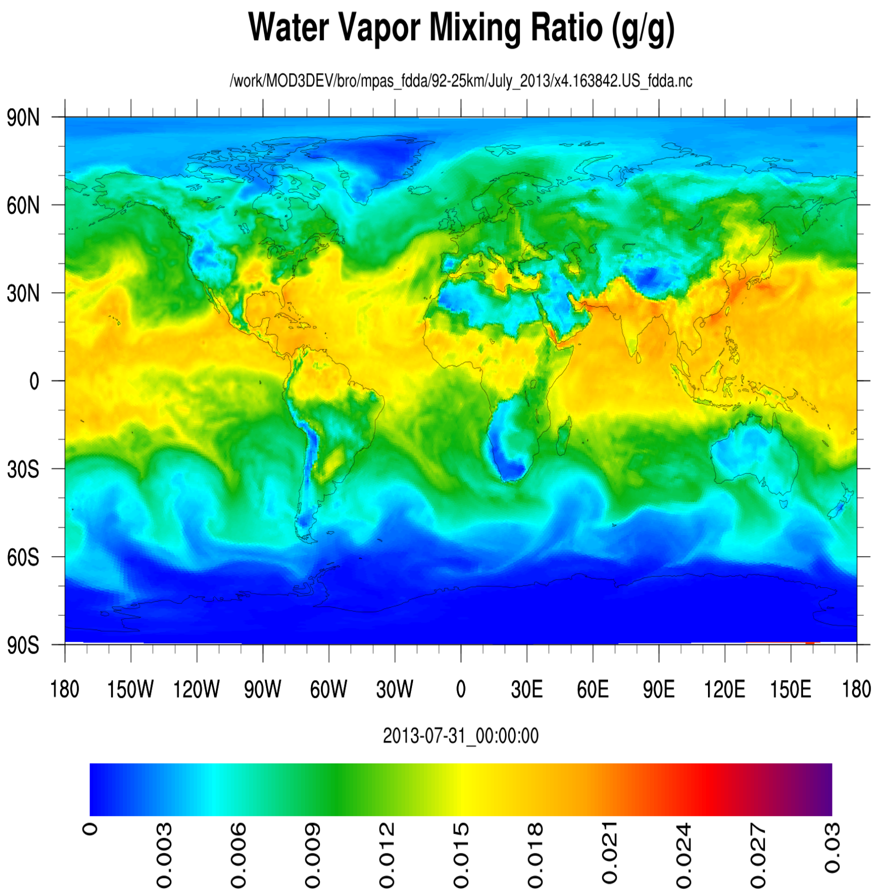


Layer 1

United States Environmental Protection Agency

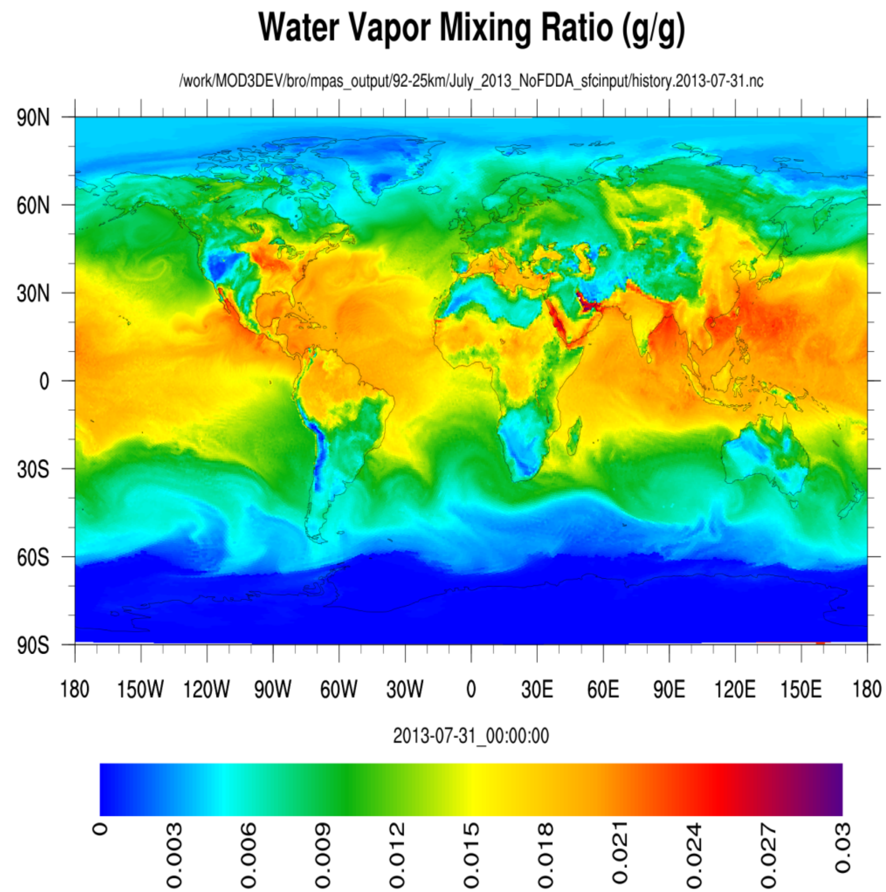
Without FDDA

FDDA Target (FNL)



Layer 1

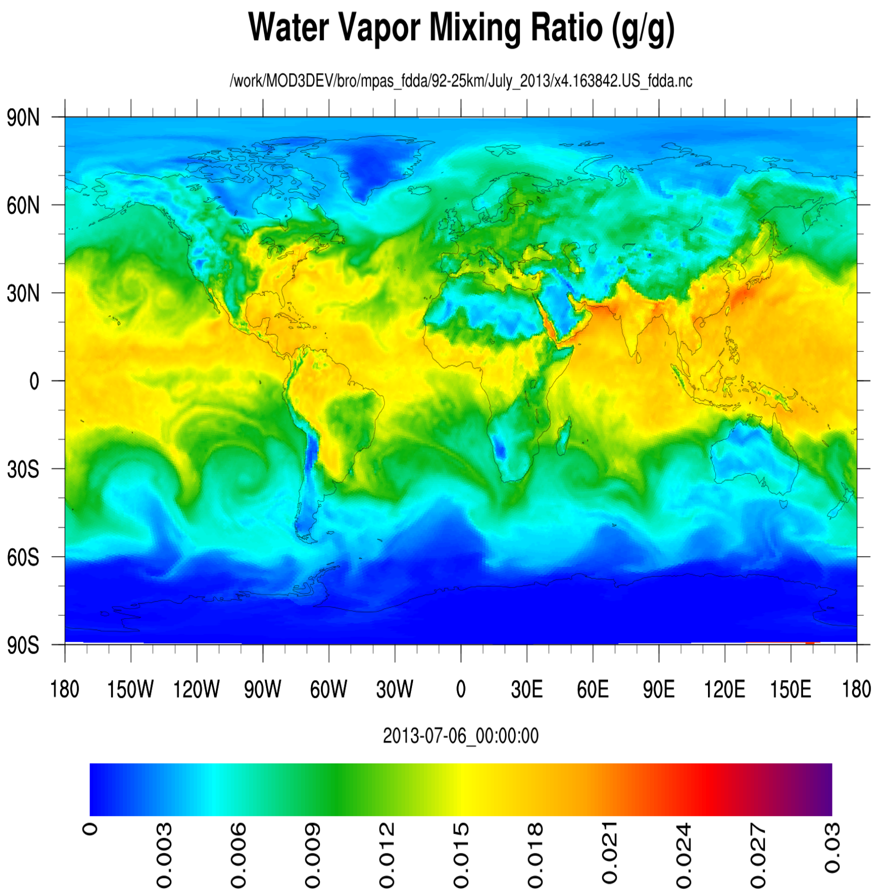
Simulation (+30 days)



Layer 1

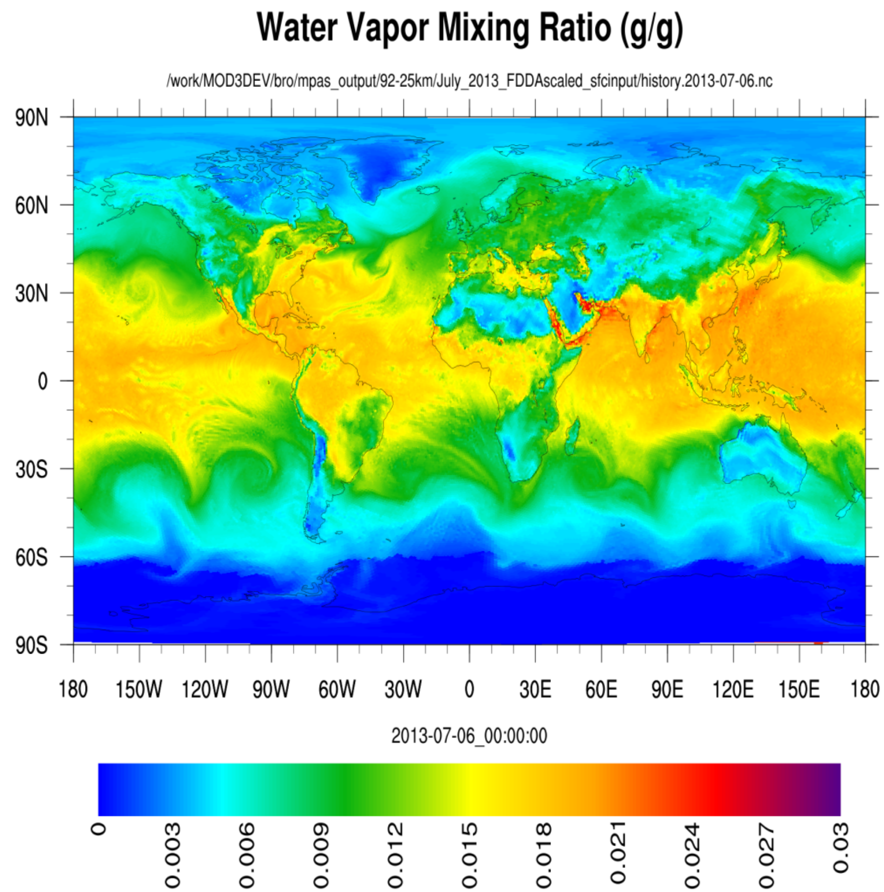
With FDDA

FDDA Target (FNL)



Layer 1

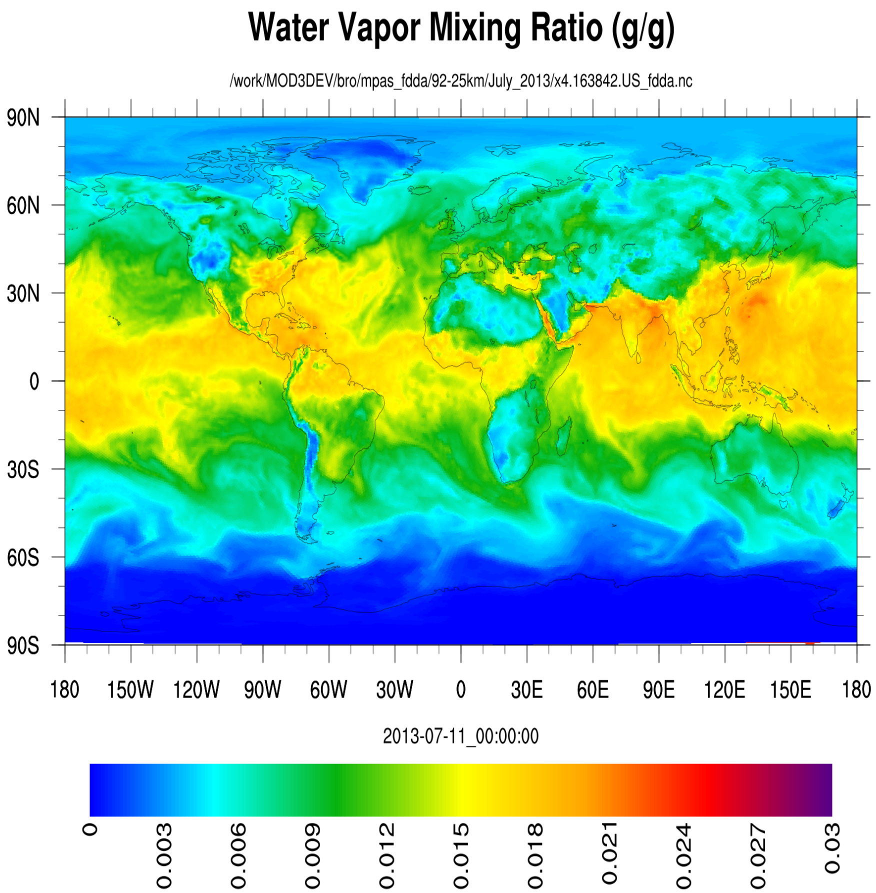
Simulation (+5 days)



Layer 1

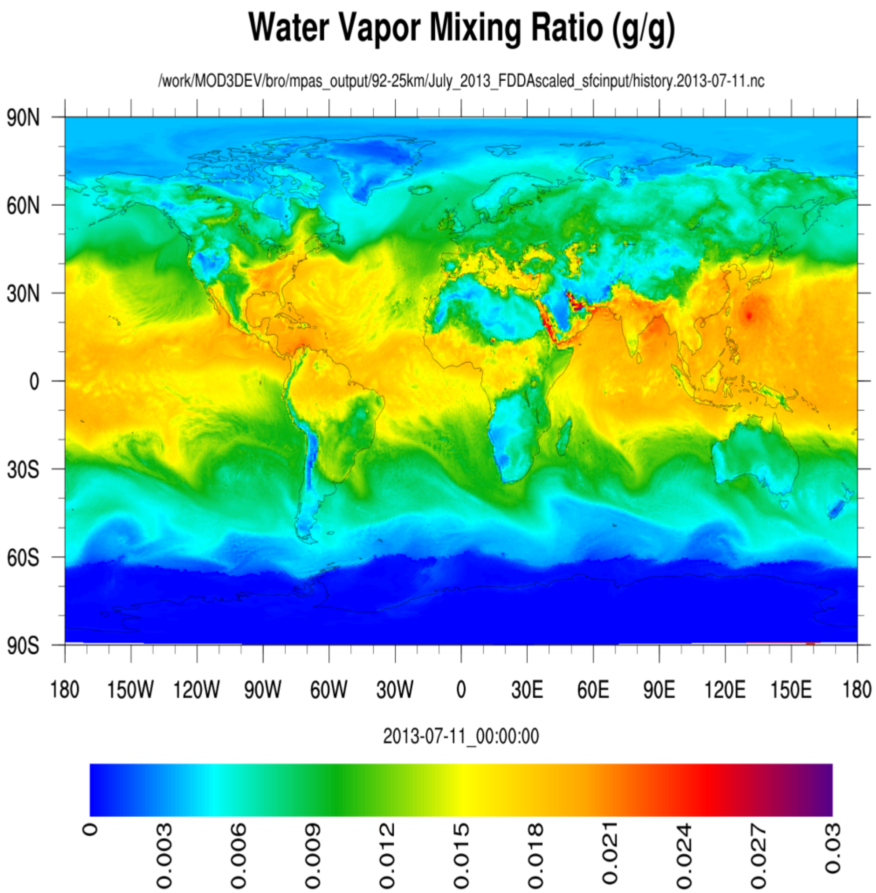
With FDDA

FDDA Target (FNL)



Layer 1

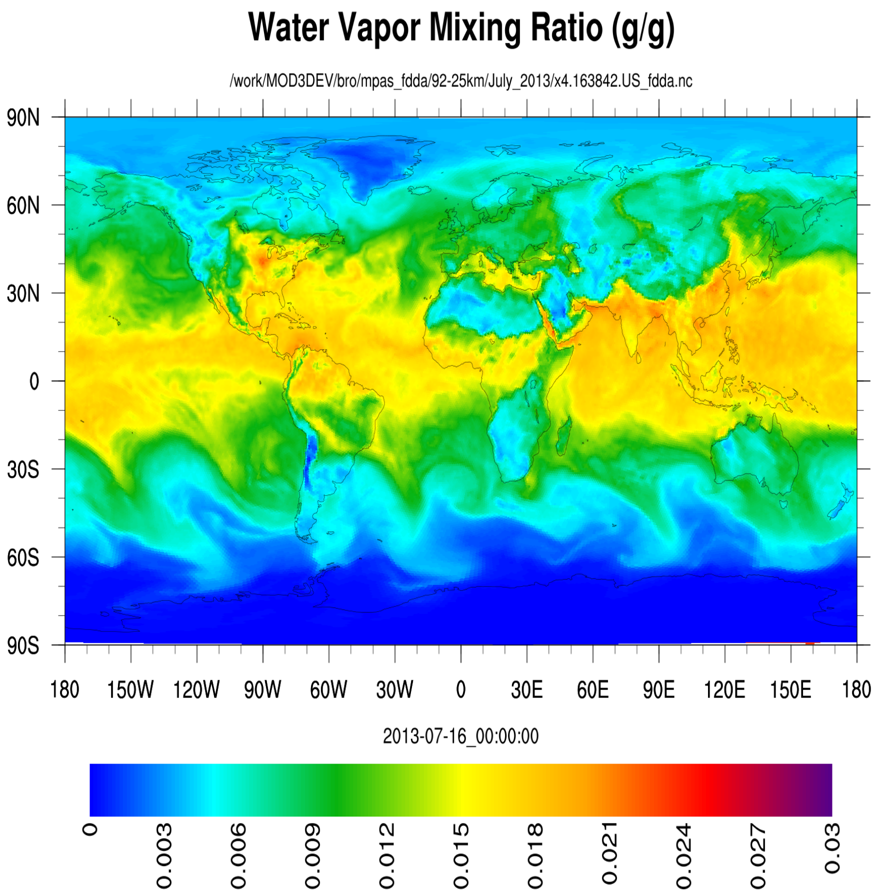
Simulation (+10 days)



Layer 1

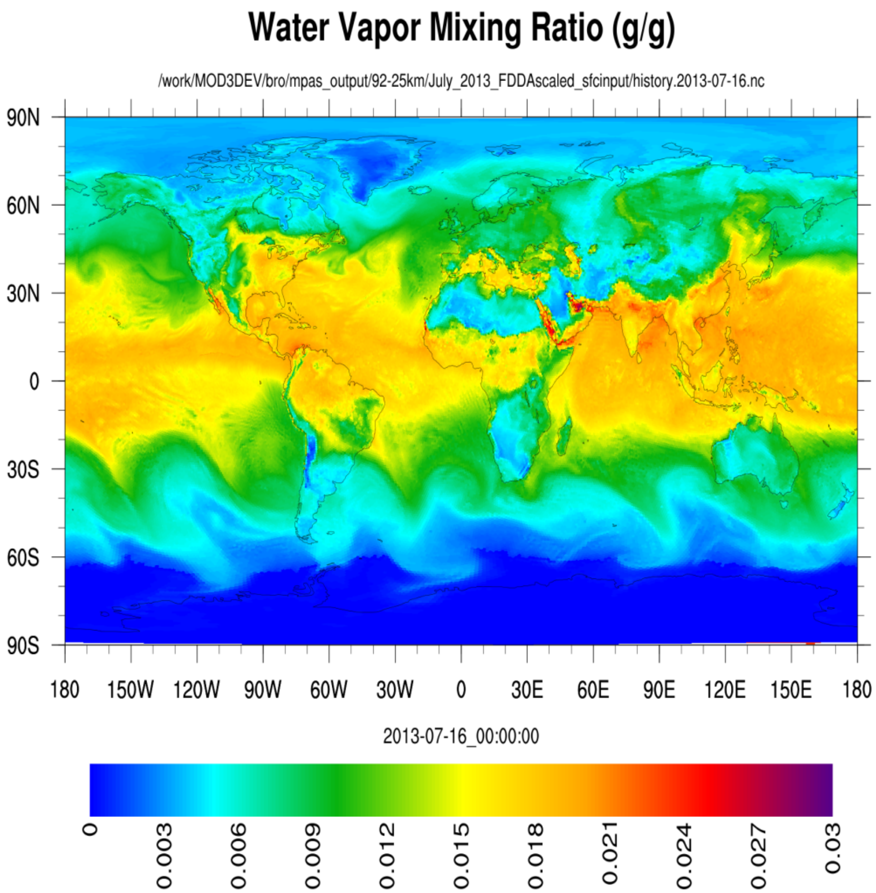
With FDDA

FDDA Target (FNL)



Layer 1

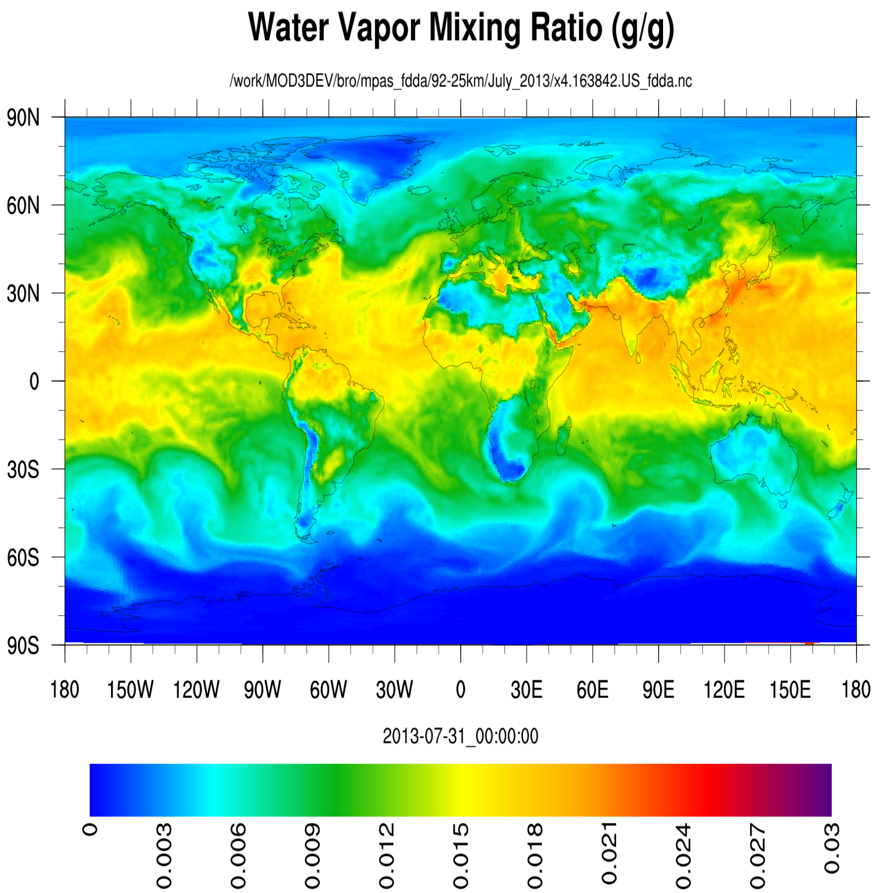
Simulation (+15 days)



Layer 1

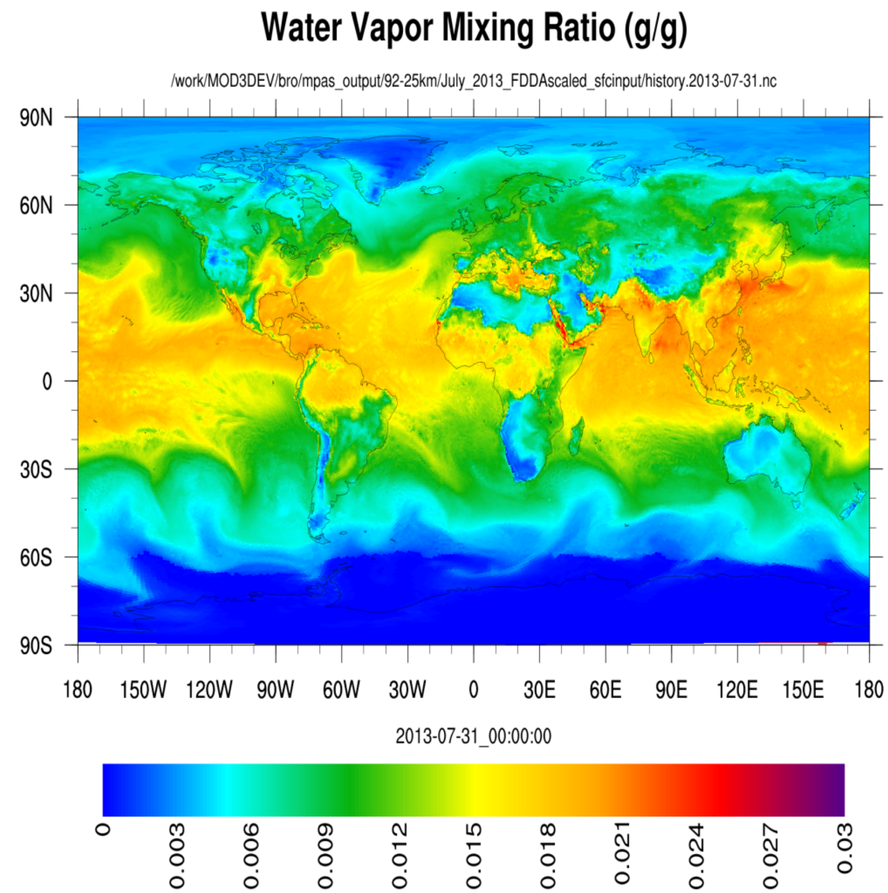
With FDDA

FDDA Target (FNL)



Layer 1

Simulation (+30 days)



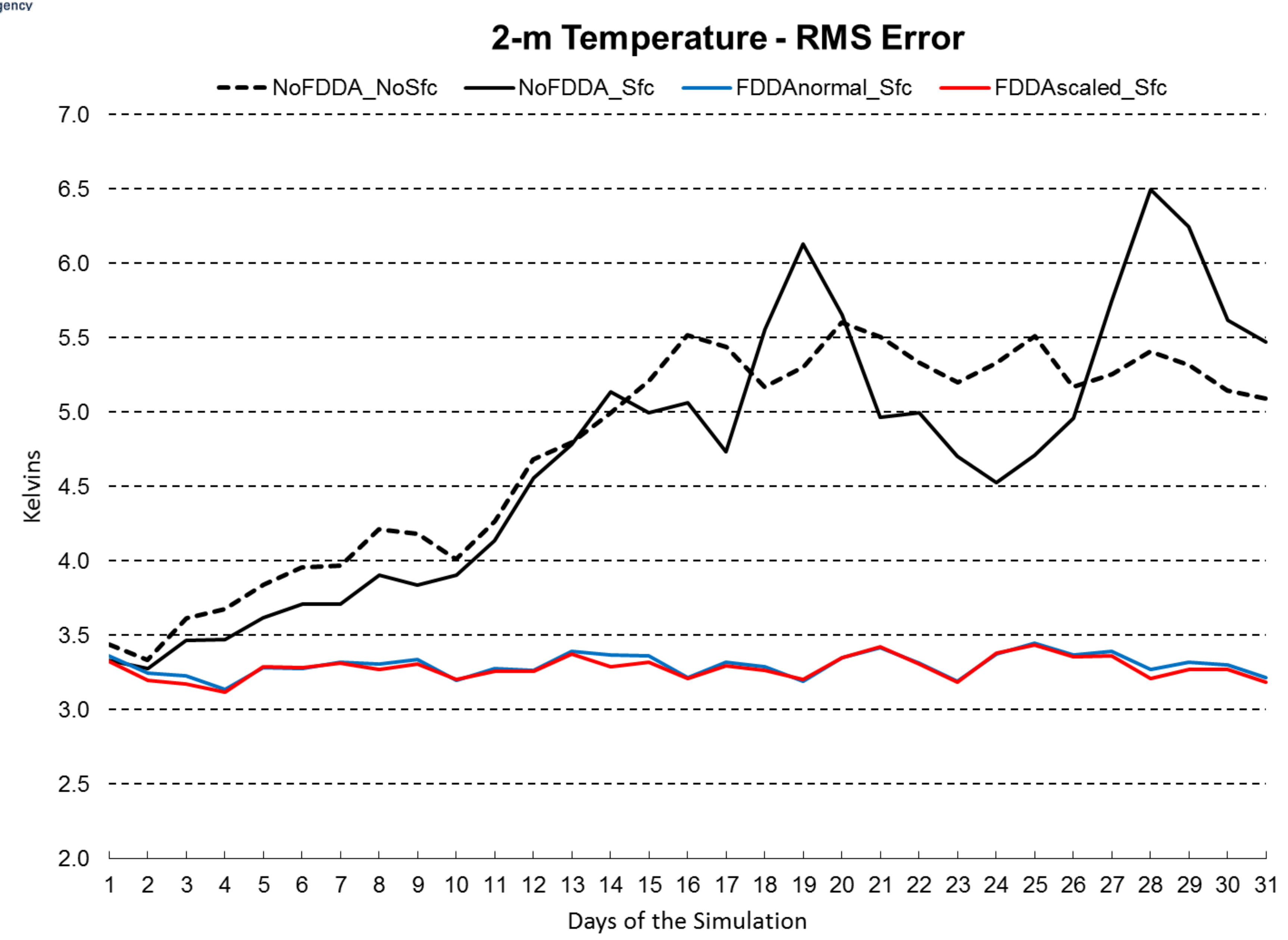
Layer 1

United States Environmental Protection Agency

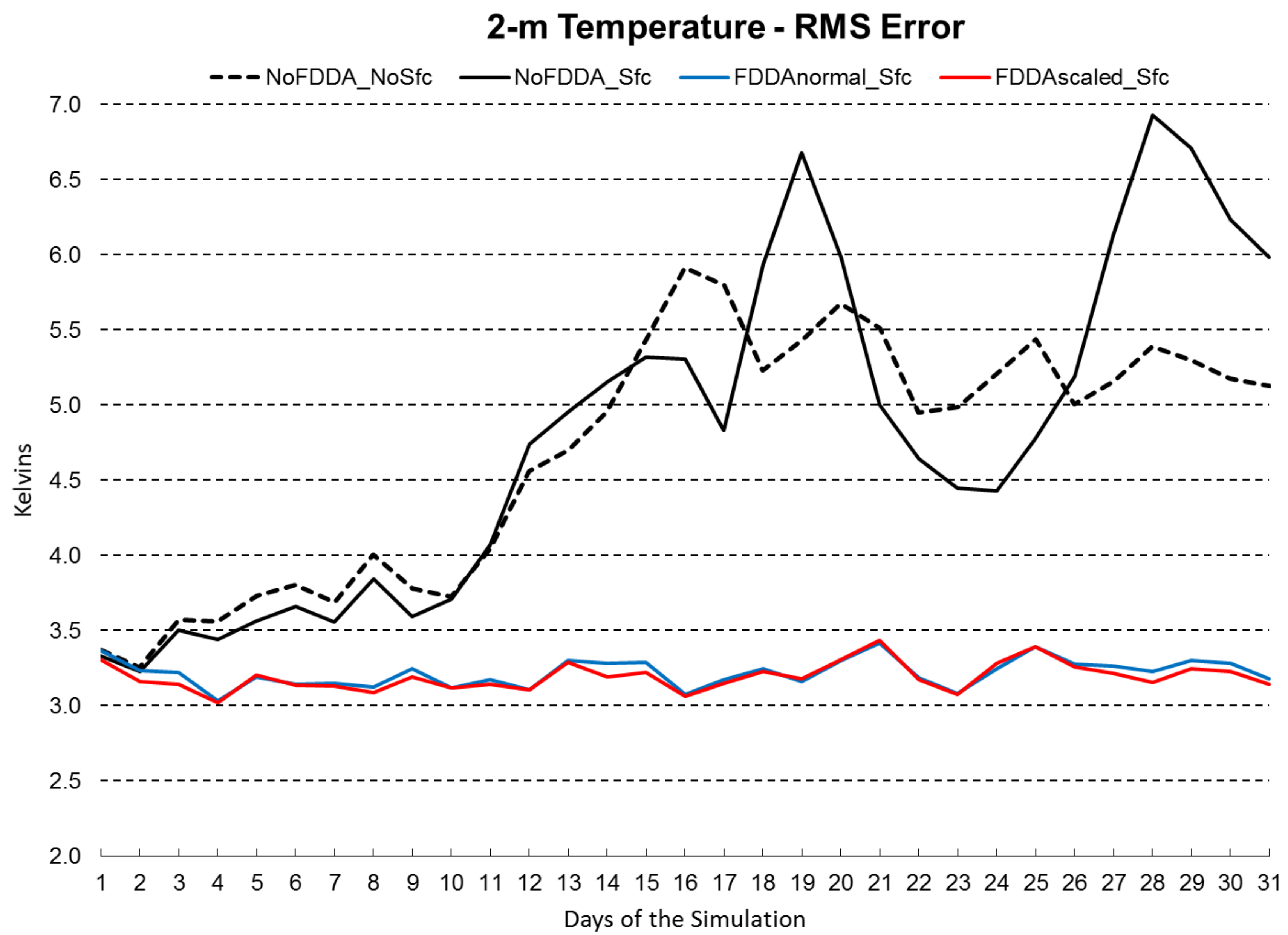
But now let's see how the test runs compare to observations

- AMET used to evaluate MPAS results against surface observations in MADIS
- ~4000 observations per hour
- Daily averaged statistics

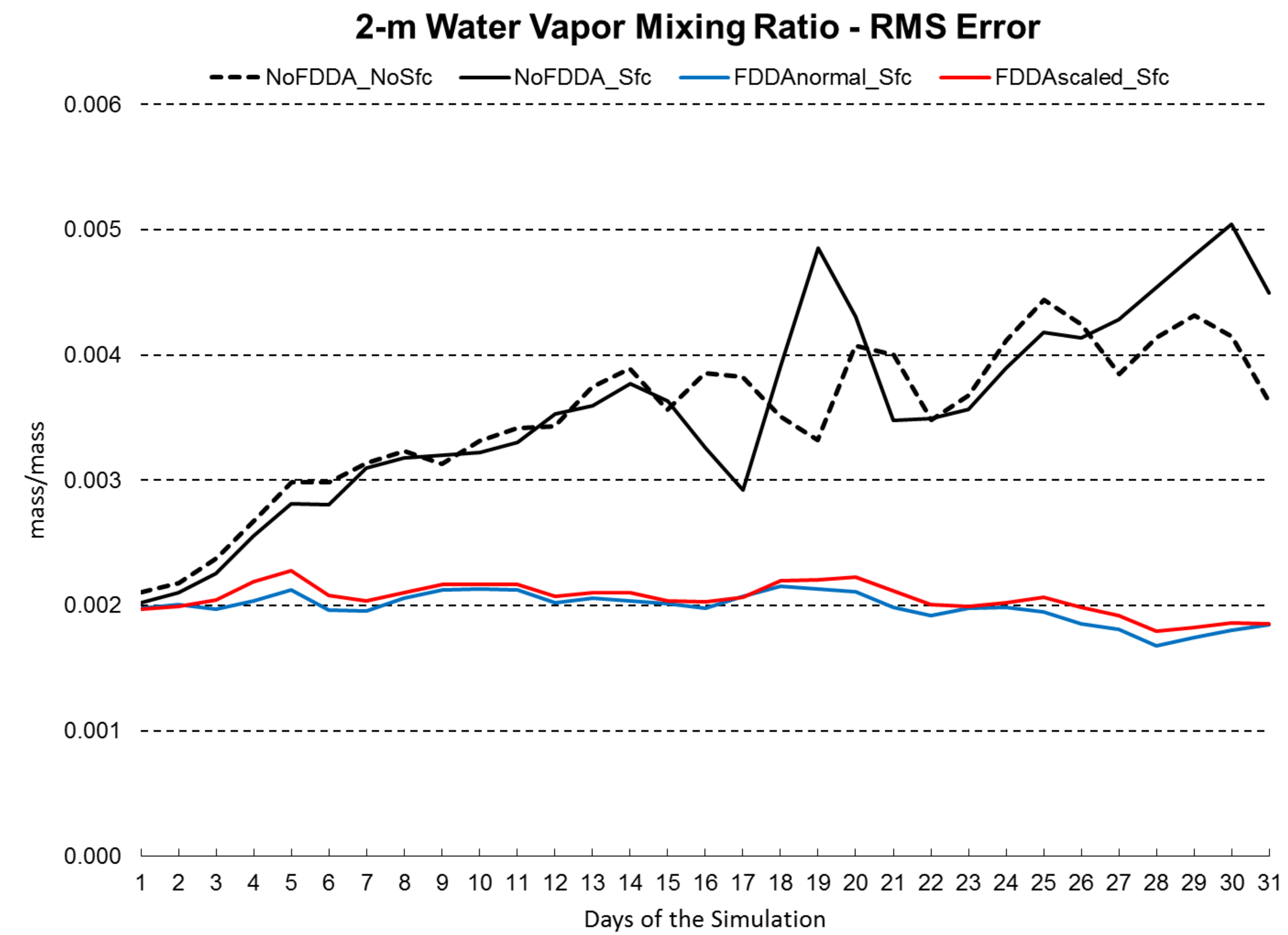
Full Global Domain



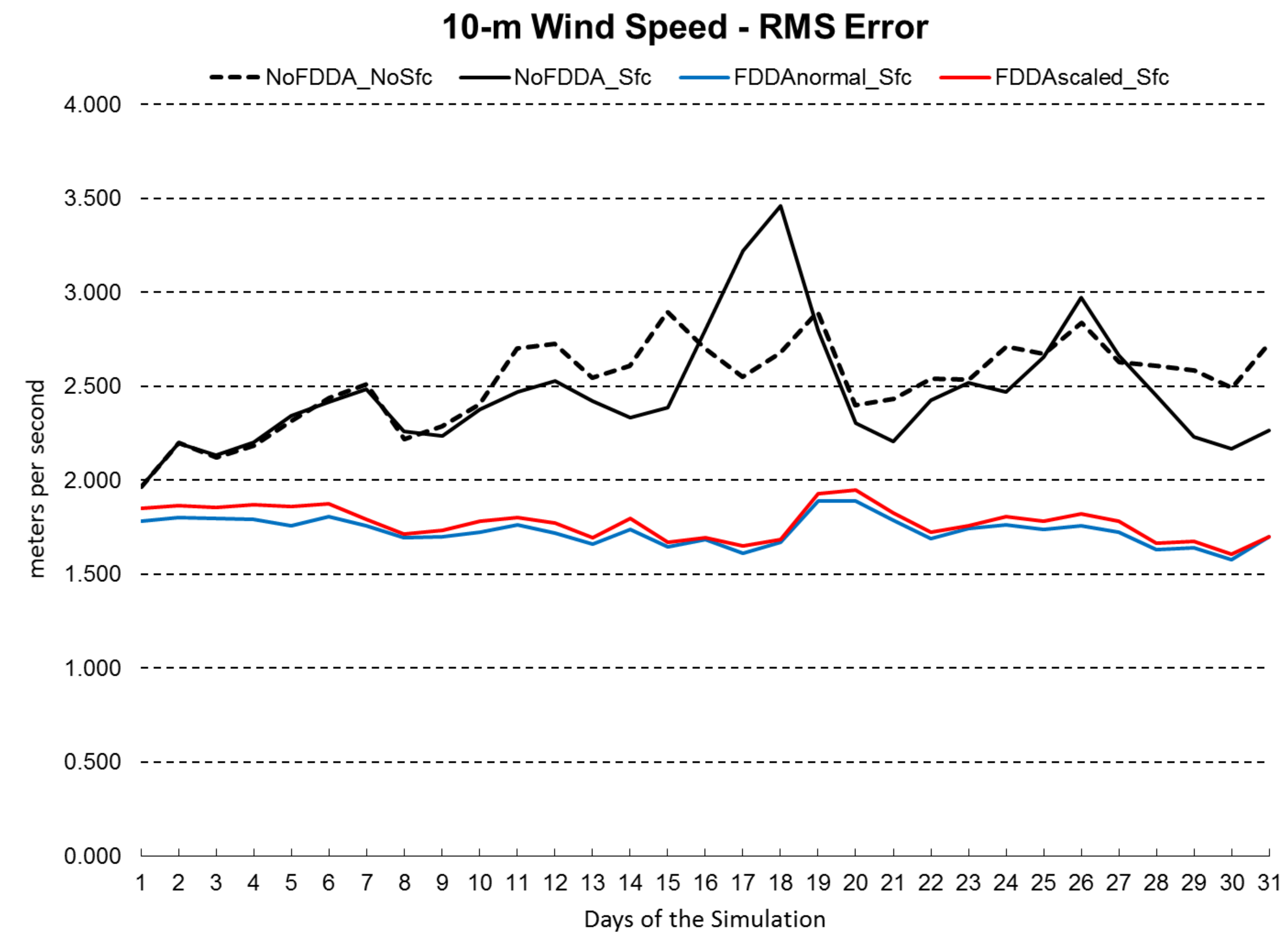
67-125°W : 25-50°N



67-125°W : 25-50°N



67-125°W : 25-50°N



Mass Conservation?

- Code was added to dynamics/mpas_atm_time_integration.F to calculate and report total dry air mass and total water vapor mass at each time step.
- The standard MPAS-Atmosphere did a very good job of conserving the total mass of dry air during July 2013. (+/- 0.003%)
- Of course, water vapor was not so constant (+/- 0.3%)
- All applications of FDDA showed similar conservation of dry air
- Water vapor in FDDA applications tended to increase about 2% in the first few days and then fluctuate within +/- 1%.

Summary and Future Work

- The new FDDA capability constrains model errors to the same magnitudes found at the start of the simulation.
- Mass conservation (w.r.t. dry air) is not degraded. Nudging water vapor mixing ratio obviously disrupts total mass balance.
- Model errors are somewhat sensitive to the nudging strength and weaker nudging for smaller mesh cells can reduce error.
- U.S. EPA will continue to test and refine the technique.
- FDDA will be offered to the MPAS Development Team for inclusion in future published versions.

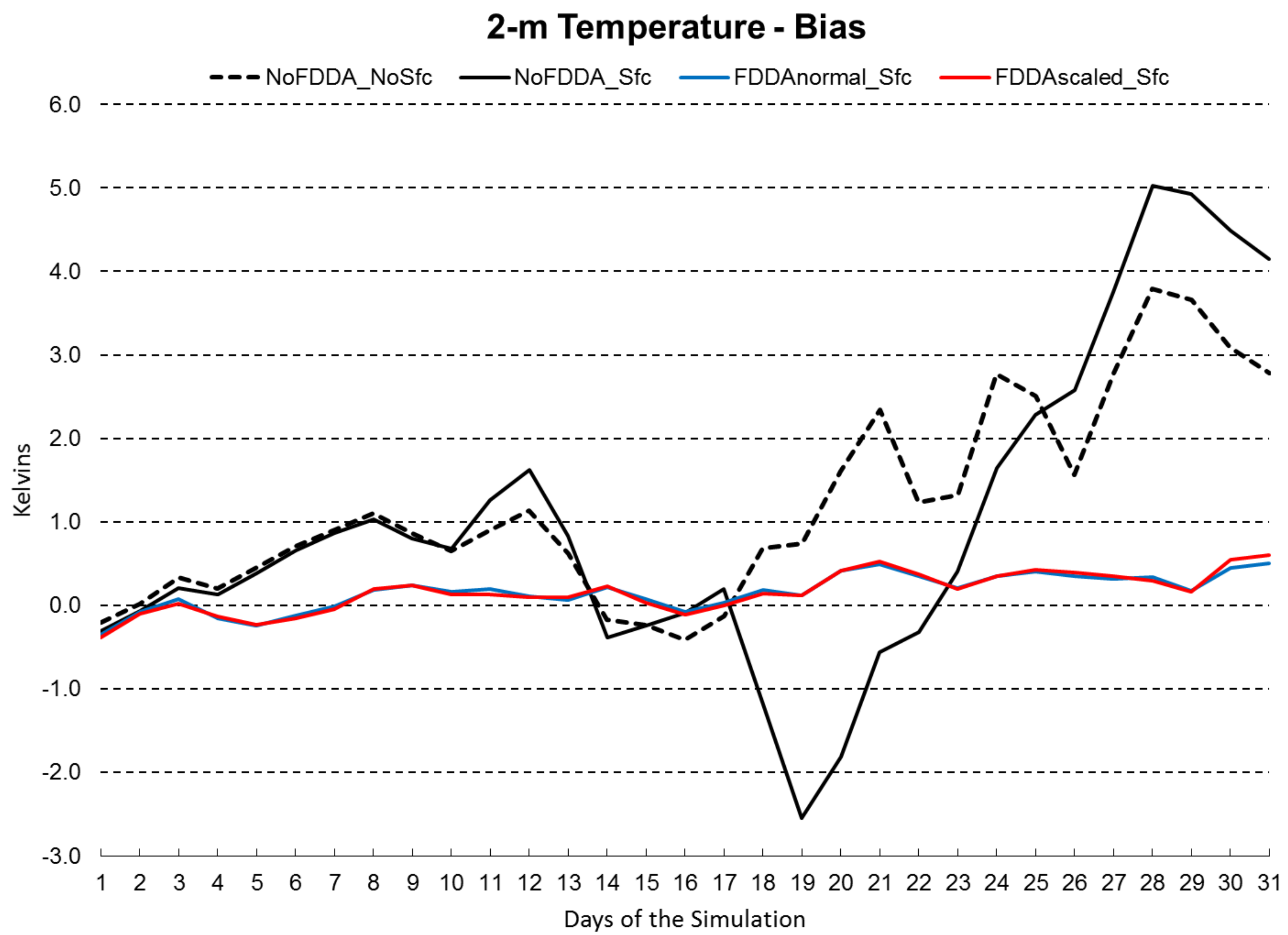
References

Stauffer, D. R., and N. L. Seaman, 1990: Use of four-dimensional data assimilation in a limited-area model. Part I: Experiments with synoptic-scale data. Mon. Wea. Rev., 118, 1250–1277.

Stauffer, D. R., and N. L. Seaman, 1994: Multiscale four-dimensional data assimilation. J. Appl. Meteor., 33, 416–434.

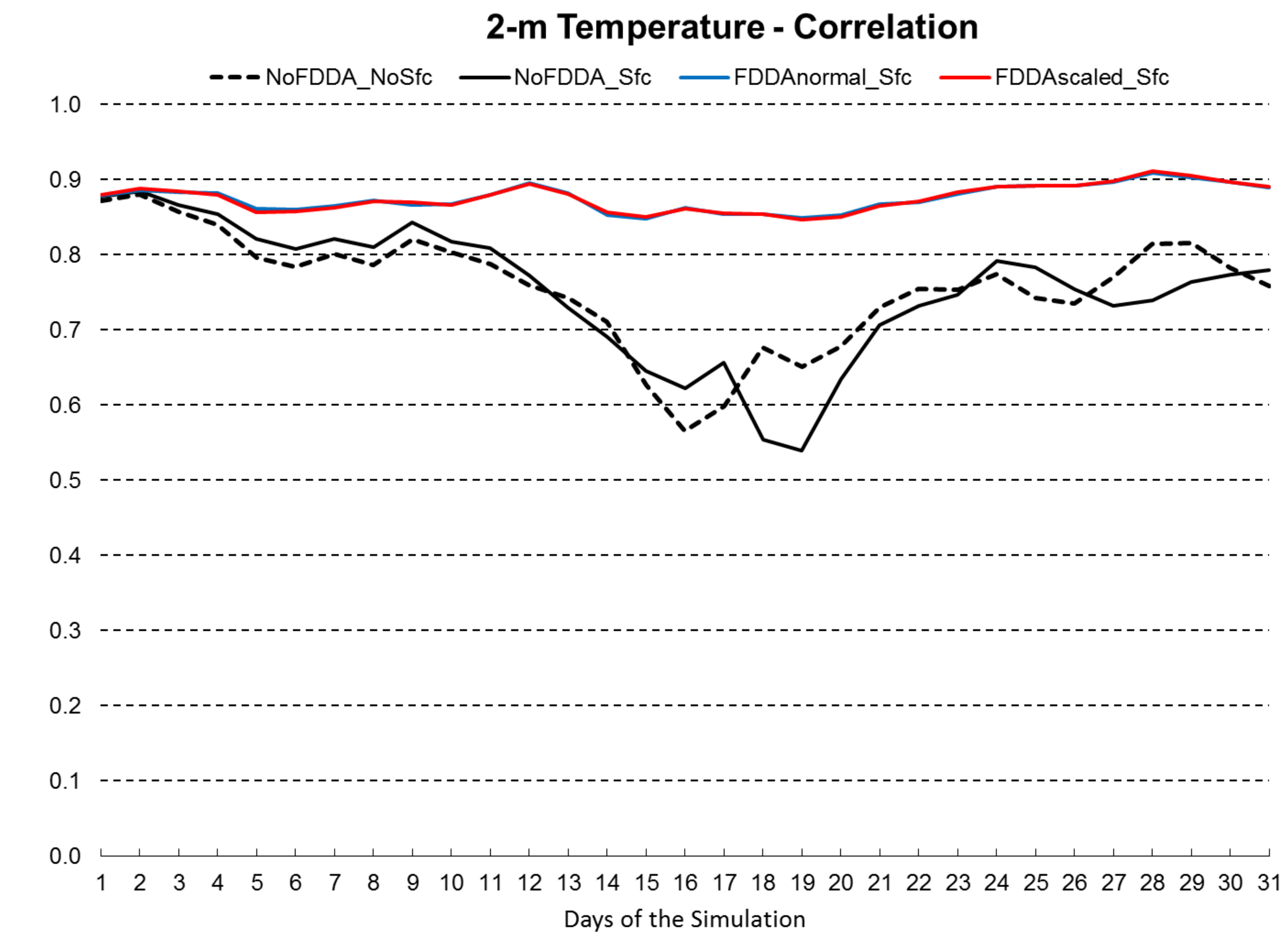
Questions?

67-125°W : 25-50°N

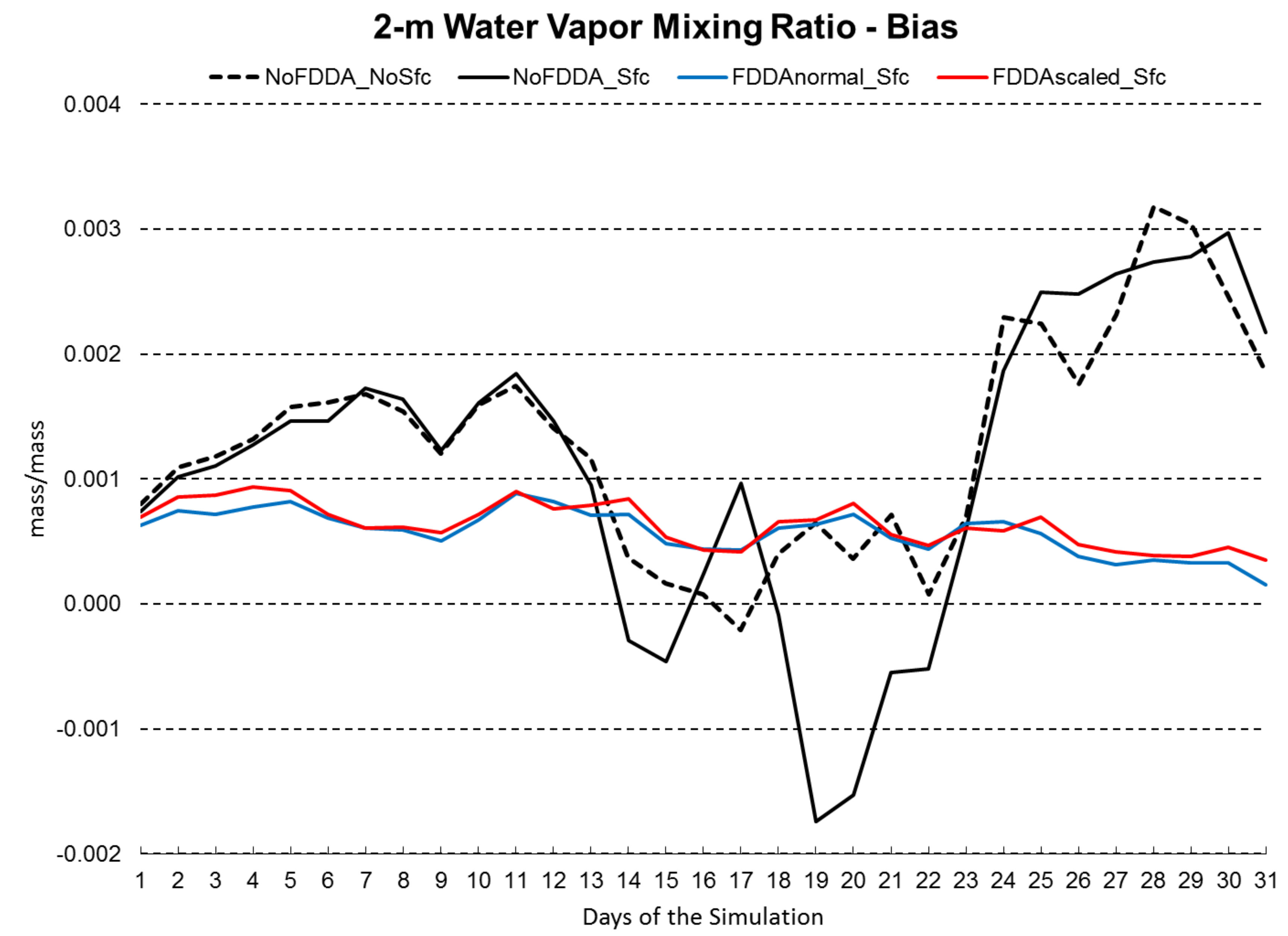


United States Environmental Protection Agency

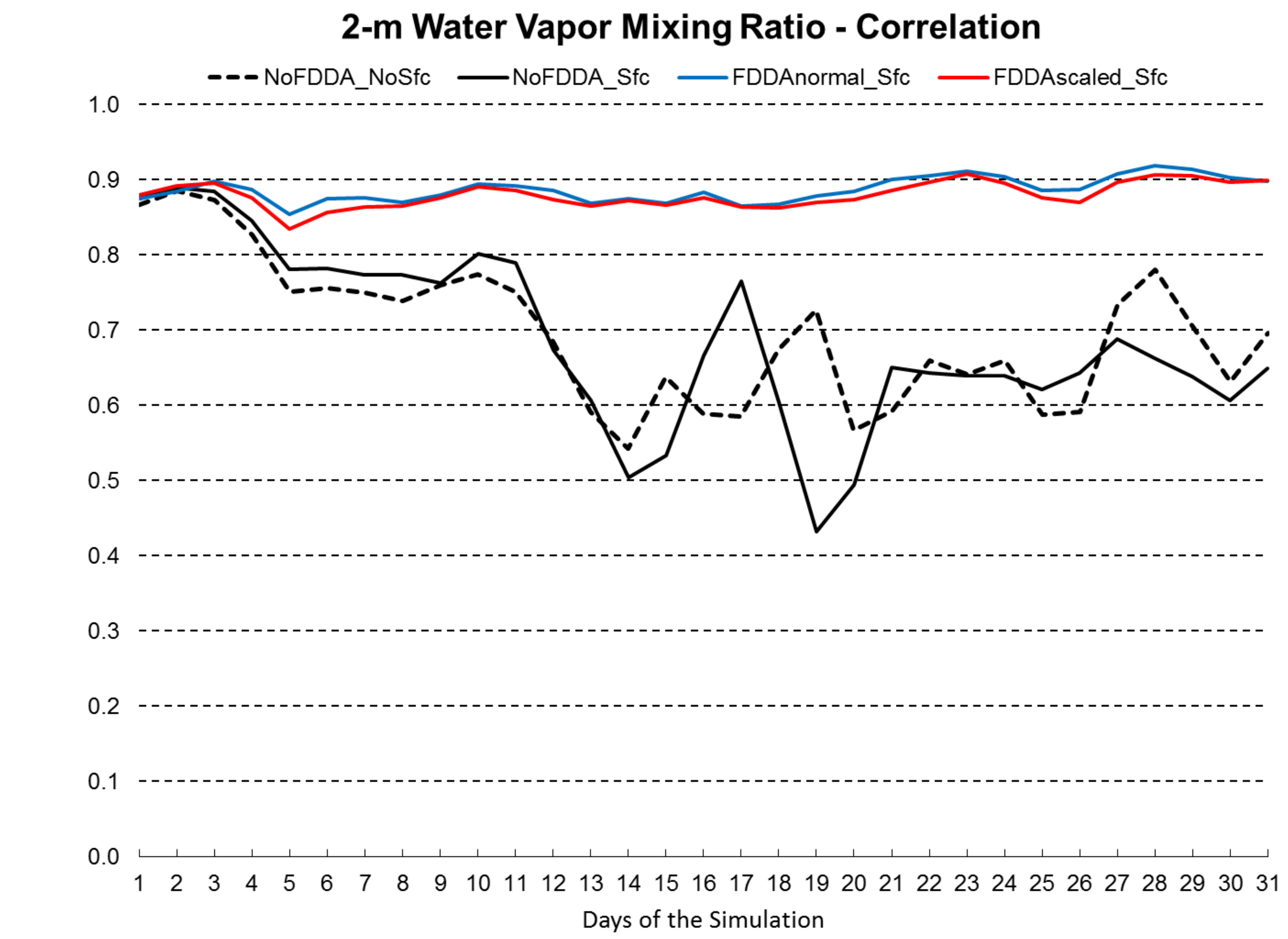
67-125°W : 25-50°N

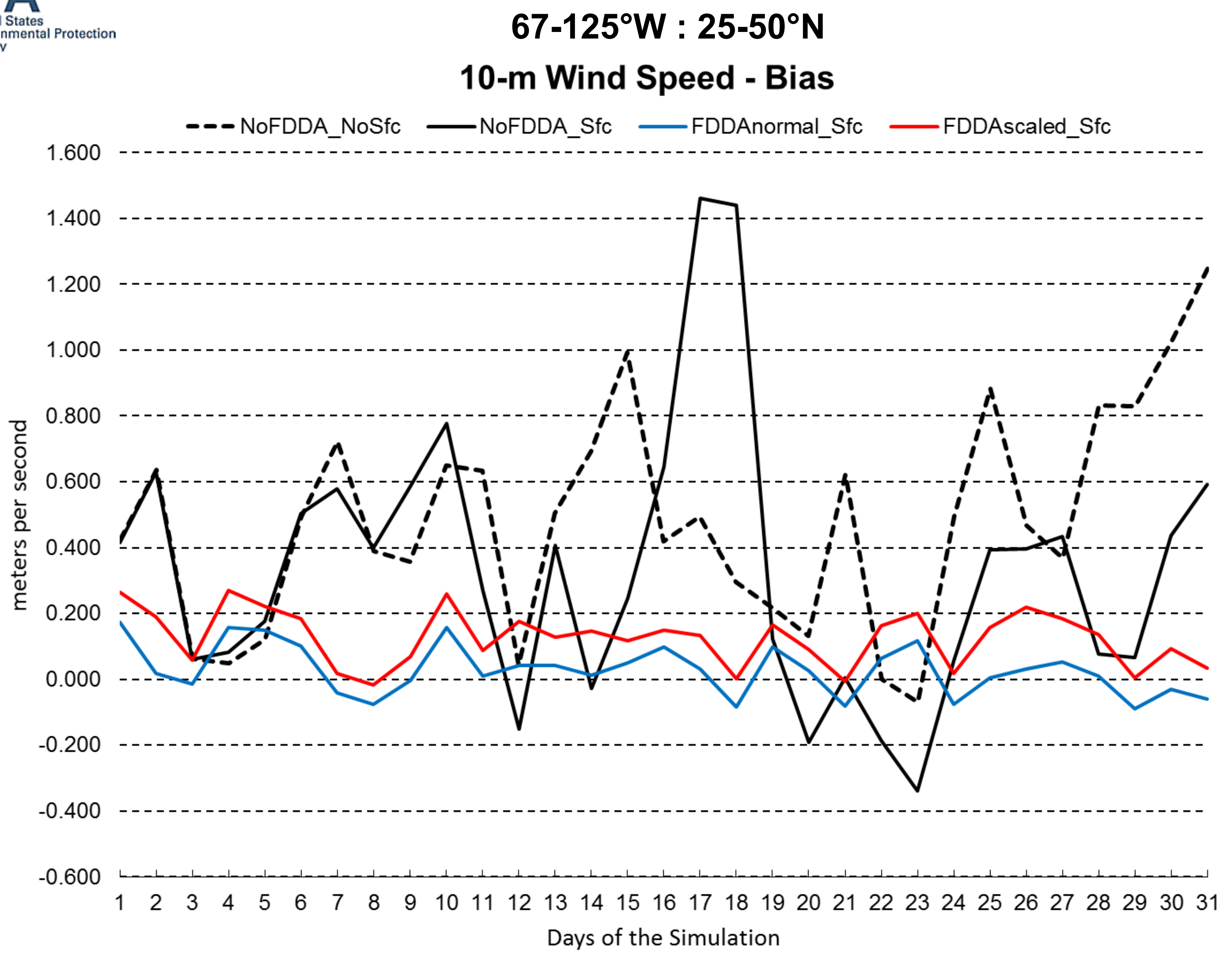


67-125°W : 25-50°N



67-125°W : 25-50°N





67-125°W : 25-50°N
10-m Wind Speed - Bias
NoFDDA_NoSfc
NoFDDA_Sfc
FDDAnormal_Sfc
FDDAscaled_Sfc
meters per second
1.600
1.400
1.200
1.000
0.800
0.600
0.400
0.200
0.000
-0.200
-0.400
-0.600
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31
Days of the Simulation

United States Environmental Protection Agency

67-125°W : 25-50°N