Overview of WRF-ARW FDDA Capabilities and Future Research and Development

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NCAR

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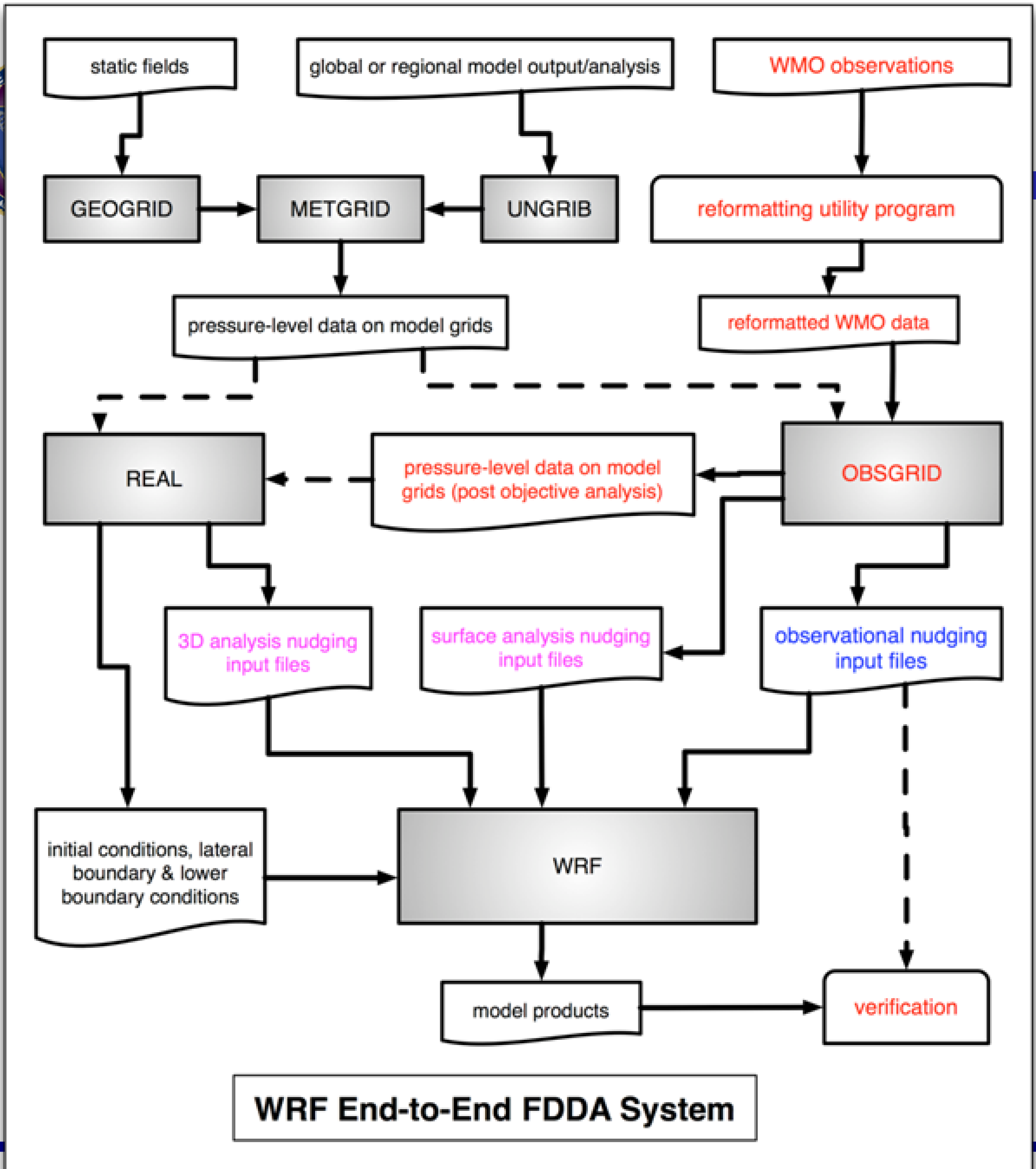
Objectives

- **Part I**
  - **Current status of the nudging FDDA capabilities in WRF-ARW, and status of the end-to-end FDDA system.**
  - **Test results of WRF nudging FDDA in a multiscale FDDA framework with several case studies.**
    - **Comparisons using NO FDDA, obs FDDA, analysis FDDA and multiscale FDDA**
    - **Comparison between MM5 and WRF**
- **Part II**
  - **Ongoing work with hybrid nudging-ensemble Kalman filter (EnKF). (Lili Lei's Ph.D research, advisor Dave Stauffer)**
- **Future Plans**


static fields
global or regional model output/analysis
WMO observations
GEOGRID
METGRID
UNGRIB
reformatting utility program
pressure-level data on model grids
reformatted WMO data
REAL
pressure-level data on model grids (post objective analysis)
OBSGRID
3D analysis nudging input files
surface analysis nudging input files
observational nudging input files
initial conditions, lateral boundary & lower boundary conditions
WRF
model products
verification
WRF End-to-End FDDA System

Flexibility and Improvement in Obs Nudging

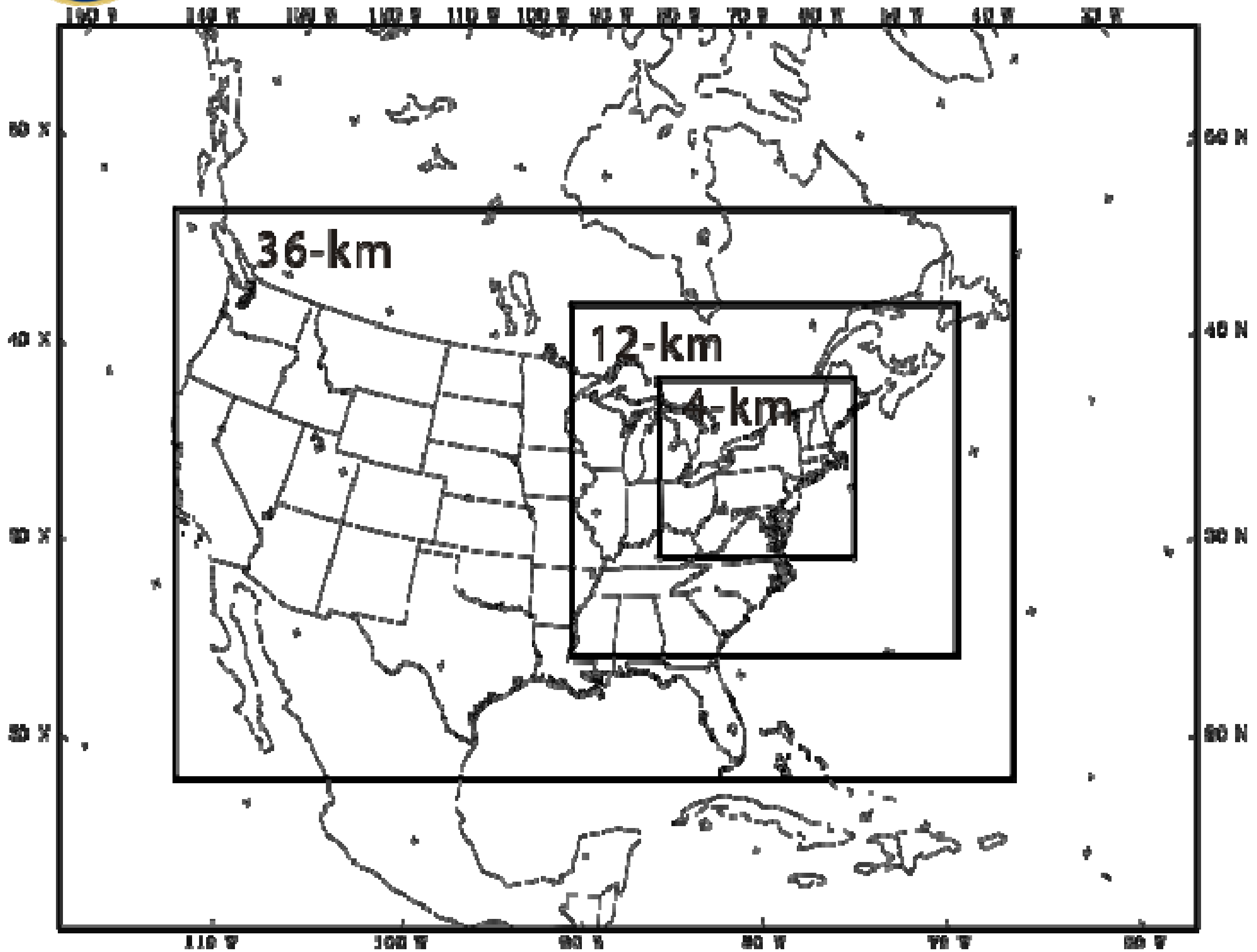
- Regime-dependent vertical influence functions for surface observations (e.g. obs_nudgezfullr1_t, obs_nudgezrampr1_t).
- Switch to exclude obs nudging from within the PBL (e.g. obs_no_pbl_nudge_t).
- Option to reduce time window (obs_sfcfact) and radius of influence for surface observations (obs_sfcfacr).
- Parameter to adjust nudging strength based on terrain difference between the obs site and grid point where the innovation is applied (obs_dpsmx).
- Improved diagnostic prints.

- **CAPTEX-83 Case**

48-h model simulation, 36-km/12-km/4-km domains,
32 vertical layers with the first half layer at ~30 m

Starting: 1200 UTC, 18 Sept. 1983
Ending: 1200 UTC, 20 Sept. 1983
(IC/LBC/FDDA inputs based on MM5 RAWINS)
Physics: MYJ PBL, KF CPS (on 36- and 12-km grids),
Dudhia SW and RRTM LW, etc

MM5/WRF Domains:
36, 12 and 4 km



Experimental Design for Multi-scale FDDA

PENNSTATE

1855

CAPTEX-83 (36/12/4-km grids)

Exp. name	36-km		12-km		4-km	
	Analysis Nudging	Obs Nudging	Analysis Nudging	Obs Nudging	Analysis Nudging	Obs Nudging
NOFDDA	NO	NO	NO	NO	NO	NO
OFDDA	NO	YES	NO	YES	NO	YES
GFDDA/S	YES	NO	YES	NO	NO	NO
MFDDA/S	YES	YES	YES	YES	NO	YES

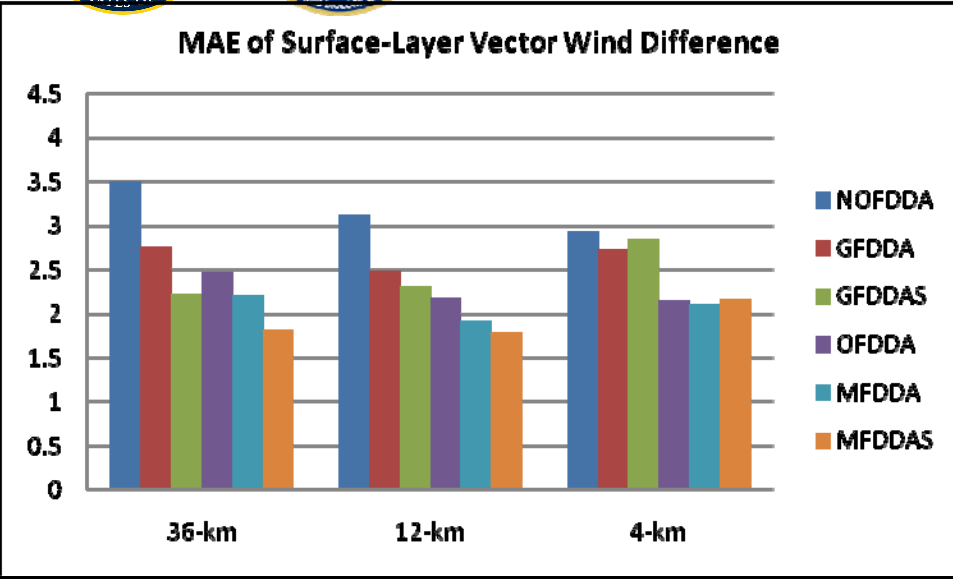
FDDA Experimental Design and Parameters CAPTEX-83 (36/12/4-km grids)

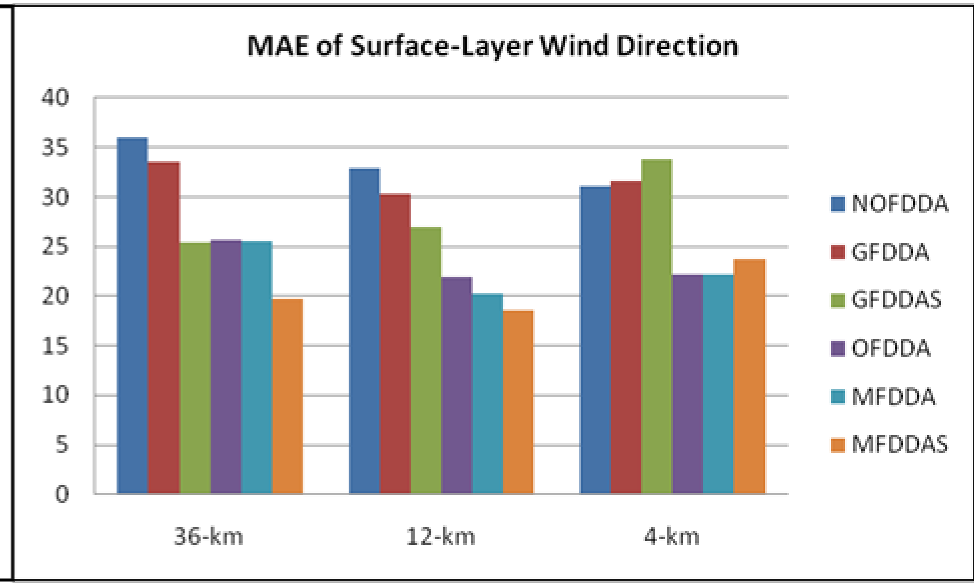
	3D and Surface Analysis Nudging			Obs Nudging		
	36-km	12-km	4-km	36-km	12-km	4-km
G (1/sec)	$3*10^{-4}$	$1*10^{-4}$	N/A	$4*10^{-4}$	$4*10^{-4}$	$4*10^{-4}$
3D Wind field	3D Nudging all layers	3D Nudging all layers	N/A	Nudging all layers	Nudging all layers	Nudging all layers
3D Mass field	3D Nudging above PBL	3D Nudging above PBL	N/A	Nudging above PBL	Nudging above PBL	Nudging above PBL
Sfc wind field	Used within PBL	Used within PBL	Used within PBL	Used within PBL	Used within PBL	Used within PBL
Sfc mass field	Used within PBL	Used within PBL	Used within PBL	Not used	Not used	Not used
RINXY (km)	N/A	N/A	N/A	150*	100*	100*
TWINDO (hr)	N/A	N/A	N/A	2**	2**	2**

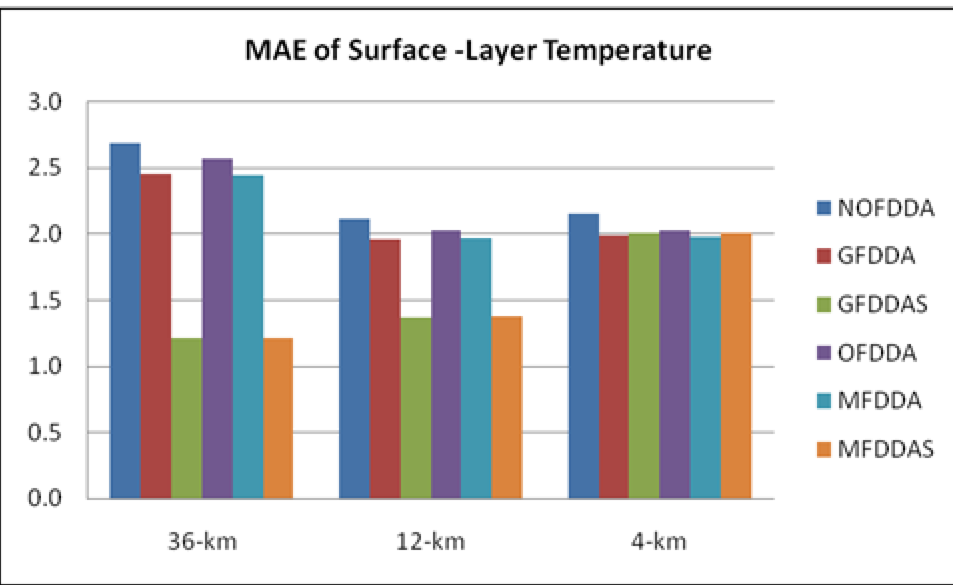
*** 0.67 factor for surface, 2.0 factor at 500 hPa and above**

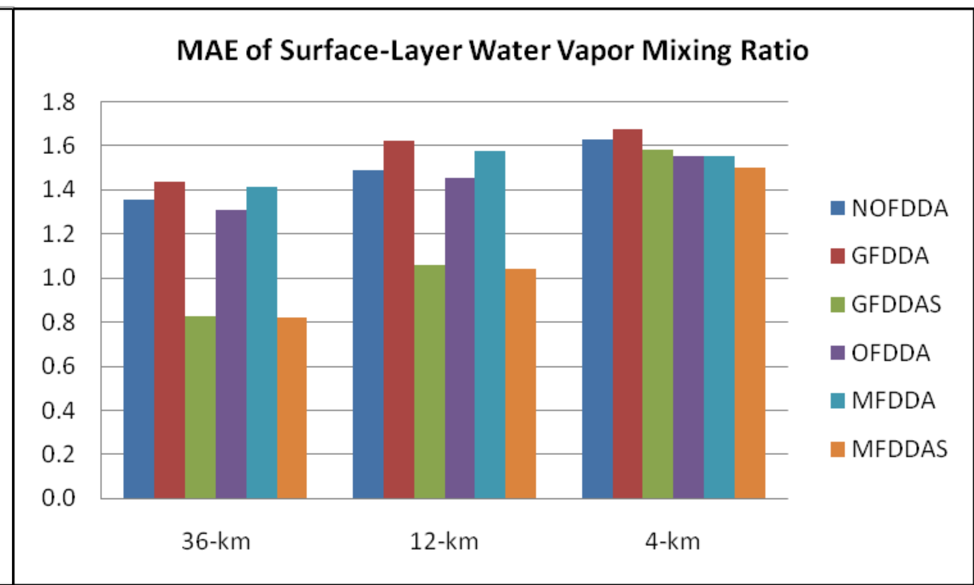
**** 0.5 factor for surface**

MAE of WRF-Simulated Surface Layer Fields Averaged Over 48-h Time Period

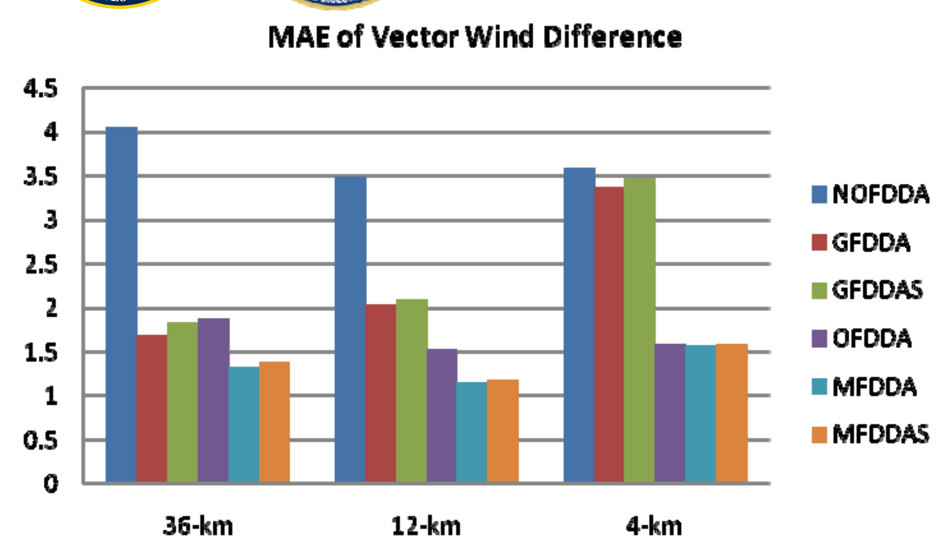


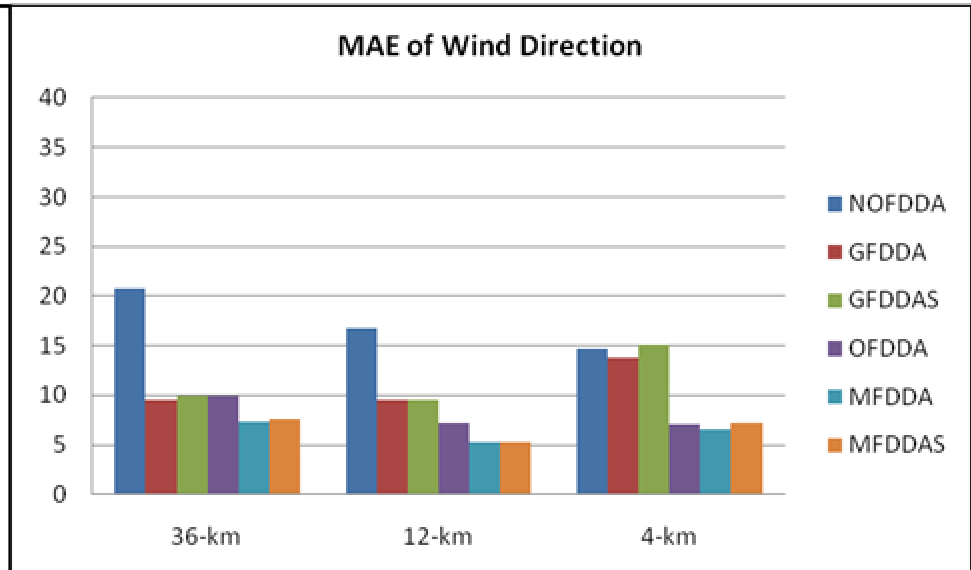


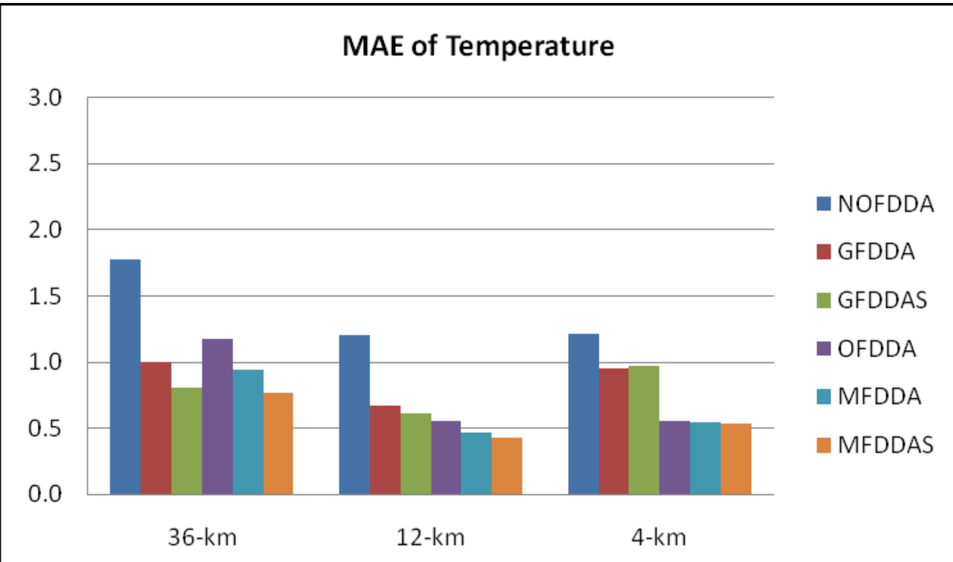


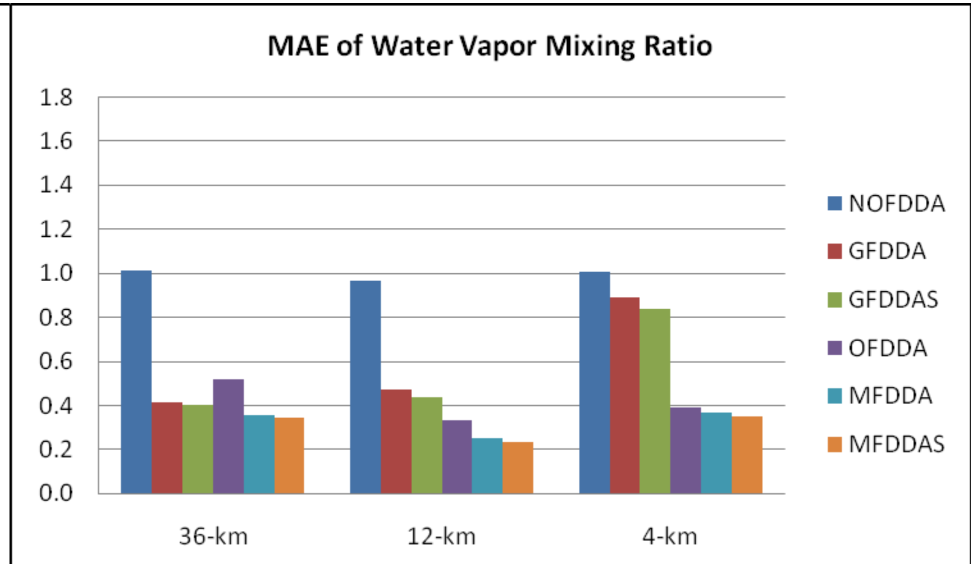


MAE of WRF-Simulated Fields Averaged Over 48-h Time Period And All Model Layers

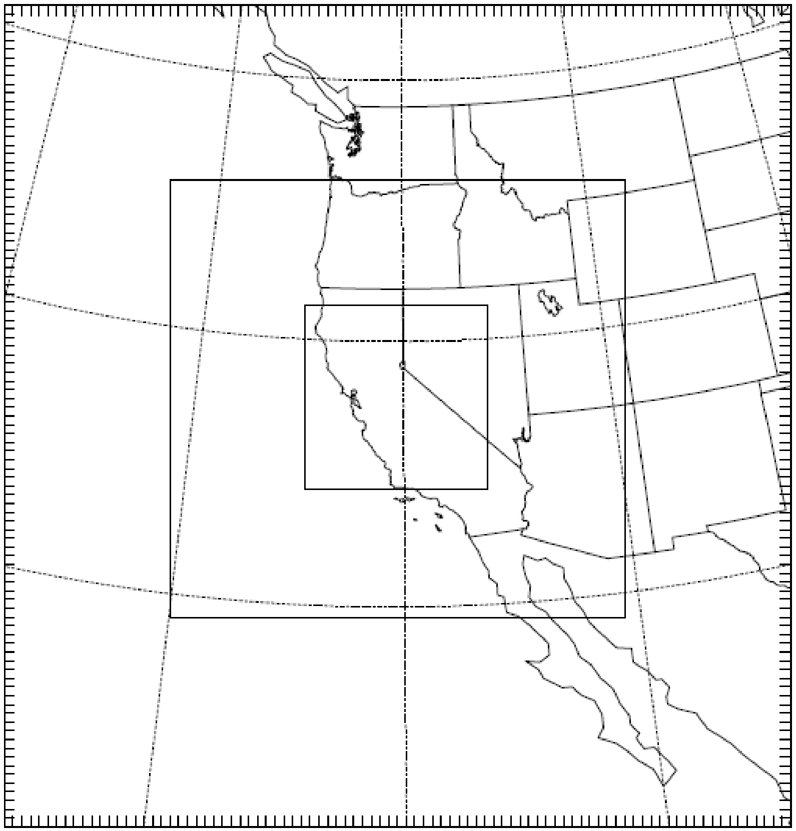


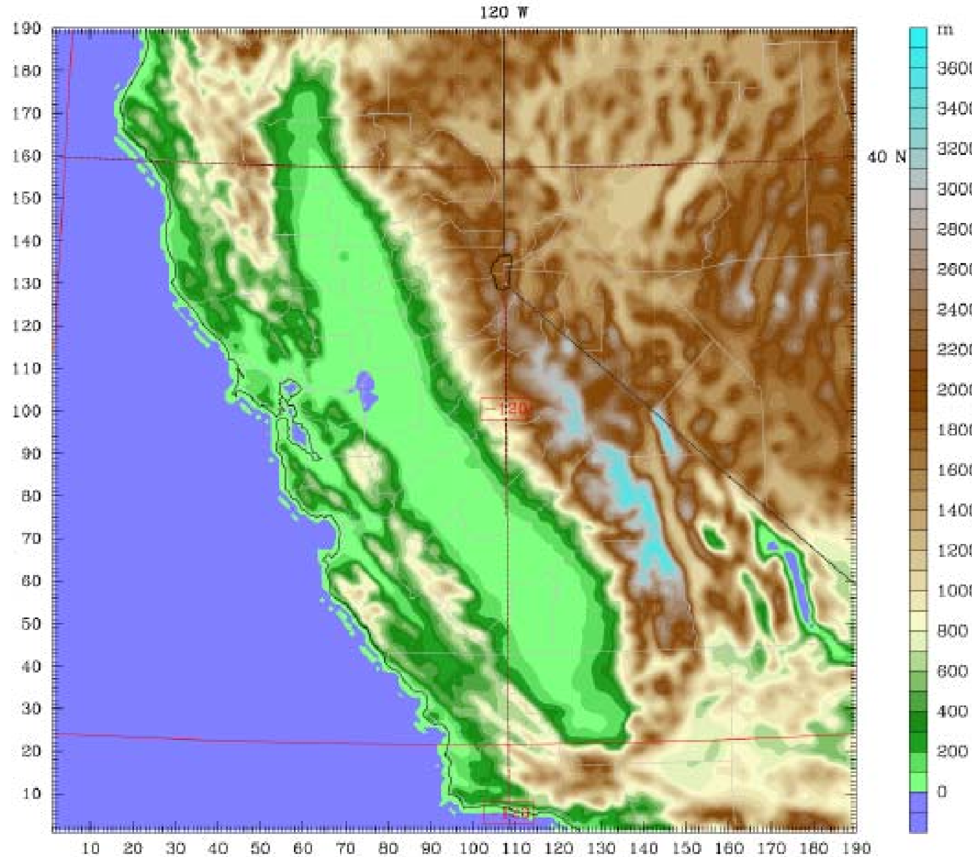






PSU West Coast Simulations

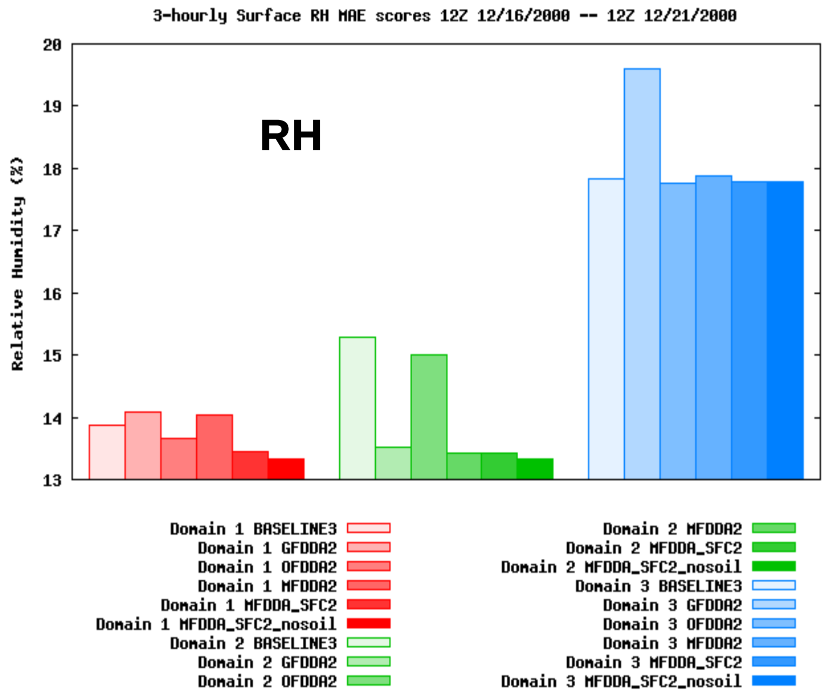


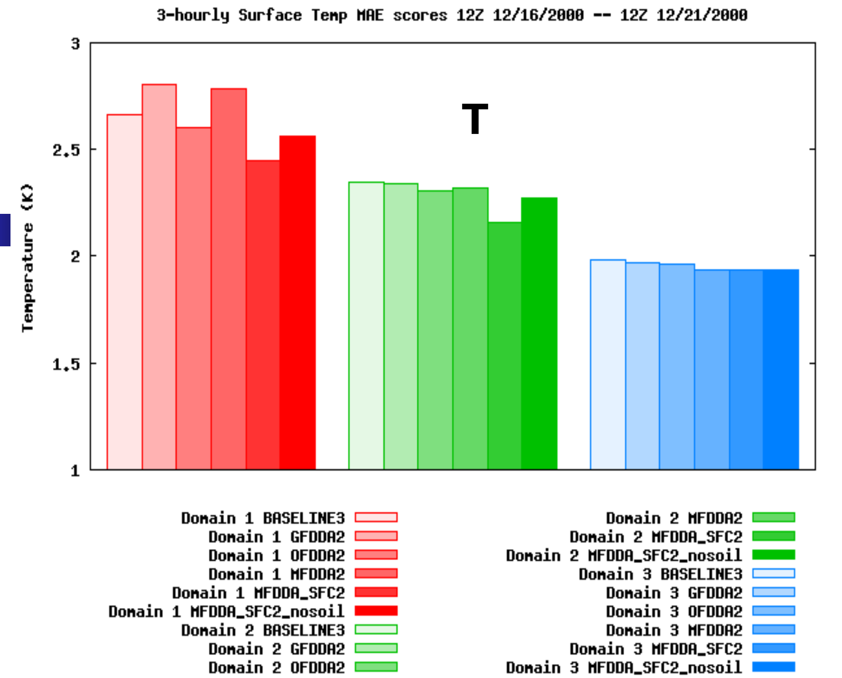


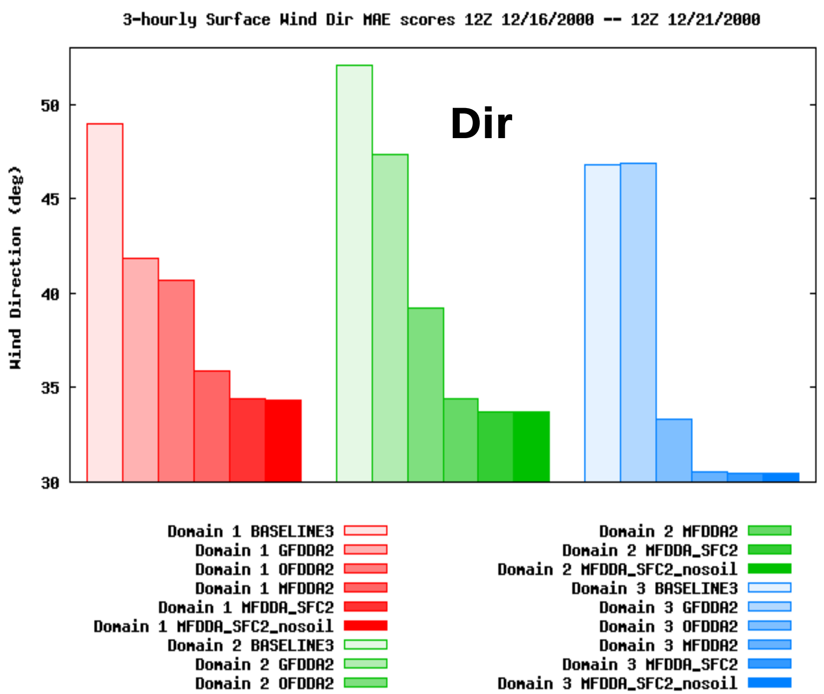
4-km Grid

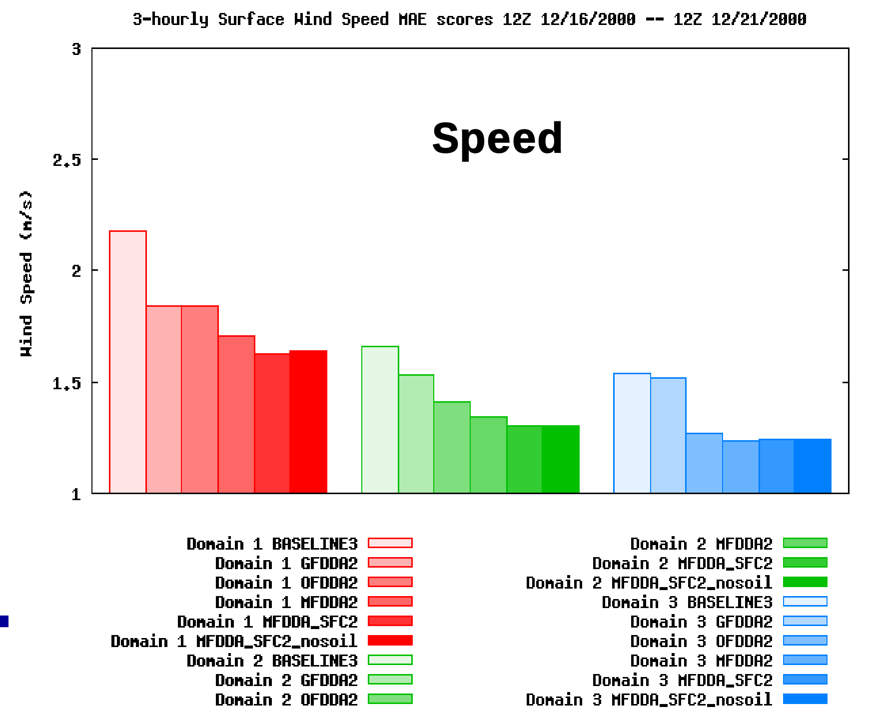
Experimental Design

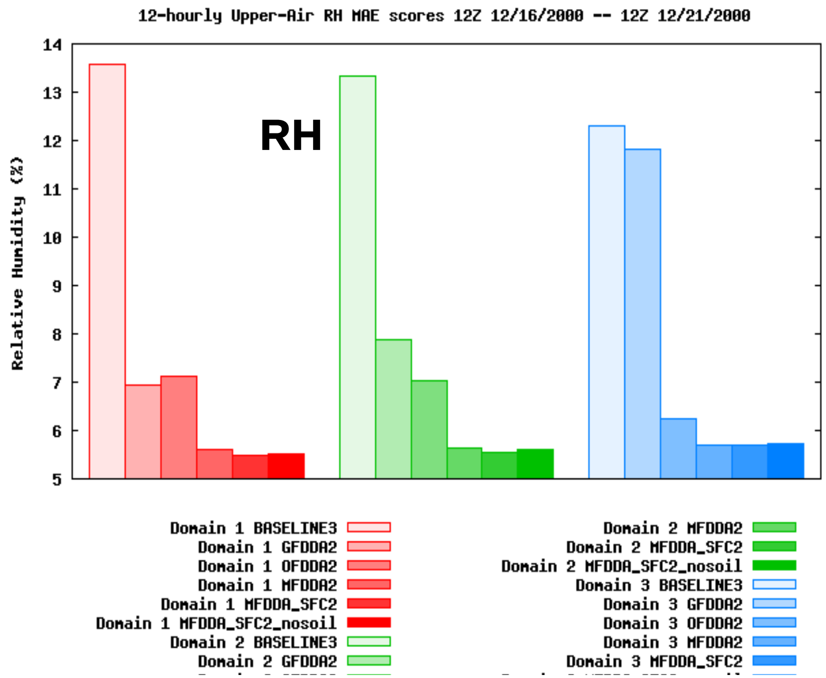
Exp. Name	36 km		12 km		4 km	
	Analysis Nudging	OBS Nudging	Analysis Nudging	OBS Nudging	Analysis Nudging	OBS Nudging
BASELINE2_PX or BASELINE3	NO	NO	NO	NO	NO	NO
GFDDA2	YES (3D)	NO	YES (3D)	NO	NO	NO
OFDDA2	NO	YES	NO	YES	NO	YES
MFDDA2	YES (3D)	YES	YES (3D)	YES	NO	YES
MFDDA_SFC2	YES (3D+Sfc+Soil)	YES	YES (3D+Sfc+Soil)	YES	NO	YES
MFDDA_SFC2_no soil	YES (3D+Sfc)	YES	YES (3D+Sfc)	YES	NO	YES

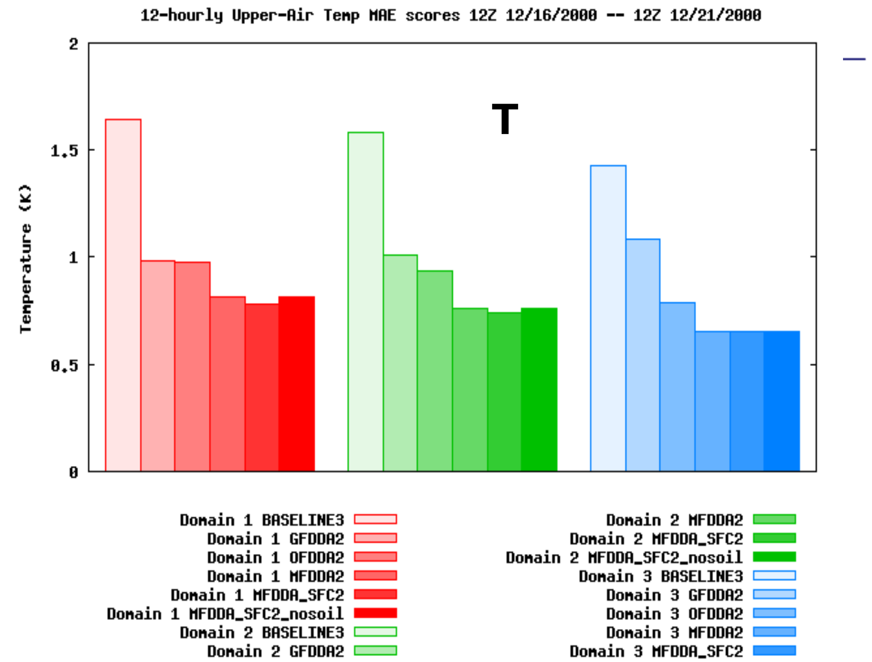

3-hourly Surface RH MAE scores 12Z 12/16/2000 -- 12Z 12/21/2000
RH
Relative Humidity (%)
20
19
18
17
16
15
14
13
Domain 1 BASELINE3
Domain 1 GFDDA2
Domain 1 OFDDA2
Domain 1 MFDDA2
Domain 1 MFDDA_SFC2
Domain 1 MFDDA_SFC2_nosoil
Domain 2 BASELINE3
Domain 2 GFDDA2
Domain 2 OFDDA2
Domain 2 MFDDA2
Domain 2 MFDDA_SFC2
Domain 2 MFDDA_SFC2_nosoil
Domain 3 BASELINE3
Domain 3 GFDDA2
Domain 3 OFDDA2
Domain 3 MFDDA2
Domain 3 MFDDA_SFC2
Domain 3 MFDDA_SFC2_nosoil

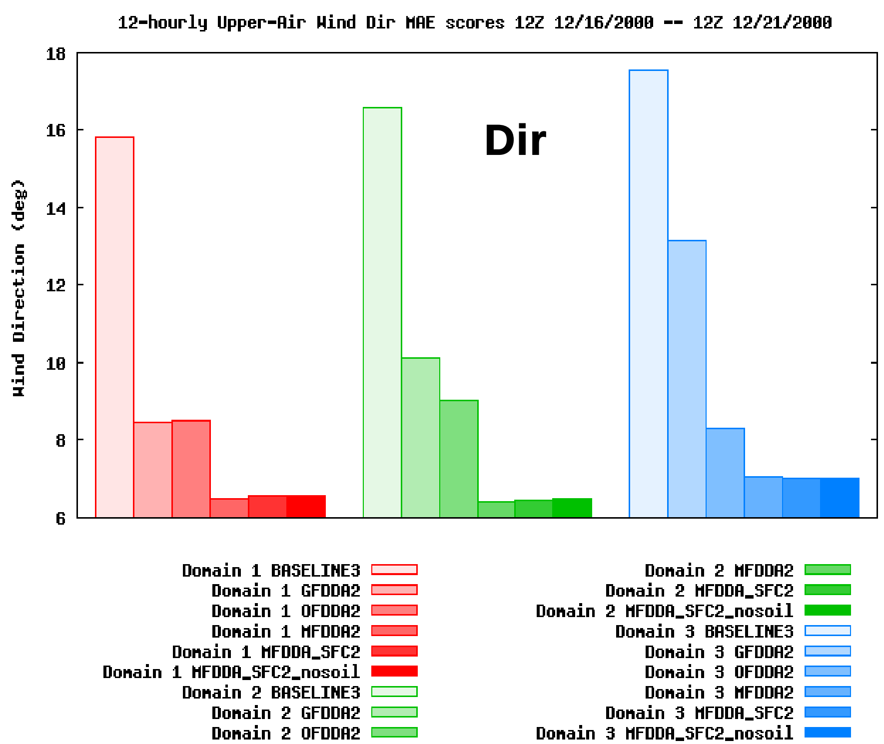

3-hourly Surface Temp MAE scores 12Z 12/16/2000 -- 12Z 12/21/2000
T
Temperature (K)
3
2.5
2
1.5
1
Domain 1 BASELINE3
Domain 1 GFDDA2
Domain 1 OFDDA2
Domain 1 MFDDA2
Domain 1 MFDDA_SFC2
Domain 1 MFDDA_SFC2_nosoil
Domain 2 BASELINE3
Domain 2 GFDDA2
Domain 2 OFDDA2
Domain 2 MFDDA2
Domain 2 MFDDA_SFC2
Domain 2 MFDDA_SFC2_nosoil
Domain 3 BASELINE3
Domain 3 GFDDA2
Domain 3 OFDDA2
Domain 3 MFDDA2
Domain 3 MFDDA_SFC2
Domain 3 MFDDA_SFC2_nosoil

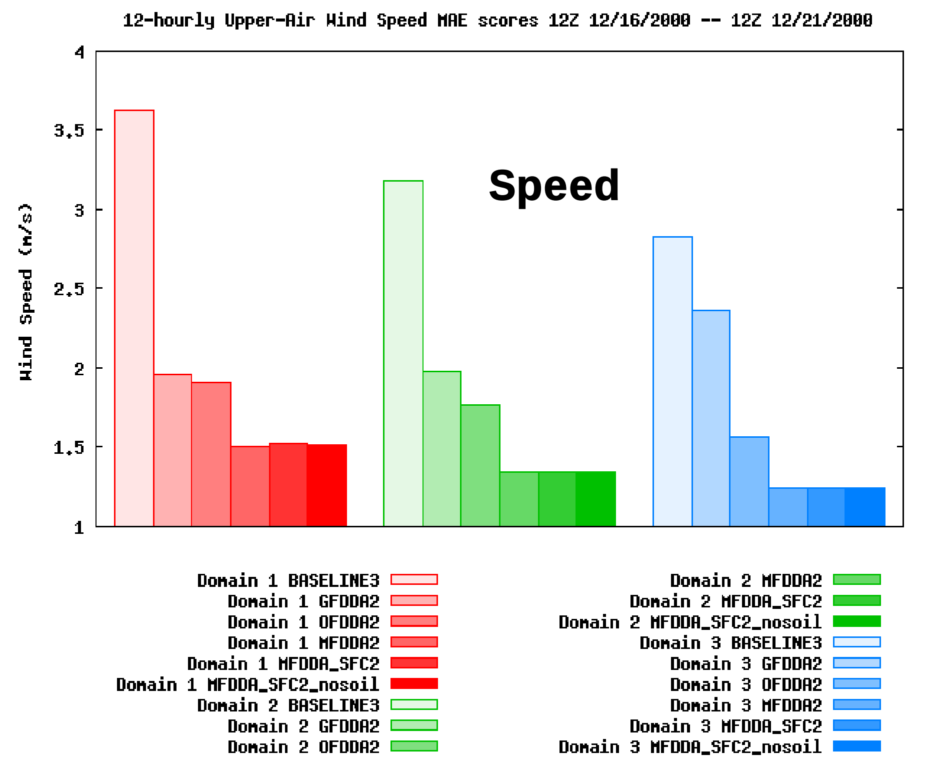

3-hourly Surface Wind Dir MAE scores 12Z 12/16/2000 -- 12Z 12/21/2000
Dir
Wind Direction (deg)
50
45
40
35
30
Domain 1 BASELINE3
Domain 1 GFDDA2
Domain 1 OFDDA2
Domain 1 MFDDA2
Domain 1 MFDDA_SFC2
Domain 1 MFDDA_SFC2_nosoil
Domain 2 BASELINE3
Domain 2 GFDDA2
Domain 2 OFDDA2
Domain 2 MFDDA2
Domain 2 MFDDA_SFC2
Domain 2 MFDDA_SFC2_nosoil
Domain 3 BASELINE3
Domain 3 GFDDA2
Domain 3 OFDDA2
Domain 3 MFDDA2
Domain 3 MFDDA_SFC2
Domain 3 MFDDA_SFC2_nosoil


3-hourly Surface Wind Speed MAE scores 12Z 12/16/2000 -- 12Z 12/21/2000
Speed
Wind Speed (m/s)
3
2.5
2
1.5
1
Domain 1 BASELINE3
Domain 1 GFDDA2
Domain 1 OFDDA2
Domain 1 MFDDA2
Domain 1 MFDDA_SFC2
Domain 1 MFDDA_SFC2_nosoil
Domain 2 BASELINE3
Domain 2 GFDDA2
Domain 2 OFDDA2
Domain 2 MFDDA2
Domain 2 MFDDA_SFC2
Domain 2 MFDDA_SFC2_nosoil
Domain 3 BASELINE3
Domain 3 GFDDA2
Domain 3 OFDDA2
Domain 3 MFDDA2
Domain 3 MFDDA_SFC2
Domain 3 MFDDA_SFC2_nosoil


12-hourly Upper-Air RH MAE scores 12Z 12/16/2000 -- 12Z 12/21/2000
RH
Relative Humidity (%)
Domain 1 BASELINE3
Domain 1 GFDDA2
Domain 1 OFDDA2
Domain 1 MFDDA2
Domain 1 MFDDA_SFC2
Domain 1 MFDDA_SFC2_nosoil
Domain 2 BASELINE3
Domain 2 GFDDA2
Domain 2 MFDDA2
Domain 2 MFDDA_SFC2
Domain 2 MFDDA_SFC2_nosoil
Domain 3 BASELINE3
Domain 3 GFDDA2
Domain 3 OFDDA2
Domain 3 MFDDA2
Domain 3 MFDDA_SFC2


12-hourly Upper-Air Temp MAE scores 12Z 12/16/2000 -- 12Z 12/21/2000
T
Temperature (K)
Domain 1 BASELINE3
Domain 1 GFDDA2
Domain 1 OFDDA2
Domain 1 MFDDA2
Domain 1 MFDDA_SFC2
Domain 1 MFDDA_SFC2_nosoil
Domain 2 BASELINE3
Domain 2 GFDDA2
Domain 2 MFDDA2
Domain 2 MFDDA_SFC2
Domain 2 MFDDA_SFC2_nosoil
Domain 3 BASELINE3
Domain 3 GFDDA2
Domain 3 OFDDA2
Domain 3 MFDDA2
Domain 3 MFDDA_SFC2


12-hourly Upper-Air Wind Dir MAE scores 12Z 12/16/2000 -- 12Z 12/21/2000
Dir
Wind Direction (deg)
Domain 1 BASELINE3
Domain 1 GFDDA2
Domain 1 OFDDA2
Domain 1 MFDDA2
Domain 1 MFDDA_SFC2
Domain 1 MFDDA_SFC2_nosoil
Domain 2 BASELINE3
Domain 2 GFDDA2
Domain 2 OFDDA2
Domain 2 MFDDA2
Domain 2 MFDDA_SFC2
Domain 2 MFDDA_SFC2_nosoil
Domain 3 BASELINE3
Domain 3 GFDDA2
Domain 3 OFDDA2
Domain 3 MFDDA2
Domain 3 MFDDA_SFC2
Domain 3 MFDDA_SFC2_nosoil


12-hourly Upper-Air Wind Speed MAE scores 12Z 12/16/2000 -- 12Z 12/21/2000
Speed
Wind Speed (m/s)
Domain 1 BASELINE3
Domain 1 GFDDA2
Domain 1 OFDDA2
Domain 1 MFDDA2
Domain 1 MFDDA_SFC2
Domain 1 MFDDA_SFC2_nosoil
Domain 2 BASELINE3
Domain 2 GFDDA2
Domain 2 OFDDA2
Domain 2 MFDDA2
Domain 2 MFDDA_SFC2
Domain 2 MFDDA_SFC2_nosoil
Domain 3 BASELINE3
Domain 3 GFDDA2
Domain 3 OFDDA2
Domain 3 MFDDA2
Domain 3 MFDDA_SFC2
Domain 3 MFDDA_SFC2_nosoil

WRF vs MM5

Obs nudging on all three grids

MM5NOFDDA:	**MM5 without FDDA**
MM5FDDA:	**MM5 with Obs nudging only**
NOFDDA:	**WRF without FDDA**
OFDDA:	**WRF with Obs nudging only**
OFDDAD:	**WRF with Obs nudging only, with improved vertical spreading for regime 4 as in surface analysis nudging**

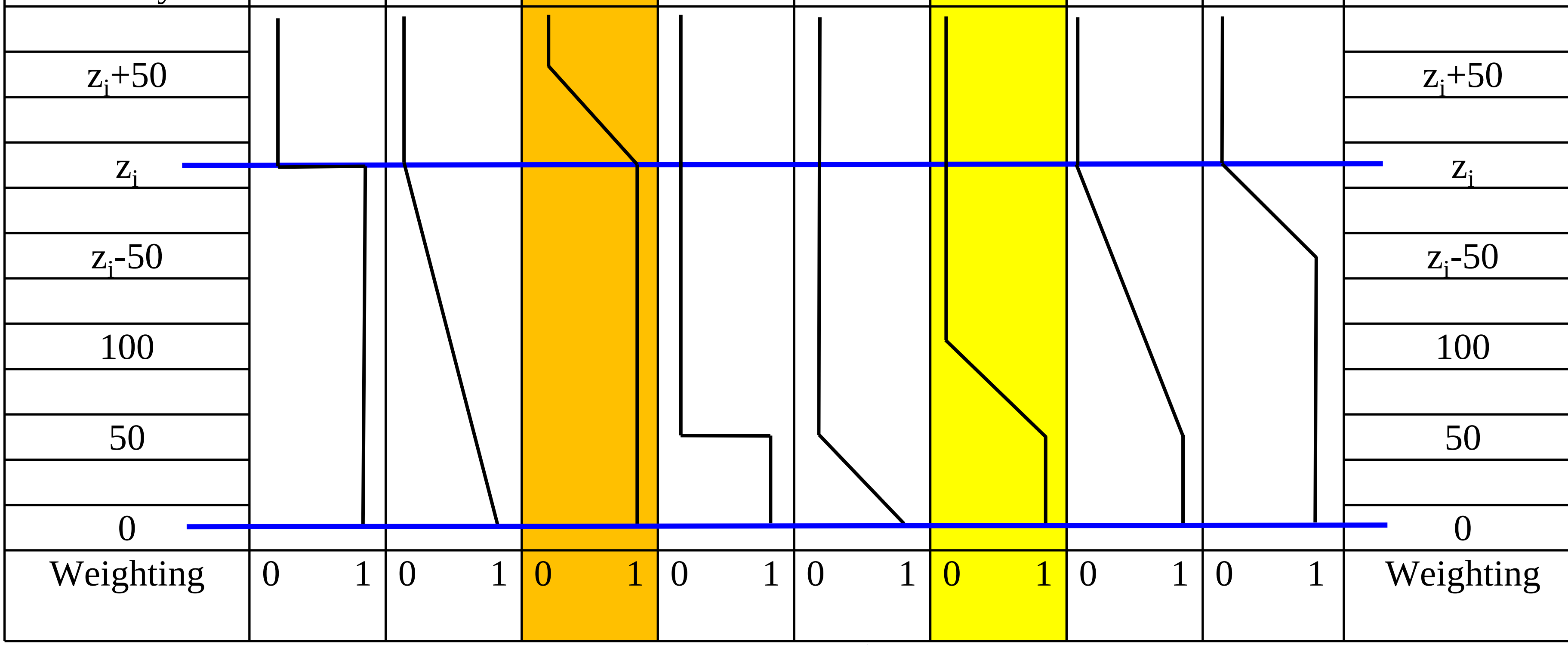
Note: Both MM5 and WRF use identical configurations, same inputs, same physics, same obs nudging parameters (e.g. same SFCFACT, SFCFACR, and same vertical spreading except OFDDAD)

Vertical Weighting Examples in WRF Obs nudging

Default for regime 4

Default for regimes 1 and 2

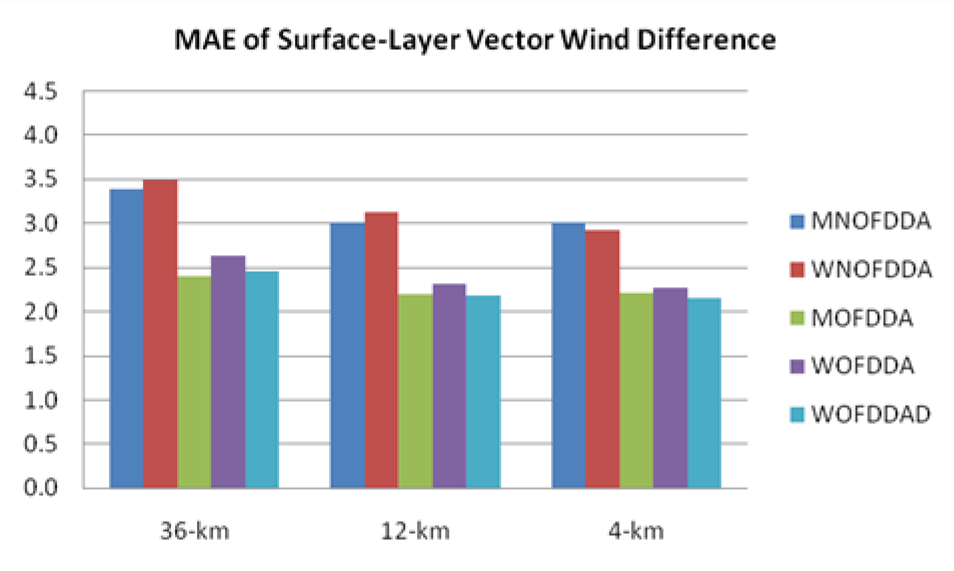
Column #	1	2	3	4	5	6	7	8	Column #
Ramp Layer	0	-5000	50	0	50	50	-5000	-5000	obs_nudgezrampr*
Full Layer	-5000	0	-5000	50	0	50	50	-4950	obs_nudgezfullr*

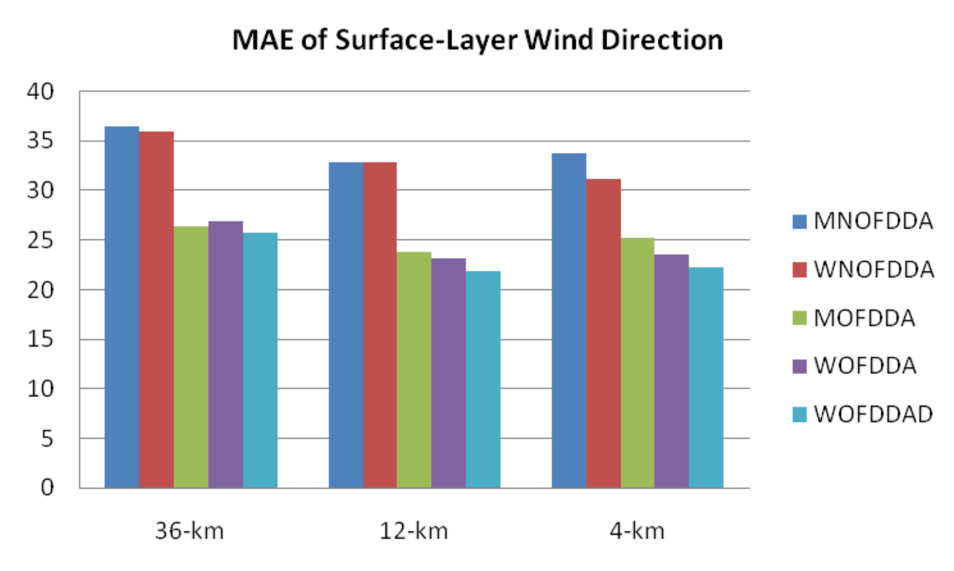


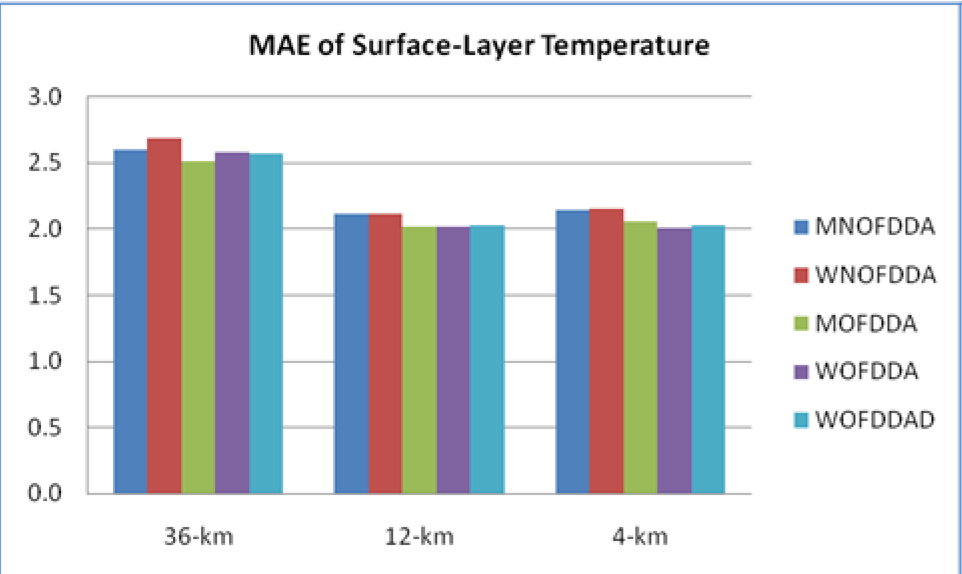
Original WRF default (all regimes)

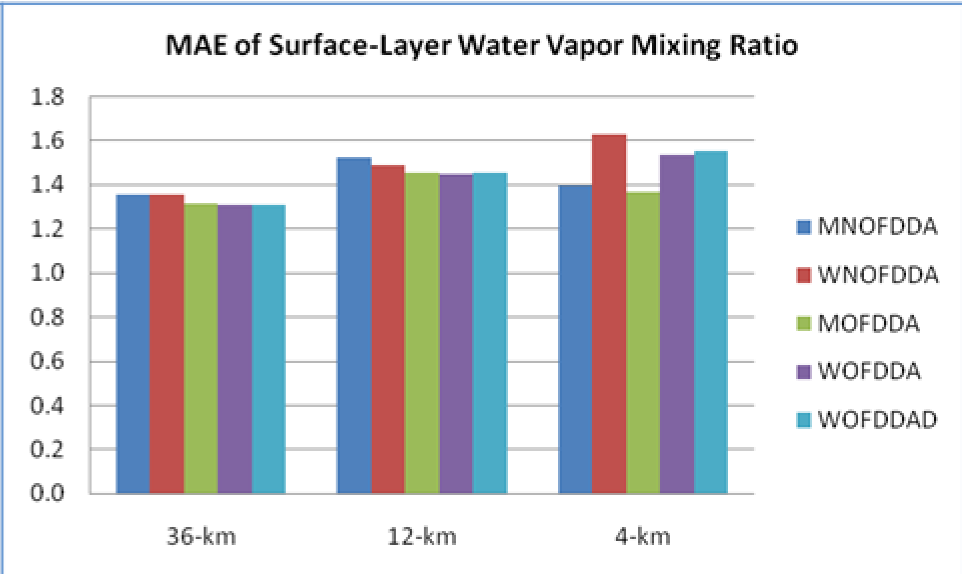
MM5 default (but lowest 3 layers and only wind; all regimes

MAE of WRF- and MM5-Simulated Surface Layer Fields Averaged Over 48-h Time Period

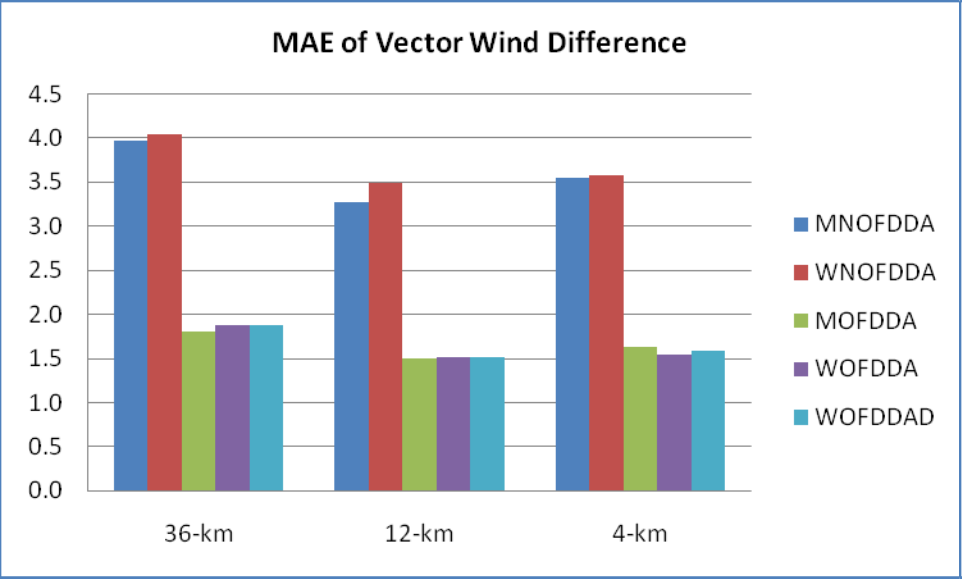


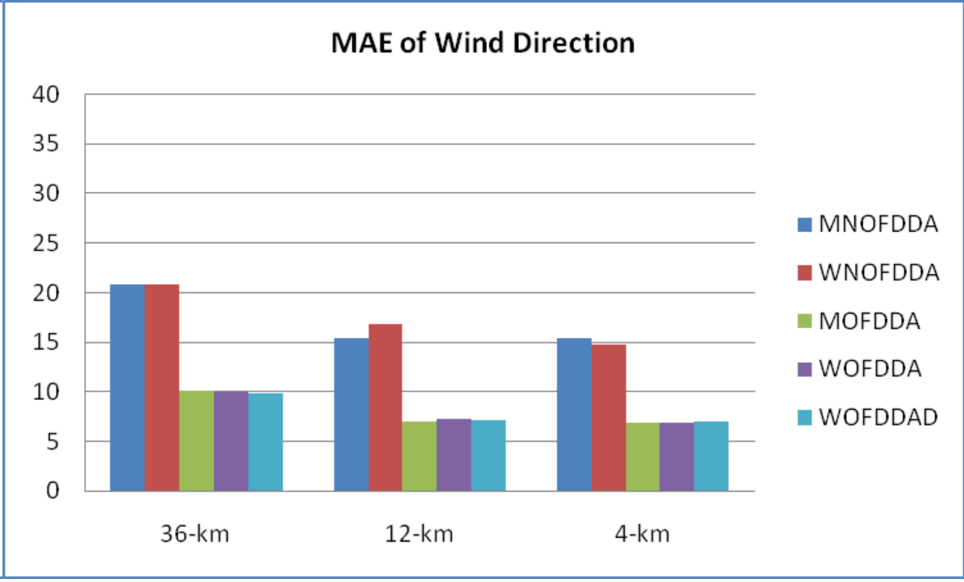


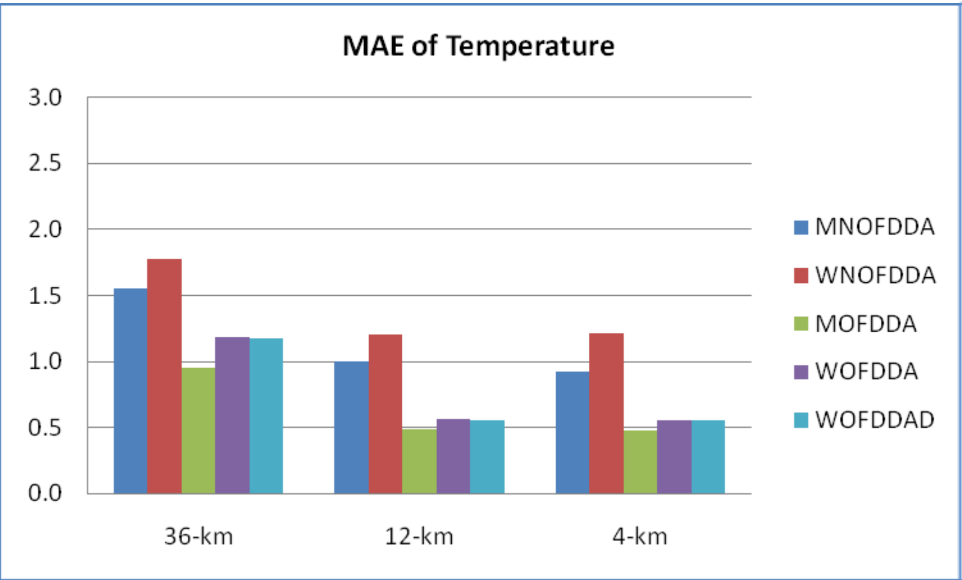


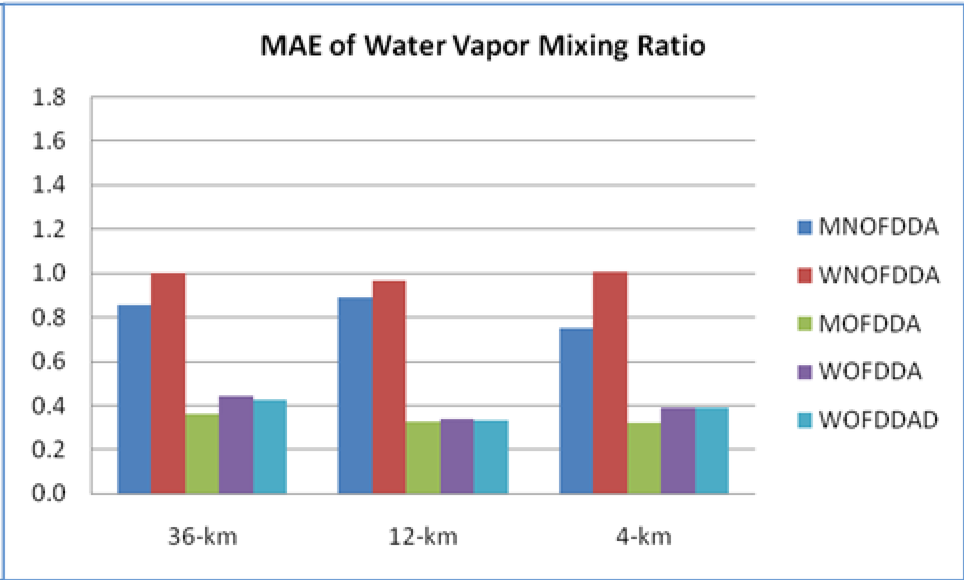


MAE of WRF- and MM5-Simulated Fields Averaged Over 48-h Time Period And All Model Layers









Part I: Summary
WRF Multiscale FDDA

- 3D/Sfc analysis-nudging only and obs-nudging only significantly reduce model error.
- Analysis nudging (with surface analysis nudging) shows closer fit to obs on the coarser 36-km grid, and obs nudging better fits the obs on the 12-km grid, as expected due to weaker analysis nudging strength.
- Multiscale FDDA (combined analysis and obs nudging) with surface analysis nudging has the best performance.
- PX soil nudging is done independently from the PSU surface analysis nudging, except for the on/off switch (user caution is needed when changing the surface analysis nudging coefficients).

Part I: Summary
WRF VS MM5 obs nudging

- **Surface (wind only, no mass fields nudged):**

  - **MM5 and WRF have similar error reduction due to use of obs nudging.**

  - **MM5 (with and without FDDA) has slightly smaller error in surface-layer VWD field. WRF with FDDA has slightly smaller error in surface-layer wind direction on 12- and 4-km grids.**

  - **The new default vertical spreading option for regime 4 in surface wind nudging in WRF appears to further improve both surface wind stats.**

Part I: Summary
WRF VS MM5 obs nudging

- **Upper Air:**
  - **MM5 has smaller error in mass field (both with and without FDDA).**
  - **MM5 and WRF have similar error reduction due to use of obs nudging.**

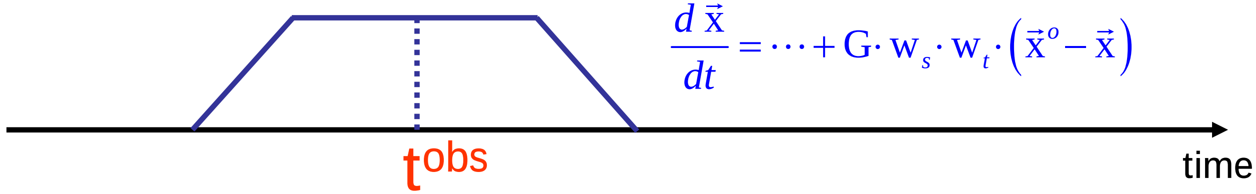
Hybrid Nudging-Ensemble Kalman Filter (EnKF)

- **WRF IC / LBC:**
  NCEP/NCAR Global Reanalysis Products enhanced by observations via OBSGRID
- **3DVAR is used to perturb the IC and LBC.**
- **Ensemble size is 24. Currently only IC and LBC perturbations are applied. Different model physics will be used to create additional ensemble members.**
- **Three-hourly WMO surface observations and twelve-hourly rawinsondes are used for assimilation and fit-to-observations statistics.**
- **The observation error variances of wind and temperature are adapted from 3DVAR. The observation error variance of relative humidity is set to 10% of the saturated specific humidity.**

WRF /SCIPUFF Experiments

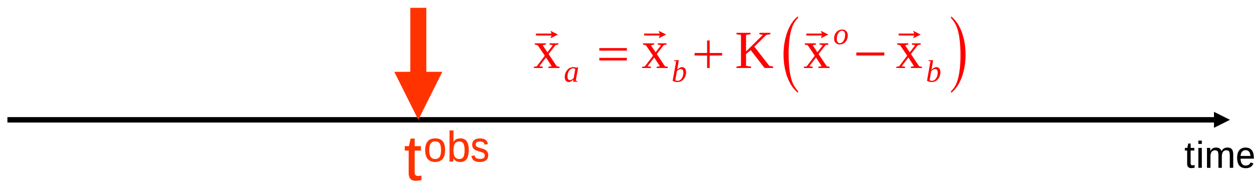
Exp. name	Exp. description
NOFDDA	Assimilate no observations
NOEnKF	Assimilate no observations in ensemble
EnKF	Assimilate observations by ensemble adjustment Kalman filter (EAKF)
FDDA	Assimilate observations by traditional observation nudging with nudging coefficients of $4*10^{-4}\ s^{-1}$
Hybrid	Assimilate observations by hybrid EnKF (in progress)
Hybrid2	Same as Hybrid except doubling of hybrid nudging coefficients

Nudging:



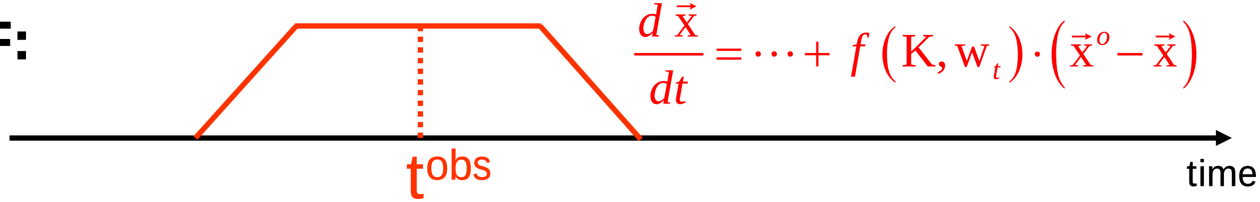
$$\frac{d\vec{x}}{dt} = \cdots + G \cdot w_s \cdot w_t \cdot \left(\vec{x}^o - \vec{x}\right)$$

EnKF:



$$\vec{x}_a = \vec{x}_b + K\left(\vec{x}^o - \vec{x}_b\right)$$

Hybrid EnKF:



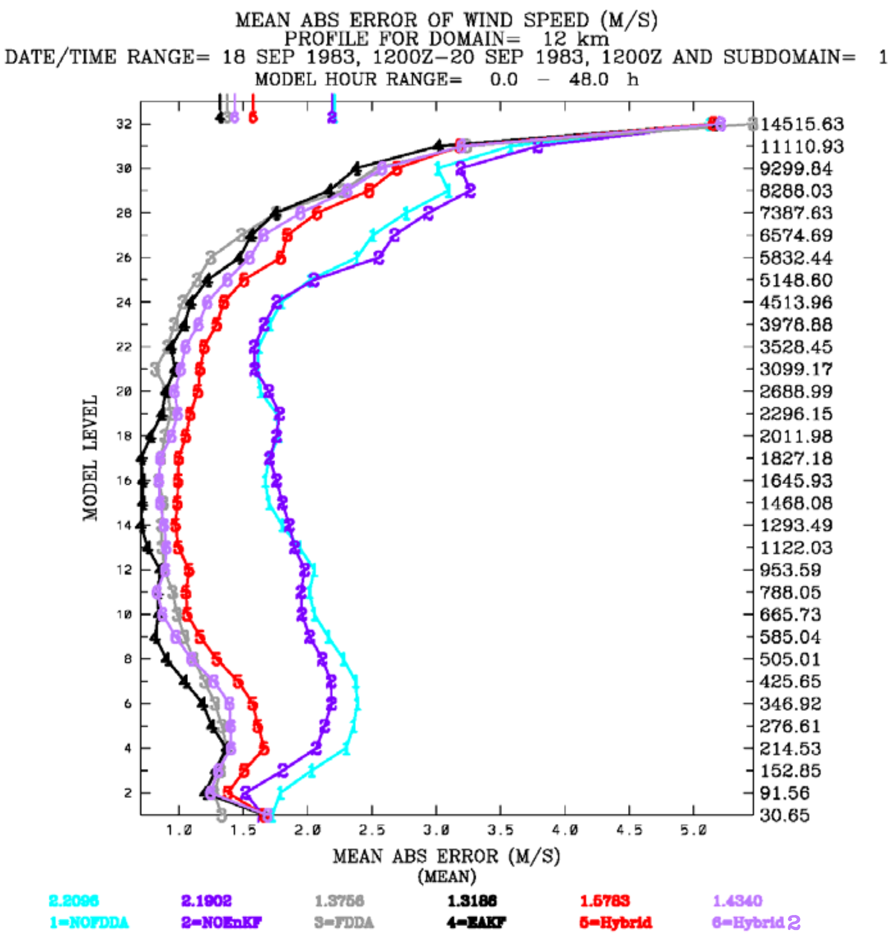
$$\frac{d\vec{x}}{dt} = \cdots + f\left(K, w_t\right) \cdot \left(\vec{x}^o - \vec{x}\right)$$

- **The hybrid nudging coefficients:**

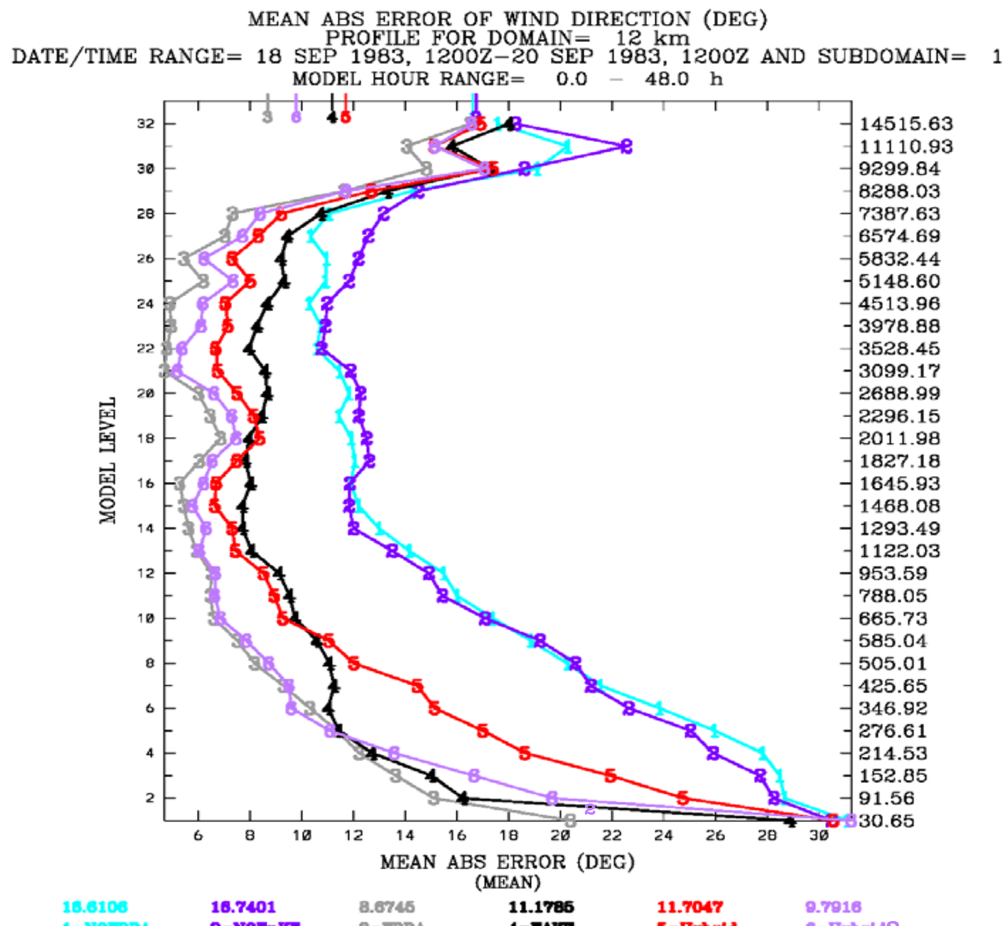
$$\frac{d\vec{x}}{dt} = \quad \cdots \quad + G \cdot w_s \cdot w_t \cdot \left(\vec{x}^o - \vec{x}\right)$$

$$G \cdot w_s = \frac{1}{\sum_t w_t \cdot \Delta t} \cdot K$$

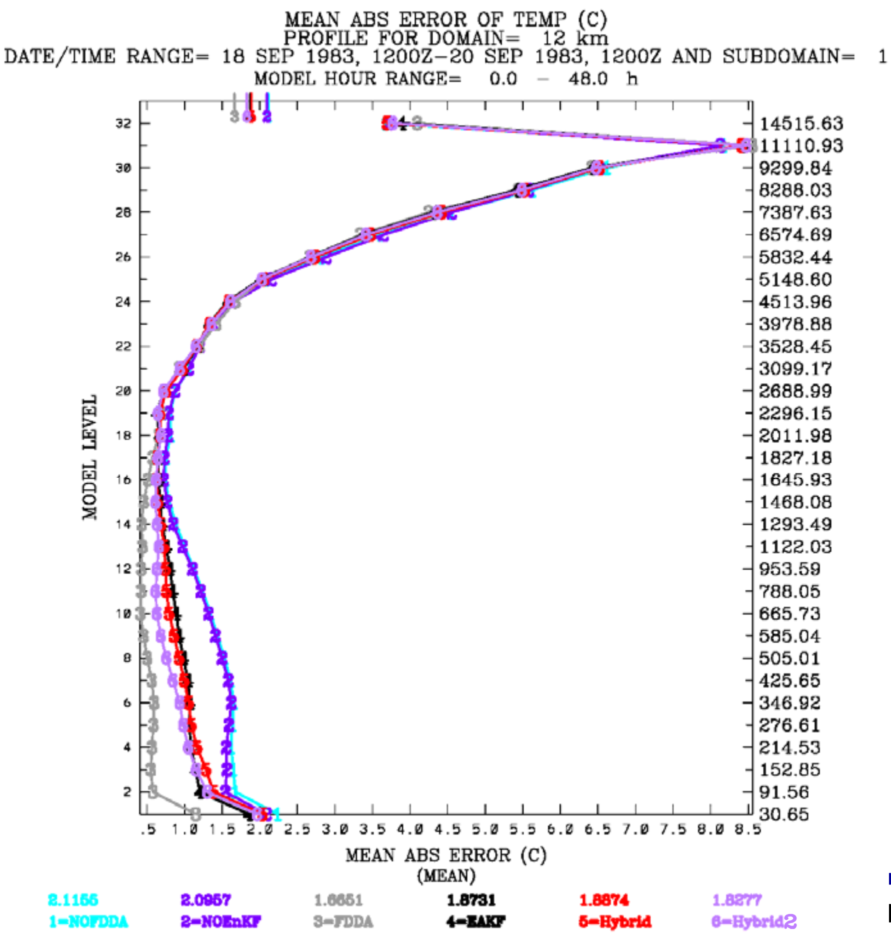
MAE Wind Speed Profile



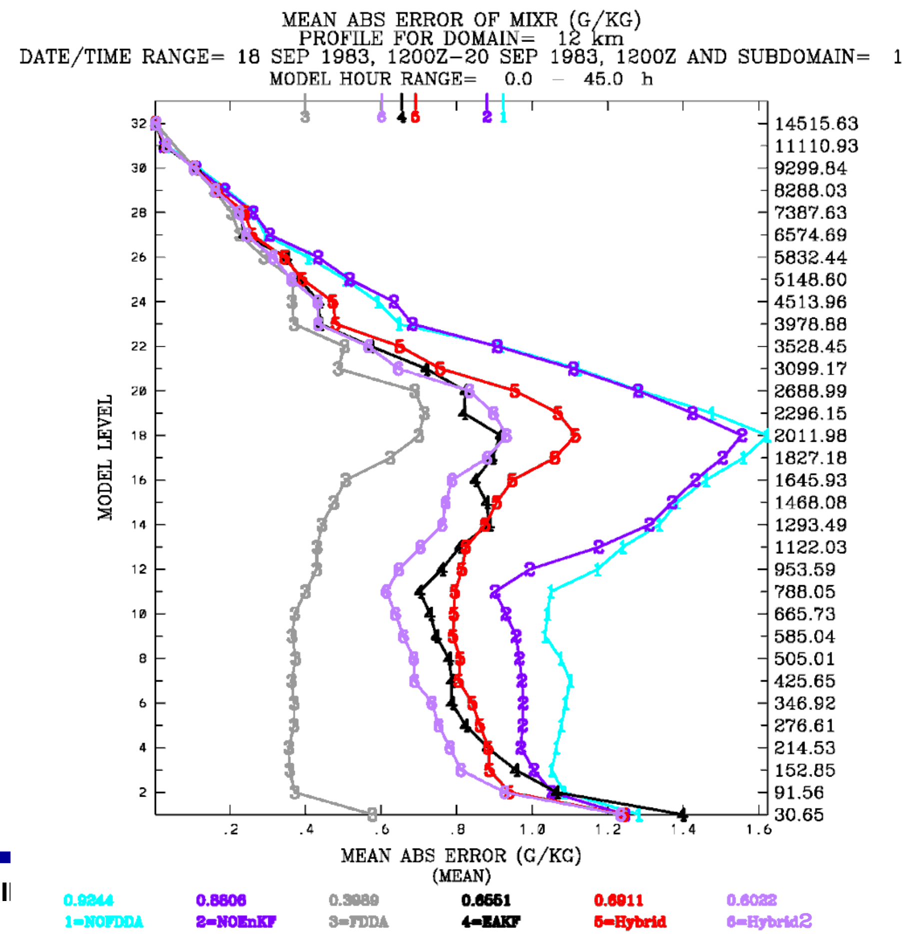
MAE Wind Direction Profile



MAE Temperature Profile



MAE Mixing Ratio Profile



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Part II: Conclusions - EnKF

- The EnKF, hybrid EnKF and FDDA experiments produce better analyses than the corresponding NOFDDA and NOEnKF simulations based on fit statistics.
- FDDA produces better analyses than the EnKF, especially for assimilation of surface observations partially due to the fact that EnKF is not using all surface obs used in FDDA.
- The hypothesis here is that the hybrid EnKF combining the advantages of both nudging (continuous small corrections) and EnKF (flow-dependent error covariances) will produce a better WRF dynamic analysis than either nudging or EnKF applied separately.