UPDATE ON ANALYSIS NUDGING FDDA IN WRF-ARW

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- Nudging FDDA techniques (both analysis and OBS nudging) was developed at Penn State for MM5 by Stauffer and Seaman in early 1990s.
- Nudging is an efficient way to reduce model errors and it has been successful in MM5 (e.g. DA, DI, better BC for coarse grid)
- Most recent applications include:
  - U.S. Army Profiler (OBS nudging)
  - U.S. Marines NEXGEN (OBS nudging)
  - DTRA in-house MM5 modeling system (OBS and analysis nudging)

- **Penn State has implemented a basic 3-D analysis nudging capability in WRF-ARW in WRF2.2 release, supported by EPA and AFWA.**

- **Basic FDDA functions in WRF-ARW (similar to MM5):**
  - **User-specified nudging end-time and rampdown period to zero**
  - **User-specified strength of nudging**
  - **User-specified nudging within the planetary boundary layer**
  - **User-specified nudging in lower model layers**

Nudging FDDA in WRF

$$For\ \alpha = \Theta = \mu \bullet \theta$$

$$\frac{\partial \Theta}{\partial t} = ... + \mu \frac{\partial \theta}{\partial t} + \theta \frac{\partial \mu}{\partial t}$$

$$\frac{\partial \Theta}{\partial t} = ... + \mu \bullet G_\theta \bullet W \bullet (\theta_{ob} - \theta)$$

$$+ \theta \bullet G_\mu \bullet W \bullet (\mu_{ob} - \mu)$$

$$where\ W = w_{xy} \bullet w_\eta \bullet w_t$$

μ

Currently

- Nudging u, v, theta, q
- μ is not being nudged

Testing Design

- CAPTEX-83, 48 hours model run, 36-km CONUS domain
  - Starting: 1200 UTC, 18 Sept. 1983
  - Ending: 1200 UTC, 20 Sept. 1983

- 3D Analyses from MM5 RAWINS and converted into WRF input format

- All experiments use M.Y.J PBL scheme, KF CPS, WSM 3-class simple ice, Dudhia shortwave and RRTM longwave radiation.

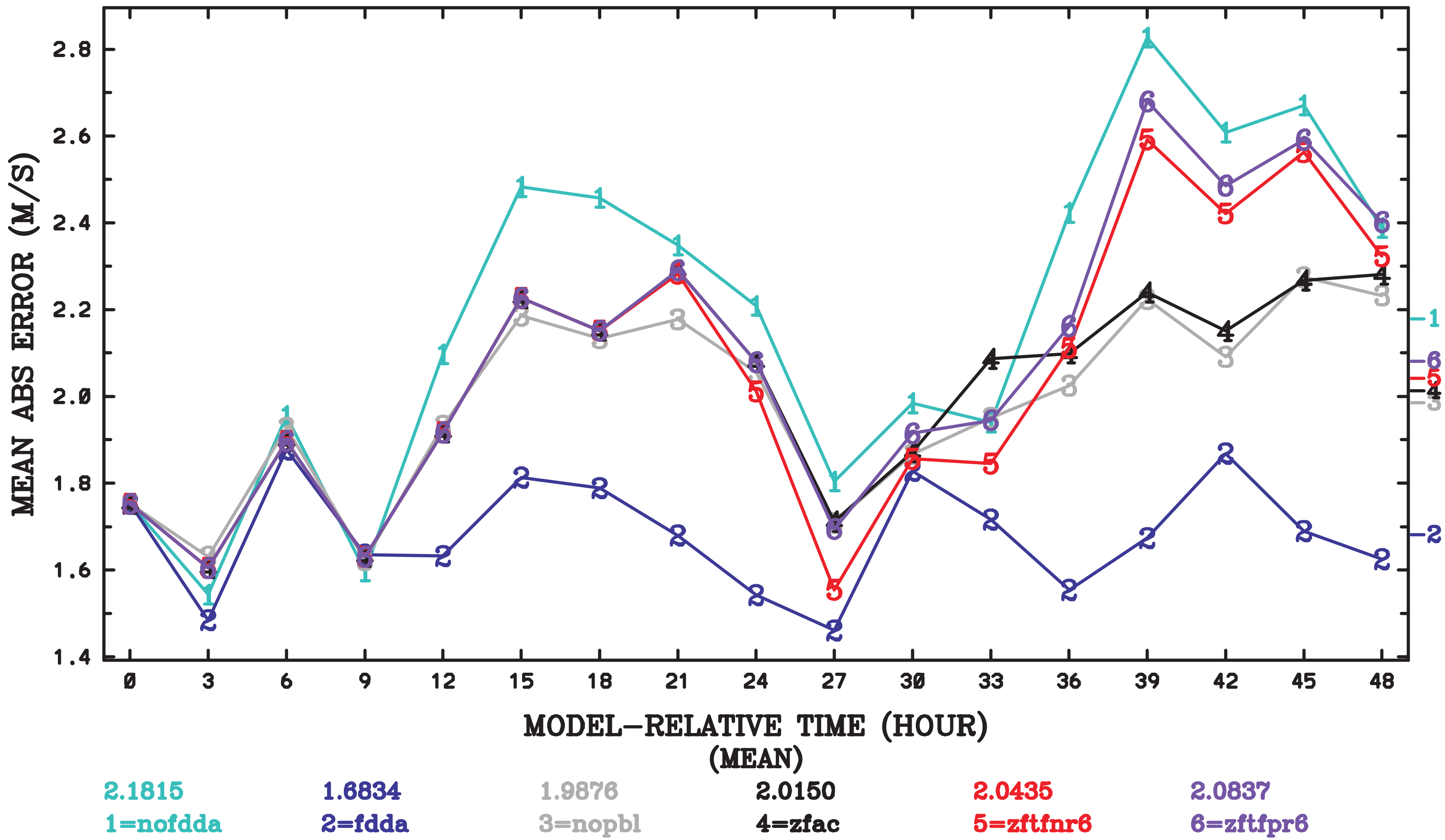
FDDA Testing Design

Exp No.	Exp Name	FDDA Options
1	nofdda	No FDDA
2	ffdda	Full 3-D FDDA
3	nopbl	FDDA excluded from PBL (by specifying W_η)
4	zfac	FDDA excluded from low model layers (by specifying W_η)
5	zftfnr6	Same as Exp. 4, except 6-h ramping down ended at 24 h (by specifying Wt)
6	zftfpr6	Same as Exp. 4, except 6-h ramping down started at 24 h (by specifying Wt)

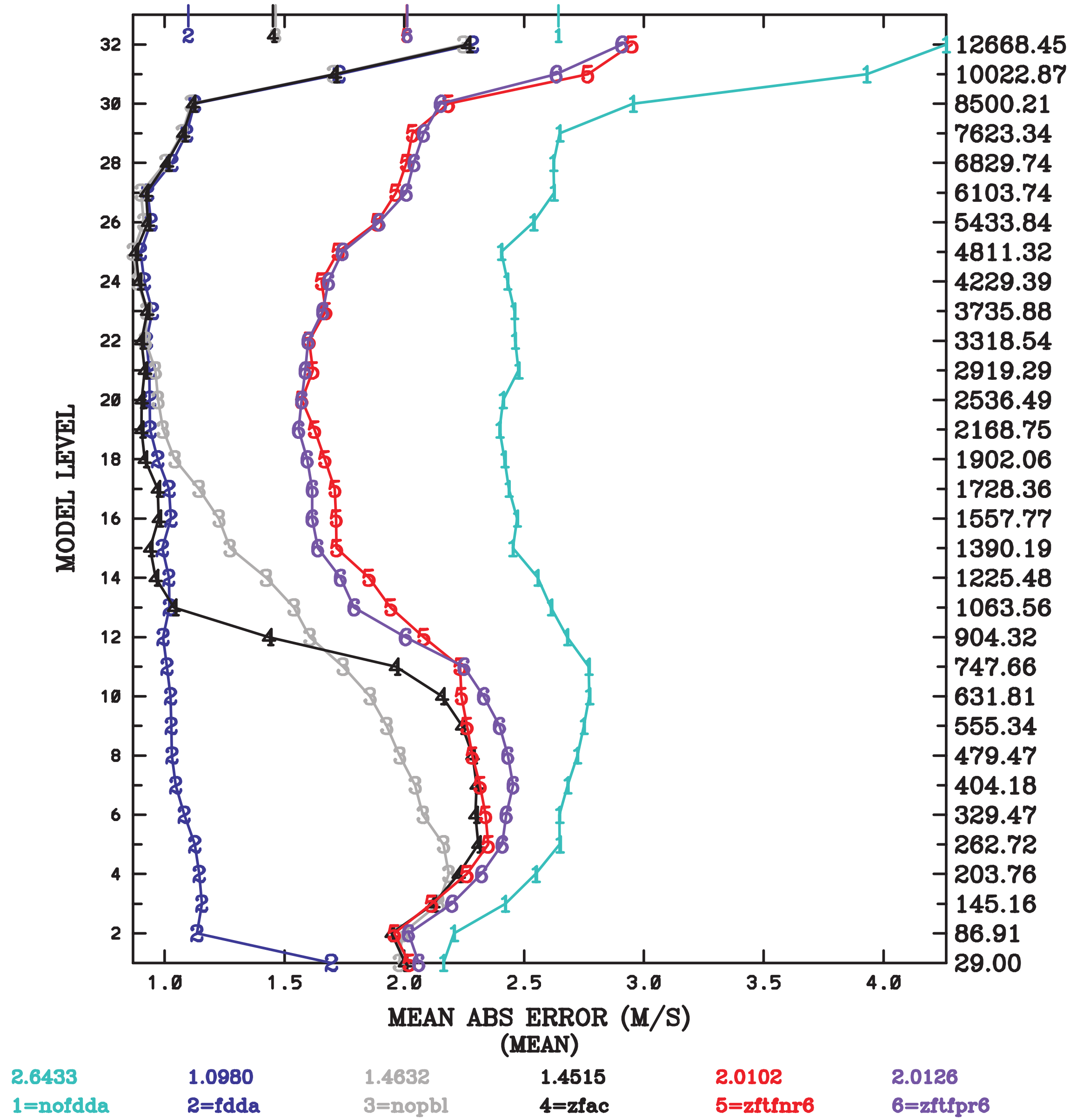
Verification Strategies

- WFR output is converted into MM5 format
- Statistic verification using Penn State VEROBS for MM5
- Subjective verification by visually looking at the model-simulated weather patterns

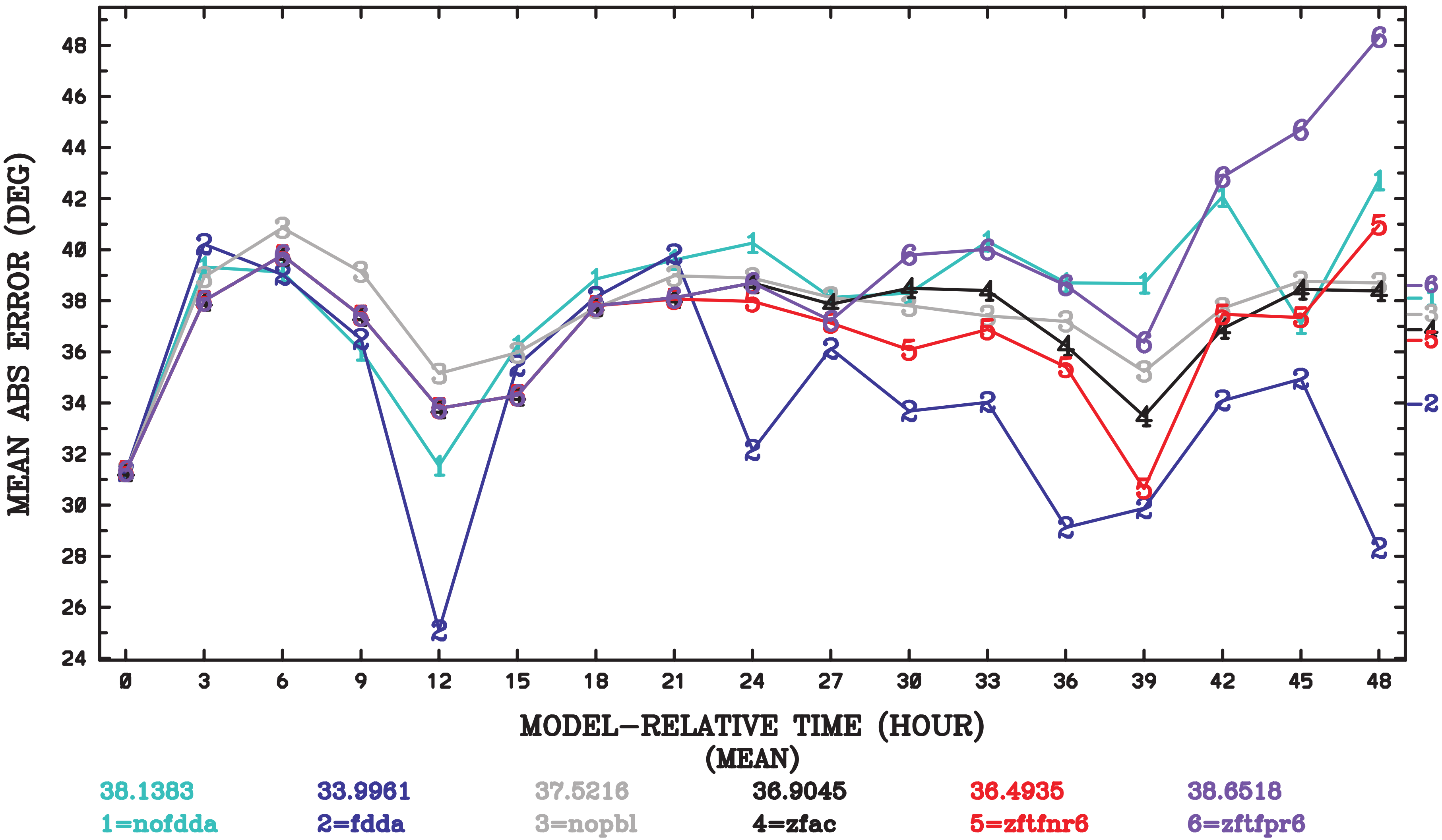
MAE of Surface Layer Wind Speed



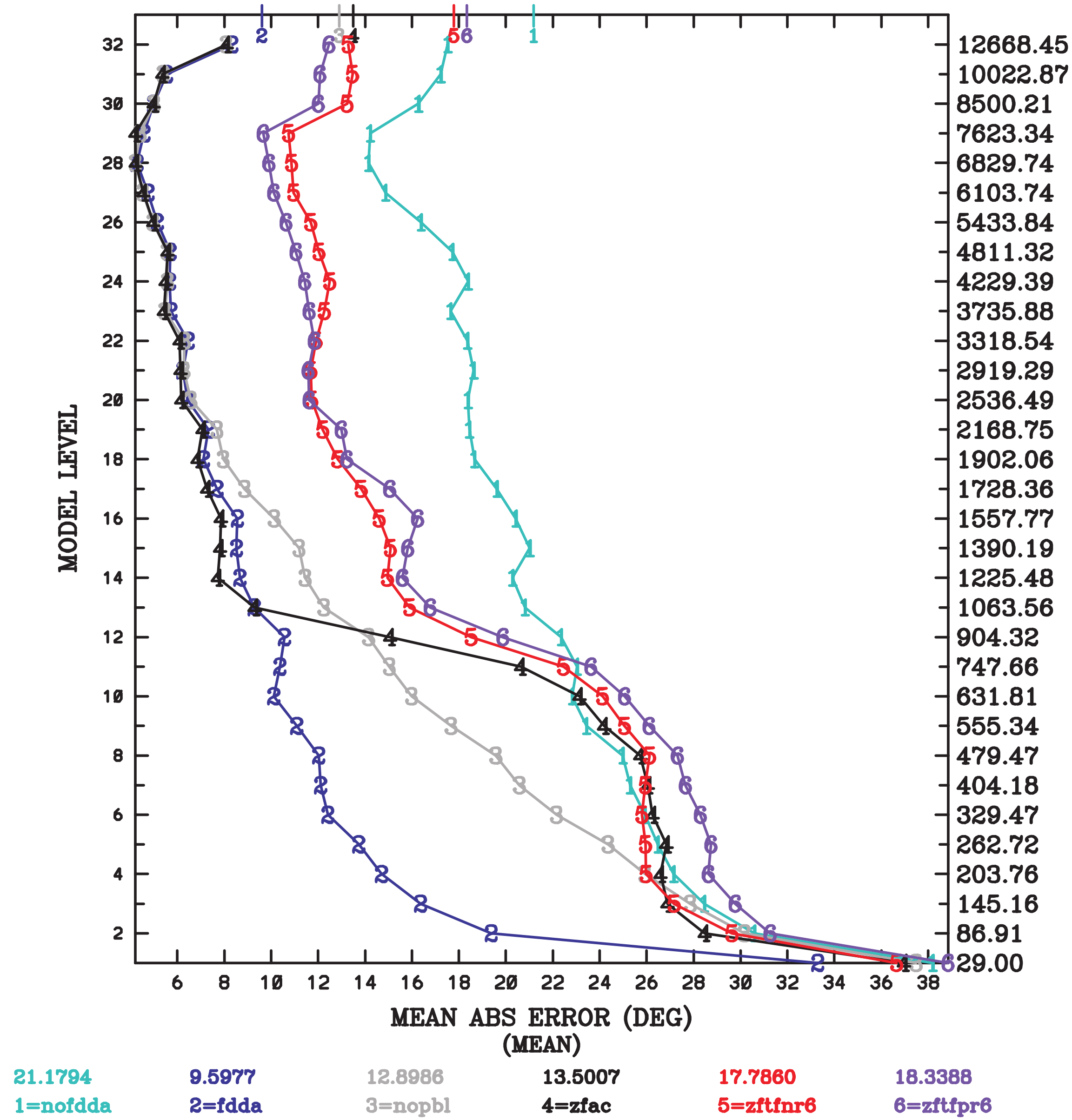
48-h Averaged MAE of Wind Speed



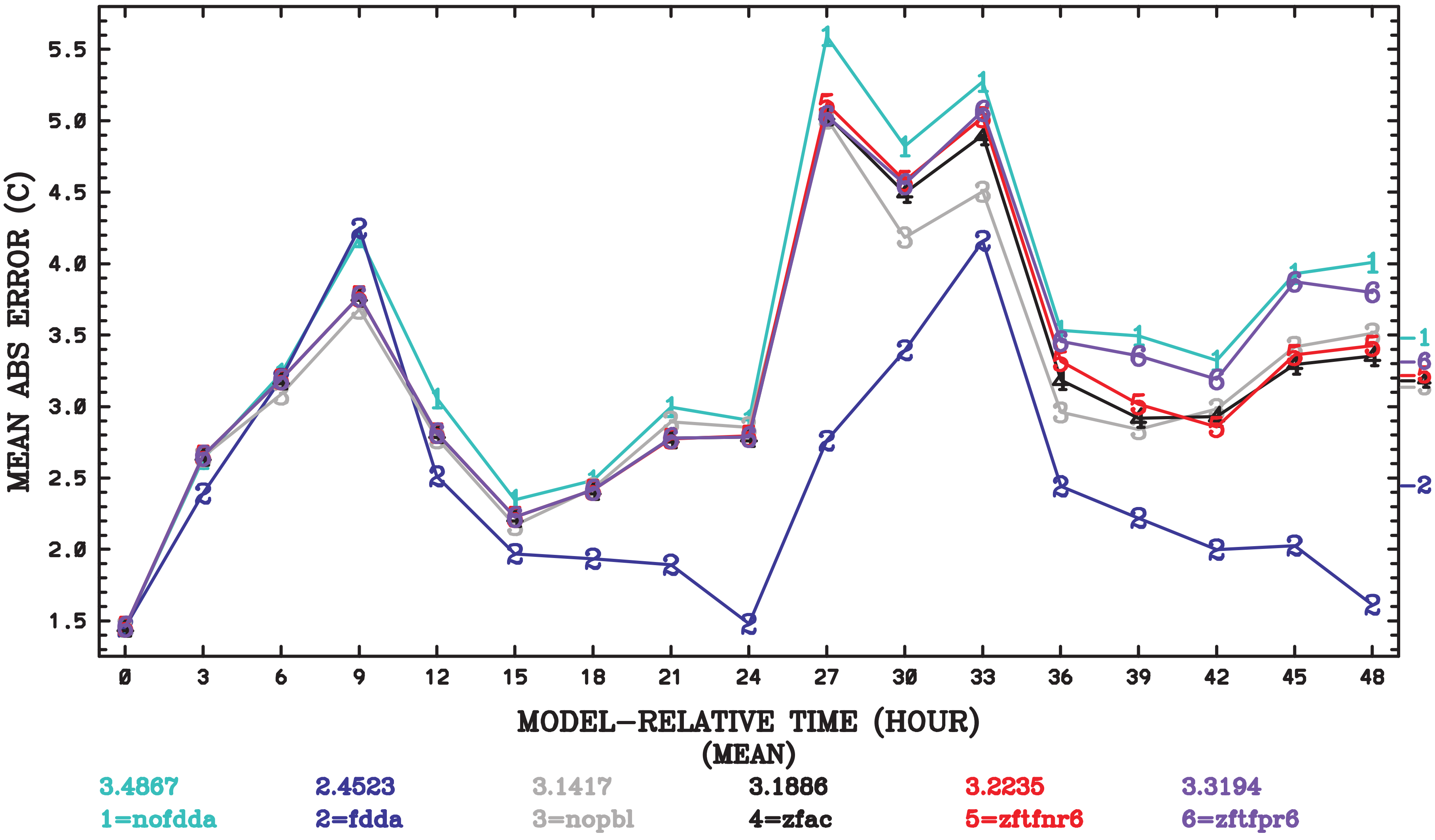
MAE of Surface Layer Wind Direction



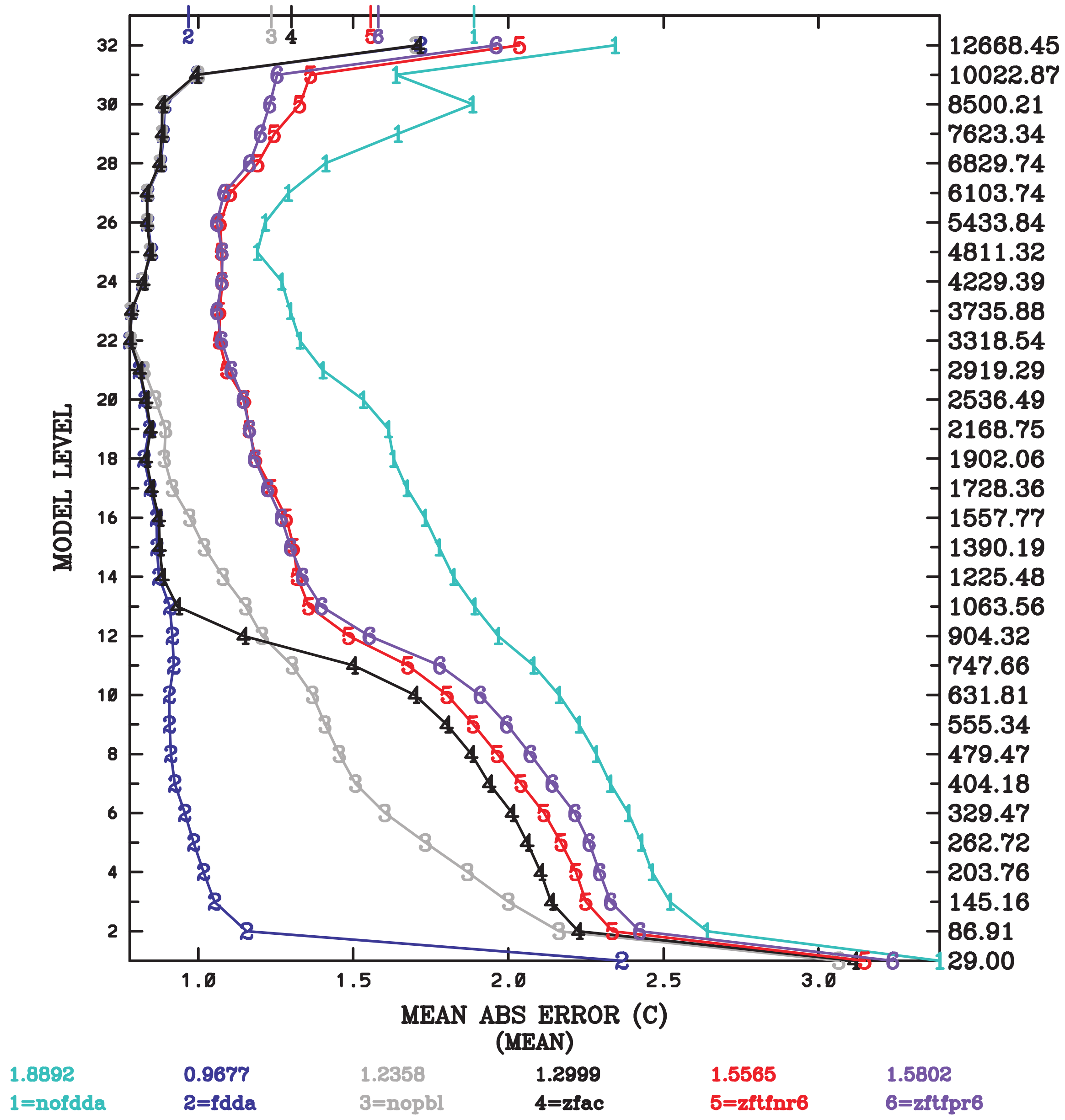
48-h Averaged MAE of Wind Direction

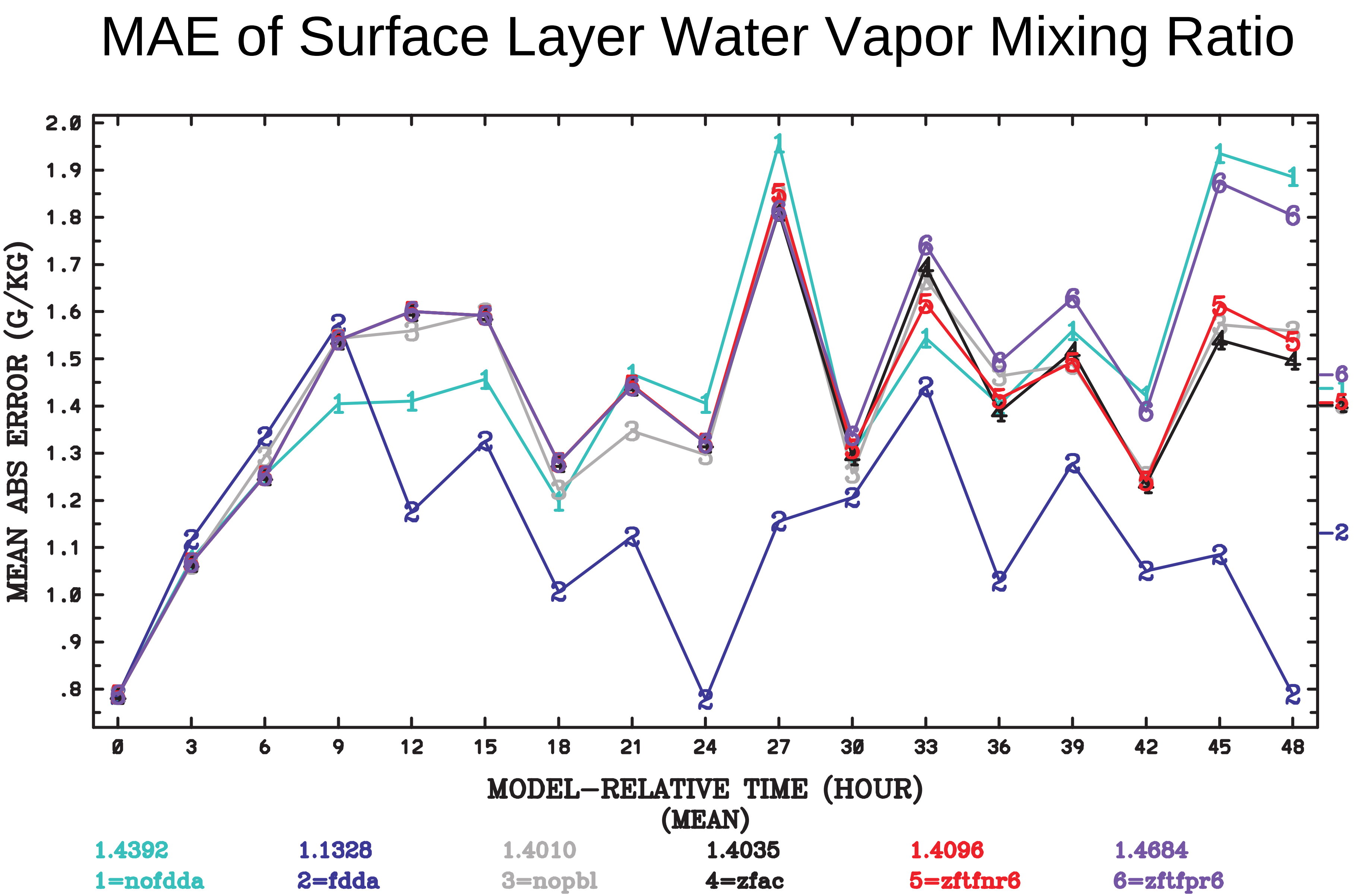


MAE of Surface Layer Temperature



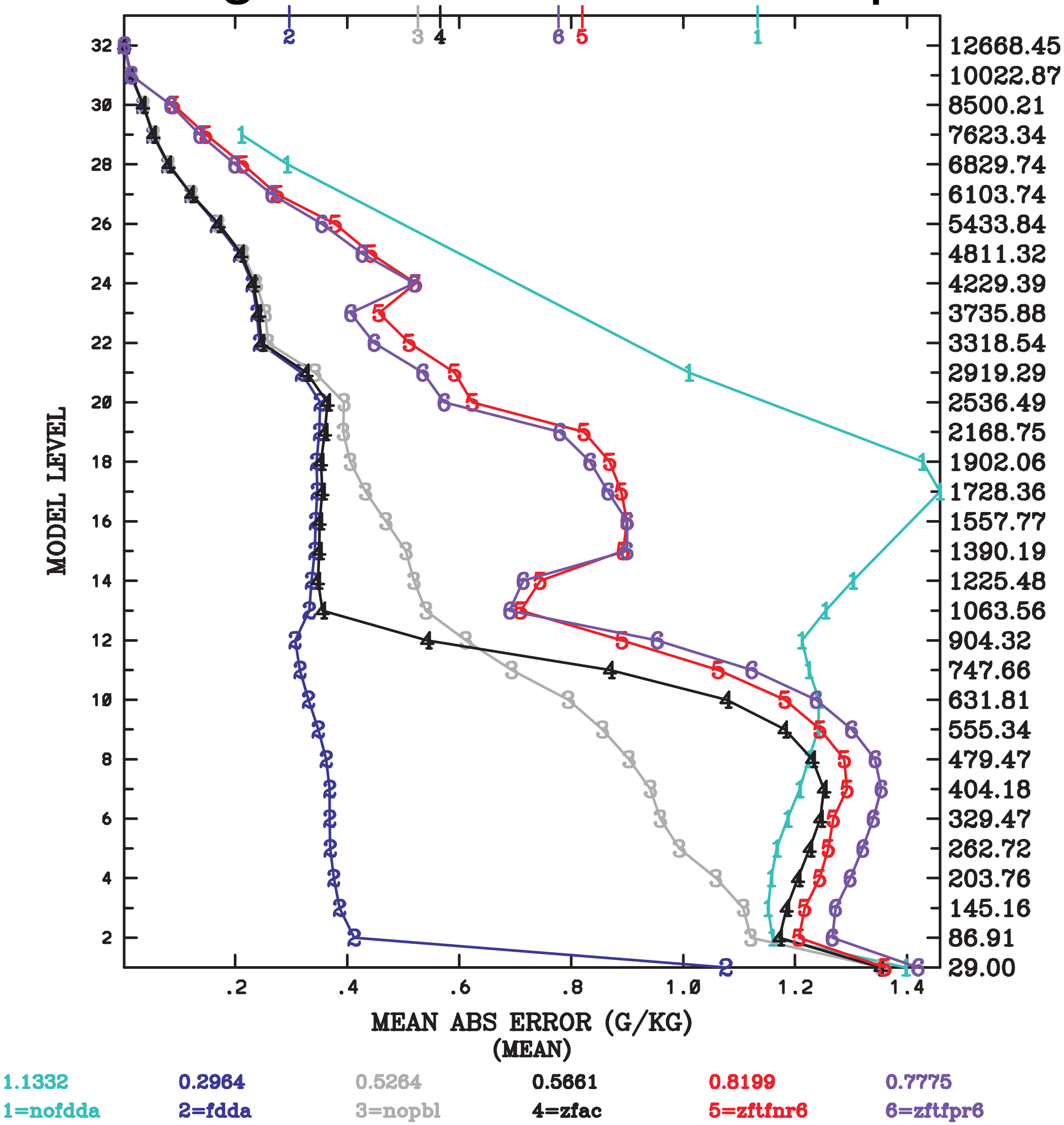
48-h Averaged MAE of Temperature



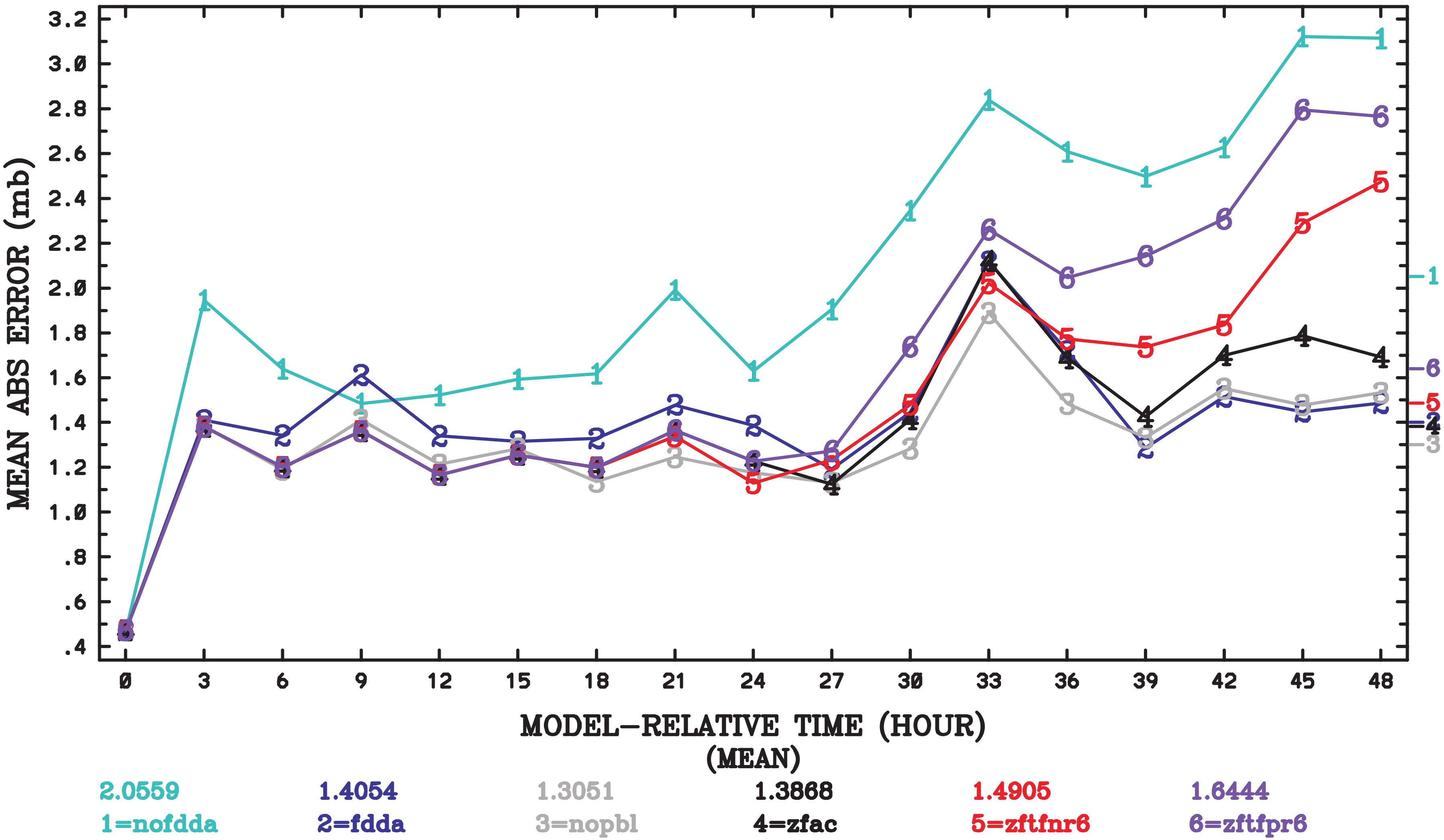


MAE of Surface Layer Water Vapor Mixing Ratio
MEAN ABS ERROR (G/KG)
2.0
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
.9
.8
0
3
6
9
12
15
18
21
24
27
30
33
36
39
42
45
48
MODEL-RELATIVE TIME (HOUR)
(MEAN)
1.4392
1=nofdda
1.1328
2=fdda
1.4010
3=nopbl
1.4035
4=zfac
1.4096
5=zftfnr6
1.4684
6=zftfpr6

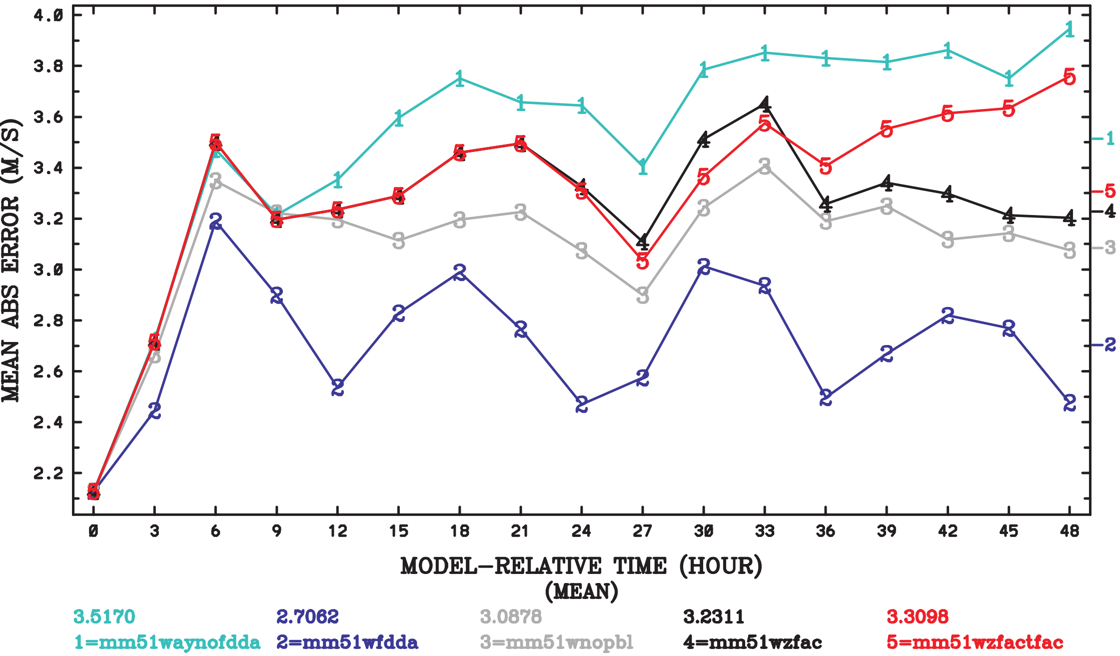
48-h Averaged MAE of Water Vapor Mixing Ratio



MAE of Sea-Level Pressure

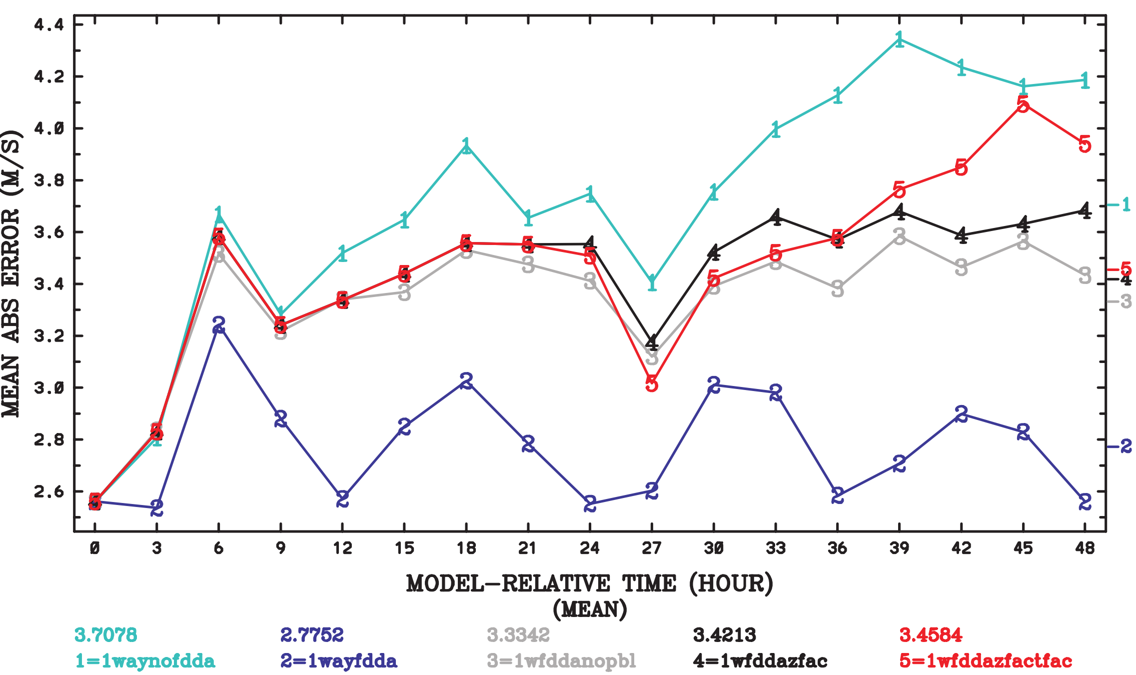


MM5 vs. WRF



MEAN ABS ERROR (M/S)
4.0
3.8
3.6
3.4
3.2
3.0
2.8
2.6
2.4
2.2
0 3 6 9 12 15 18 21 24 27 30 33 36 39 42 45 48
MODEL-RELATIVE TIME (HOUR)
(MEAN)
3.5170 1=mm51waynofdda
2.7062 2=mm51wfdda
3.0878 3=mm51wnopbl
3.2311 4=mm51wzfac
3.3098 5=mm51wzfactfac

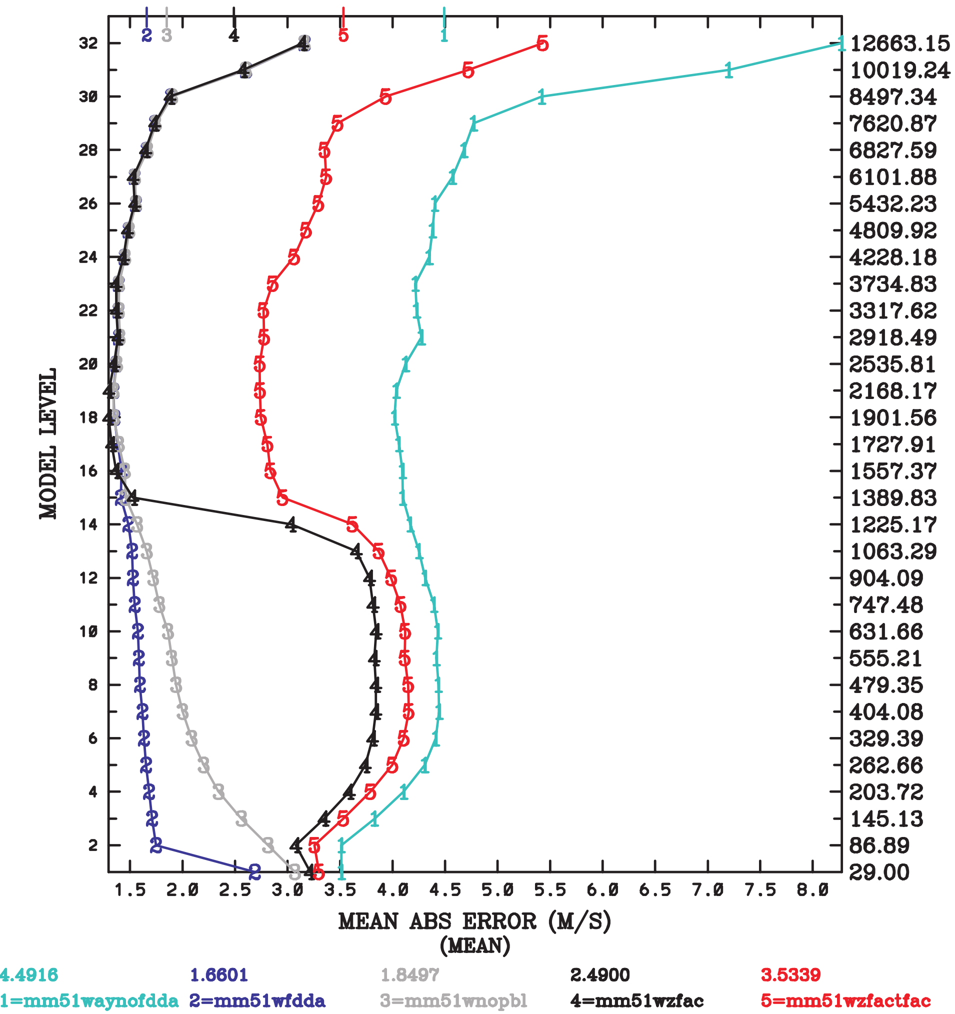
MM5



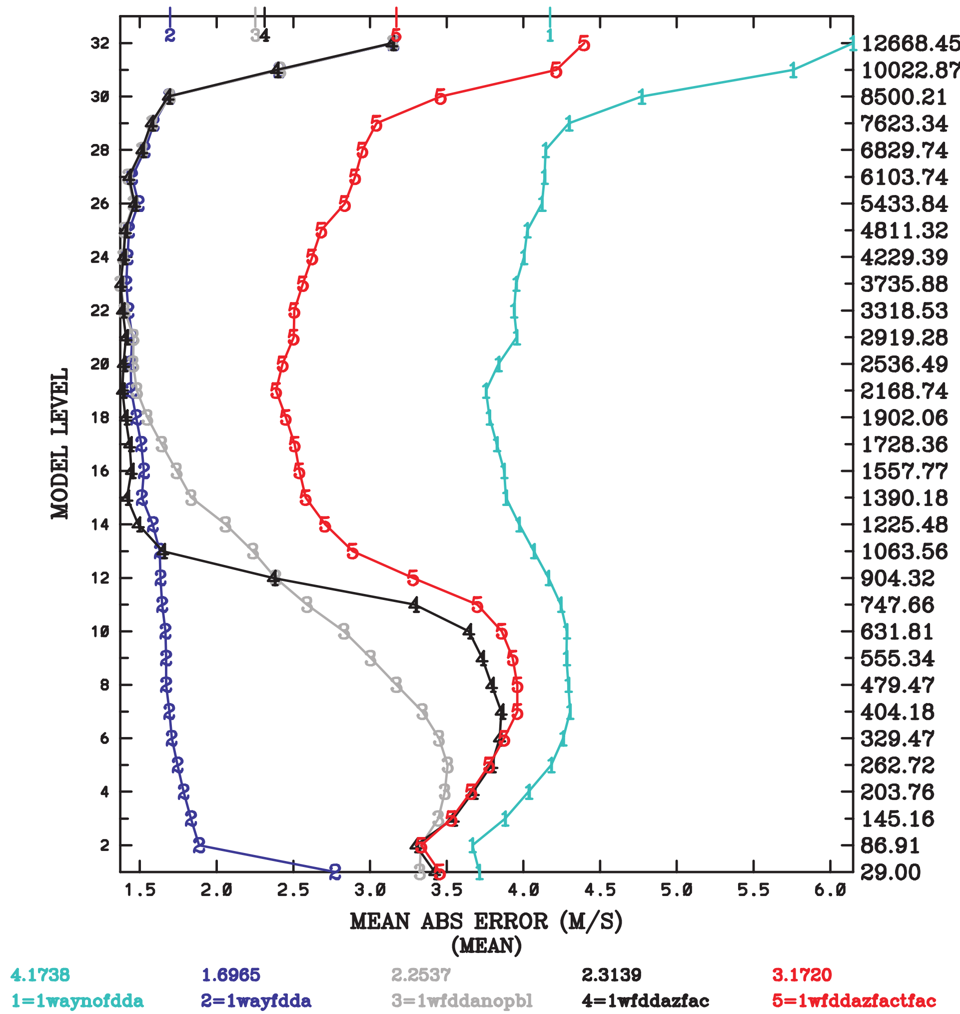
MEAN ABS ERROR (M/S)
4.4
4.2
4.0
3.8
3.6
3.4
3.2
3.0
2.8
2.6
0 3 6 9 12 15 18 21 24 27 30 33 36 39 42 45 48
MODEL-RELATIVE TIME (HOUR)
(MEAN)
3.7078 1=1waynofdda
2.7752 2=1wayfdda
3.3342 3=1wfddanopbl
3.4213 4=1wfddazfac
3.4584 5=1wfddazfactfac

WRF

MM5

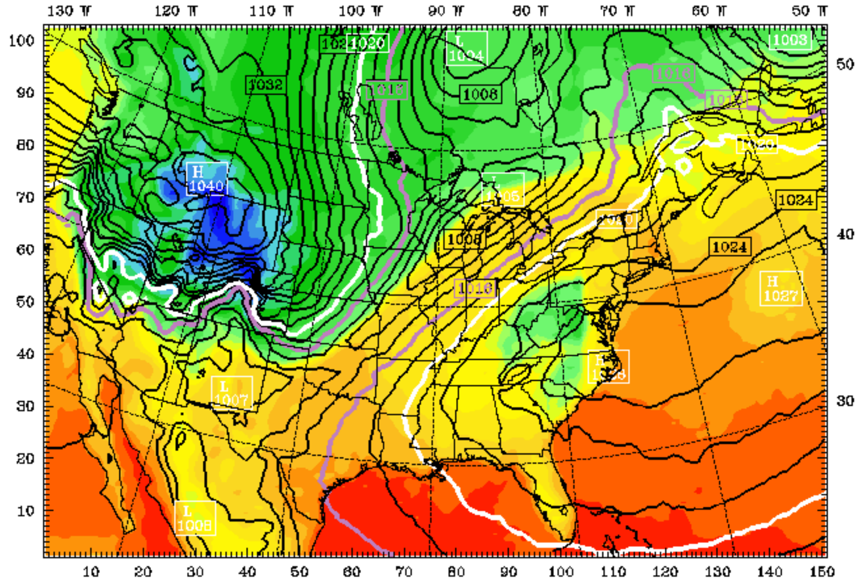

MODEL LEVEL
12663.15
10019.24
8497.34
7620.87
6827.59
6101.88
5432.23
4809.92
4228.18
3734.83
3317.62
2918.49
2535.81
2168.17
1901.56
1727.91
1557.37
1389.83
1225.17
1063.29
904.09
747.48
631.66
555.21
479.35
404.08
329.39
262.66
203.72
145.13
86.89
29.00
MEAN ABS ERROR (M/S)
(MEAN)
4.4916
1=mm51waynofdda
1.6601
2=mm51wfdda
1.8497
3=mm51wnopbl
2.4900
4=mm51wzfac
3.5339
5=mm51wzfactfac

WRF

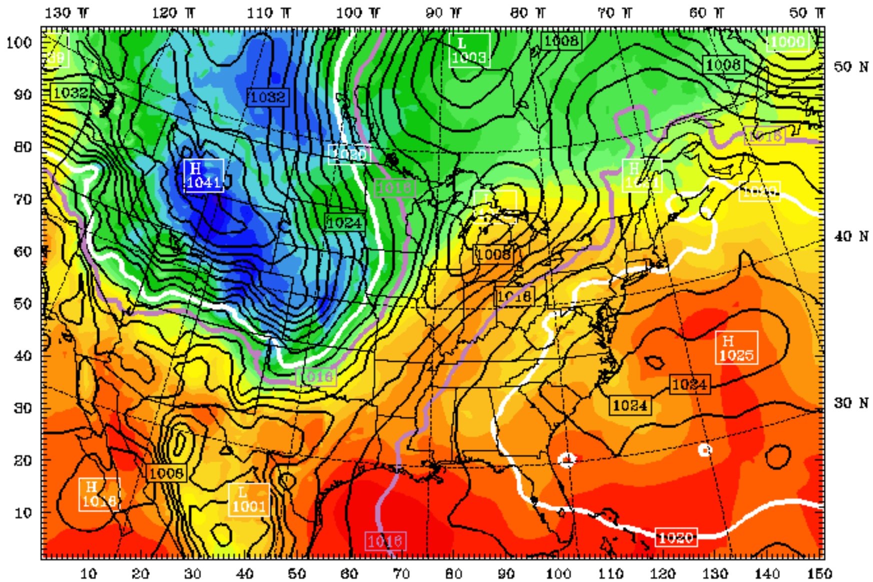

MODEL LEVEL
12668.45
10022.87
8500.21
7623.34
6829.74
6103.74
5433.84
4811.32
4229.39
3735.88
3318.53
2919.28
2536.49
2168.74
1902.06
1728.36
1557.77
1390.18
1225.48
1063.56
904.32
747.66
631.81
555.34
479.47
404.18
329.47
262.72
203.76
145.16
86.91
29.00
MEAN ABS ERROR (M/S)
(MEAN)
4.1738
1=1waynofdda
1.6965
2=1wayfdda
2.2537
3=1wfddanopbl
2.3139
4=1wfddazfac
3.1720
5=1wfddazfactfac

Subjective Verification

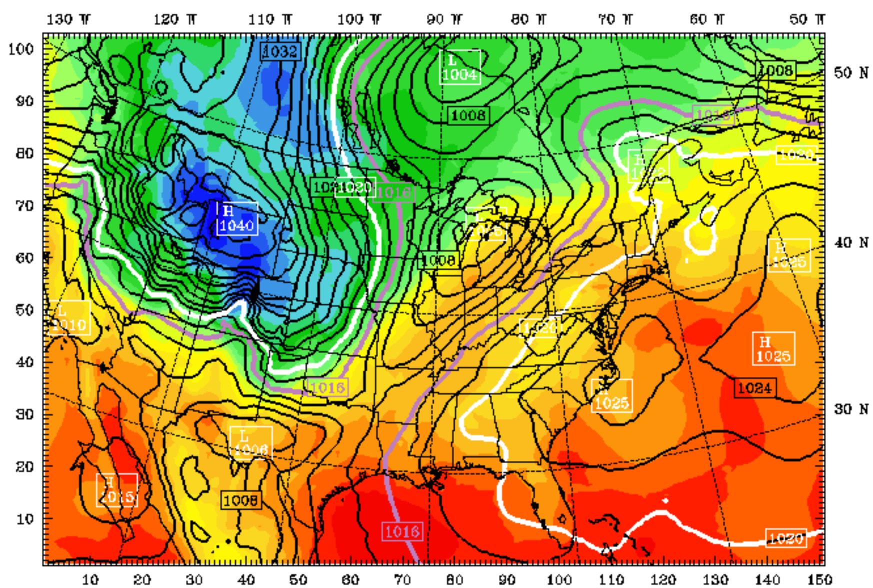
Surface Temperature and Sea Level Pressure



WRF NO FDDA



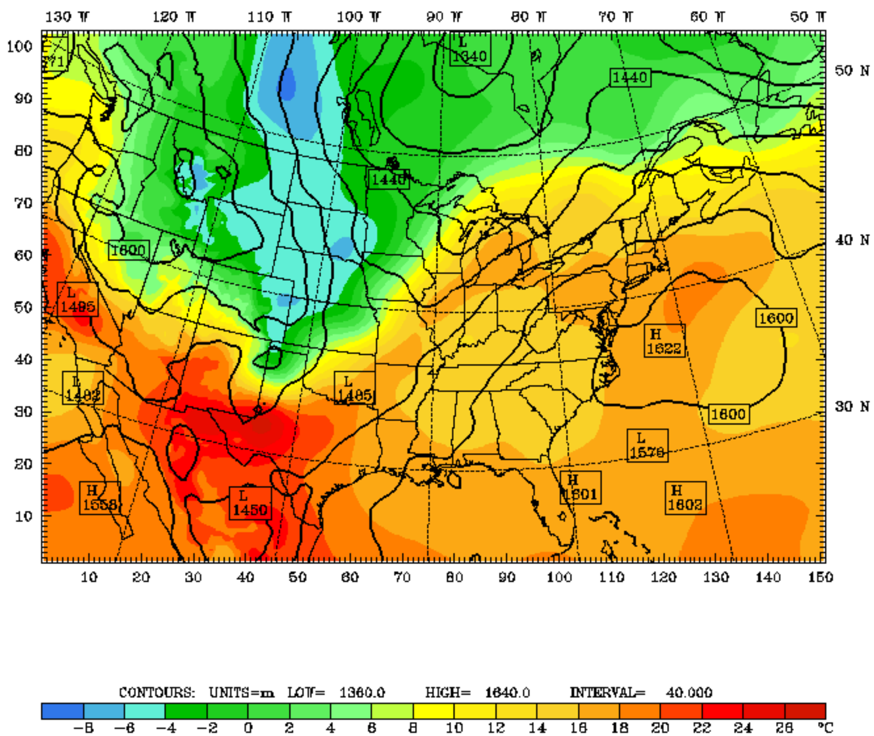
MM5 ANALYSIS



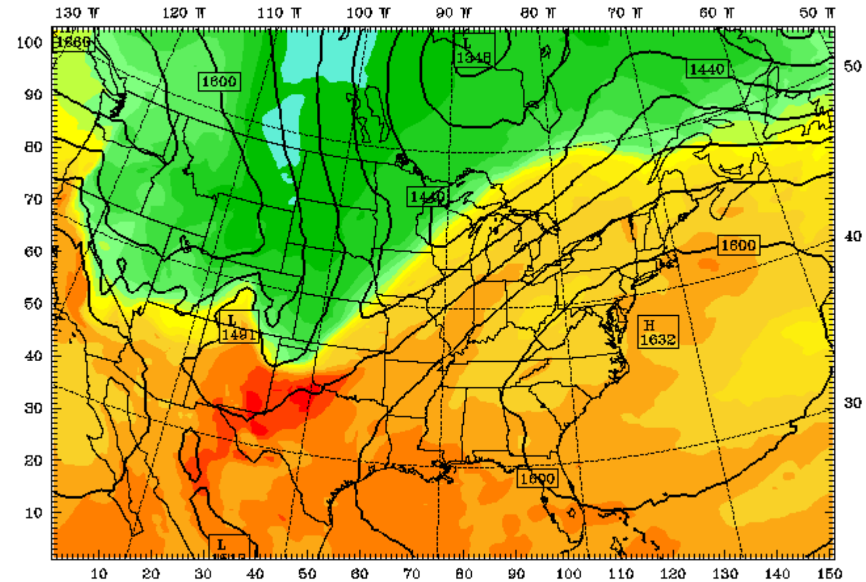
WRF FDDA

850 hPa Temperature and Geopotential Height

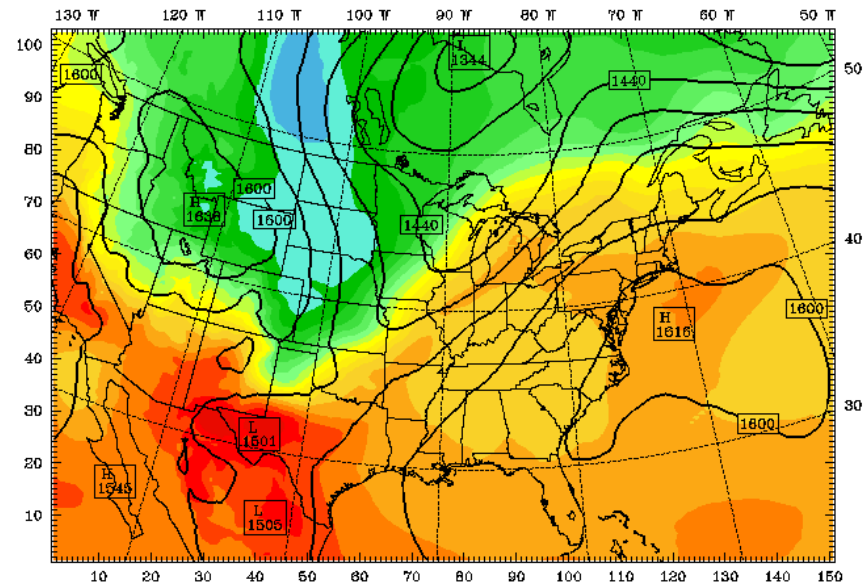
Dataset: 36km RIP: mm5 interp 36km Init: 1200 UTC Sun 18 Sep 83
Fcst: 48.00 h Valid: 1200 UTC Tue 20 Sep 83 (0900 LDT Tue 20 Sep 83)
Temperature at pressure = 850 hPa
Geopotential height at pressure = 850 hPa



MM5 ANALYSIS



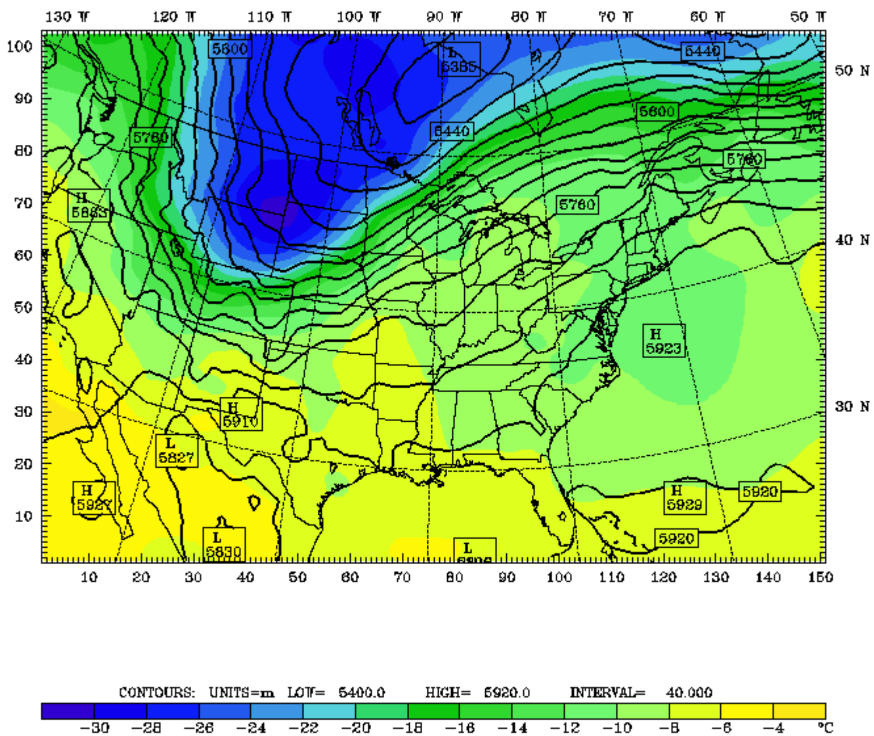
WRF NO FDDA



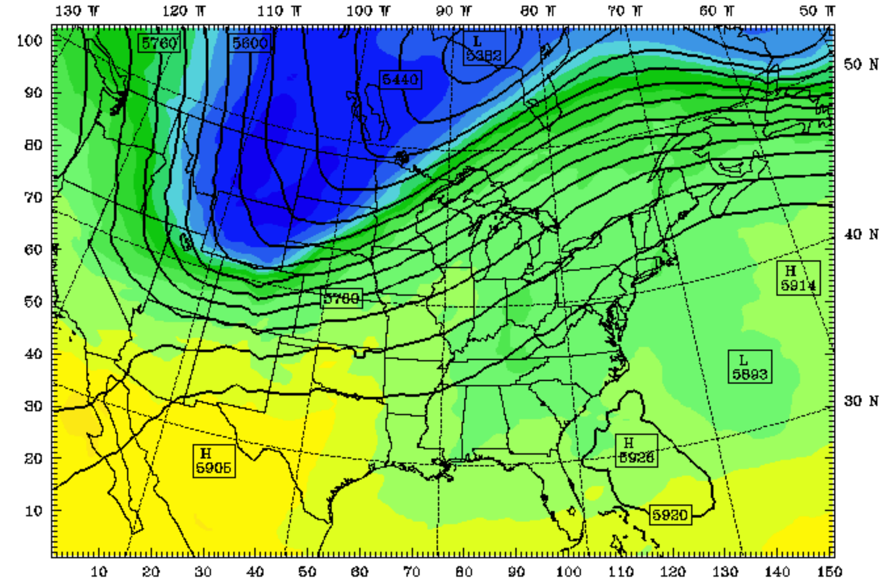
WRF FDDA

500 hPa Temperature and Geopotential Height

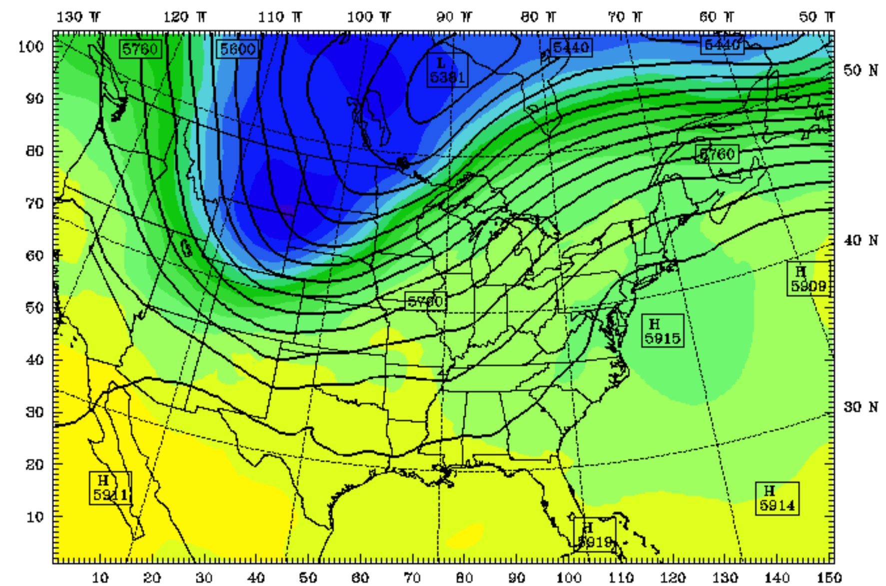
Dataset: 36km RIP: mm5 interp 36km Init: 1200 UTC Sun 18 Sep 83
Fcst: 48.00 h Valid: 1200 UTC Tue 20 Sep 83 (0900 LDT Tue 20 Sep 83)
Temperature at pressure = 500 hPa
Geopotential height at pressure = 500 hPa



MM5 ANALYSIS



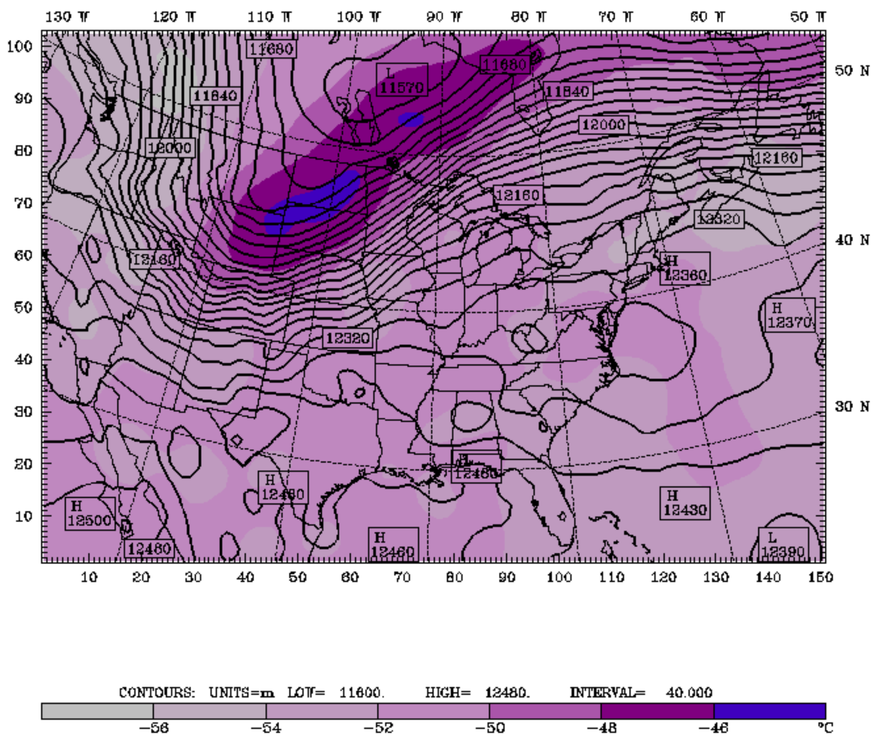
WRF NO FDDA



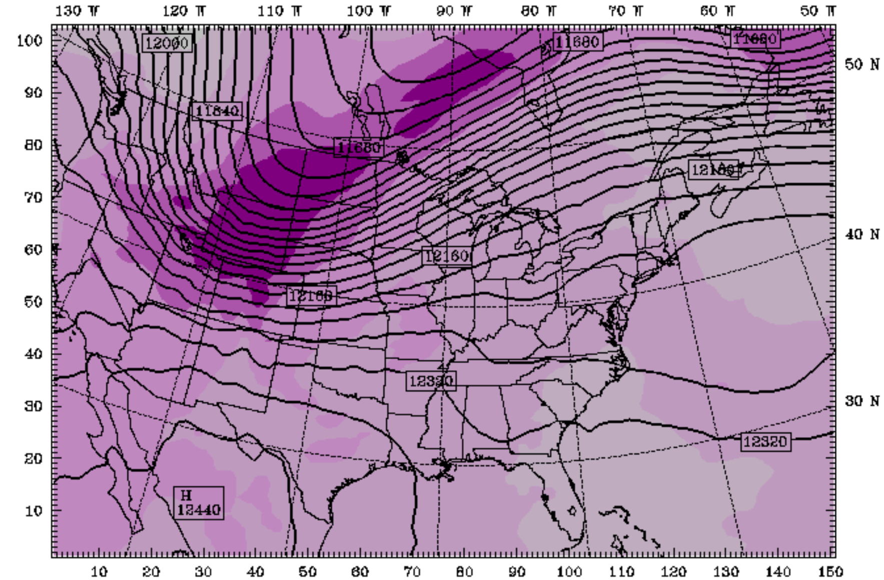
WRF FDDA

200 hPa Temperature and Geopotential Height

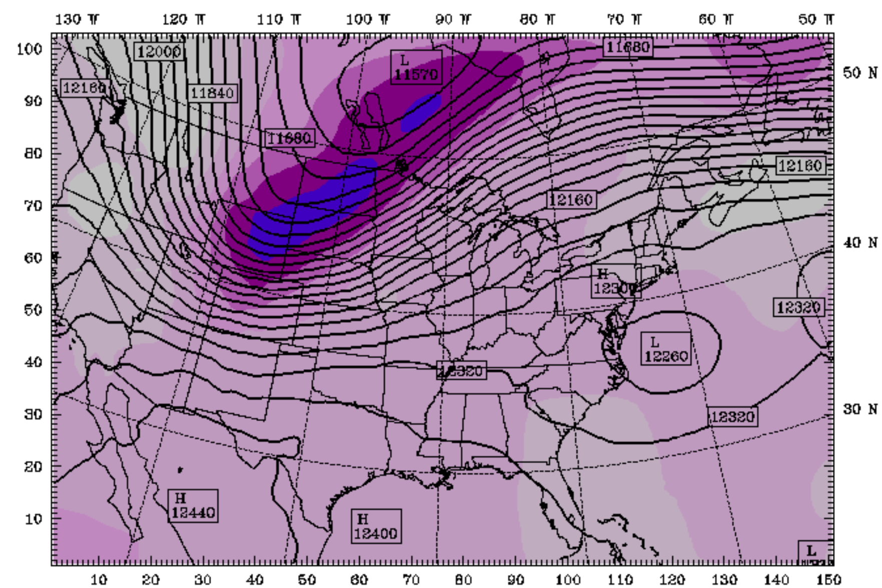
Dataset: 36km RIP: mm5 interp 36km Init: 1200 UTC Sun 18 Sep 83
Fcst: 48.00 h Valid: 1200 UTC Tue 20 Sep 83 (0900 LDT Tue 20 Sep 83)
Temperature at pressure = 200 hPa
Geopotential height at pressure = 200 hPa



MM5
ANALYSIS



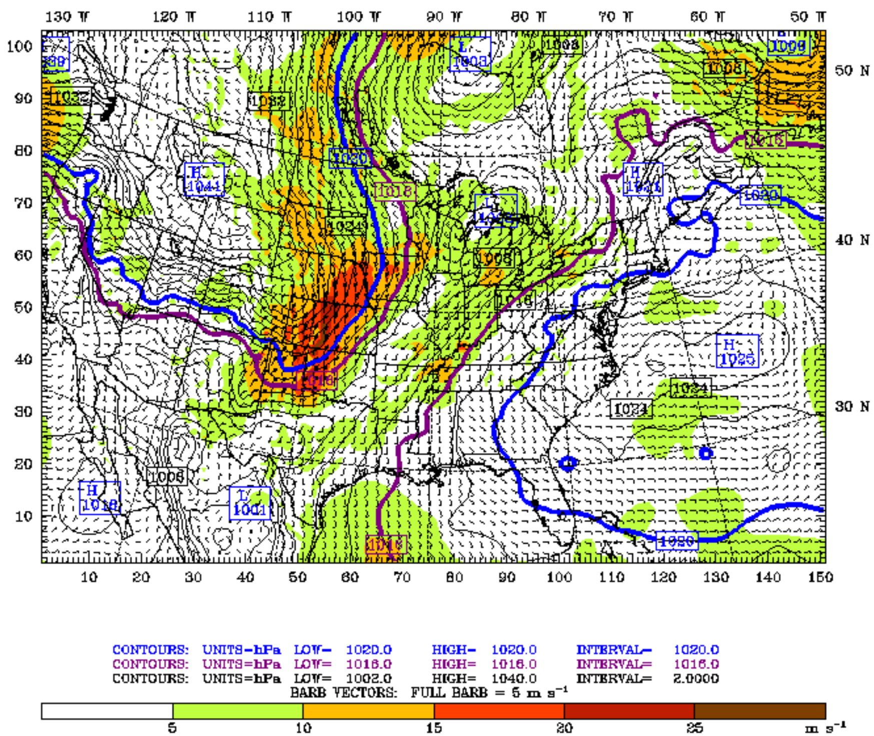
WRF NO FDDA



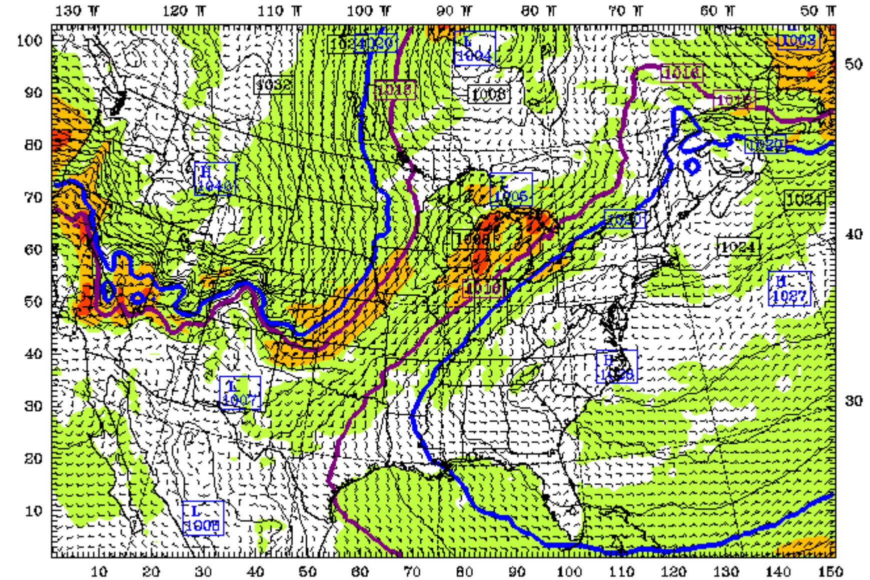
WRF FDDA

Surface Winds and Sea Level Pressure

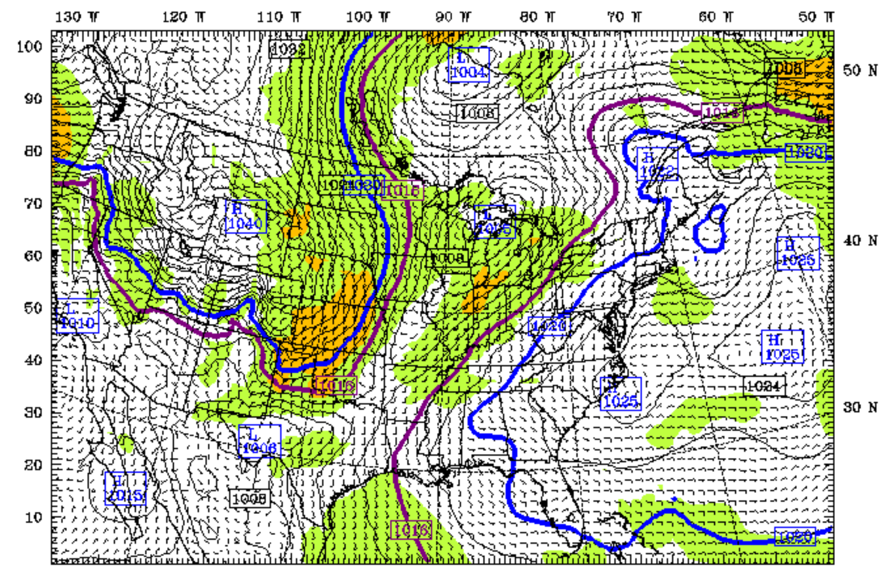
Dataset: 36km RIP: mm5 interp 36km Init: 1200 UTC Sun 18 Sep 83
Fcst: 48.00 h Valid: 1200 UTC Tue 20 Sep 83 (0900 LDT Tue 20 Sep 83)
Horizontal wind speed at k-index = 32
Horizontal wind vectors at k-index = 32
Sea-level pressure
Sea-level pressure
Sea-level pressure



MM5
ANALYSIS

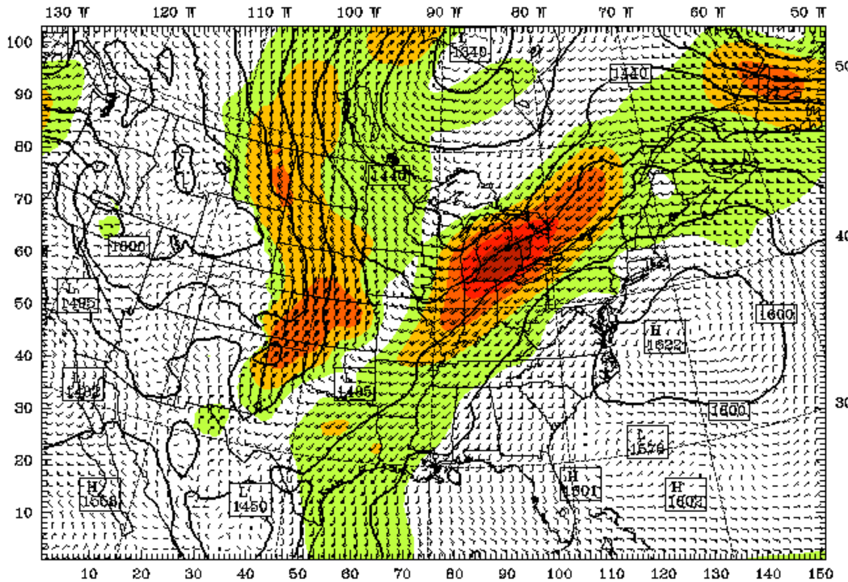


WRF NO FDDA

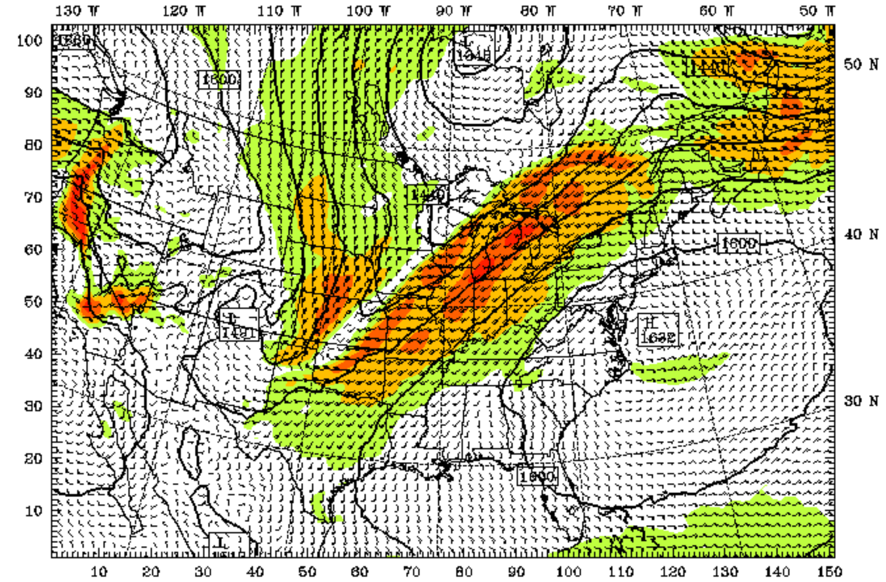


WRF FDDA

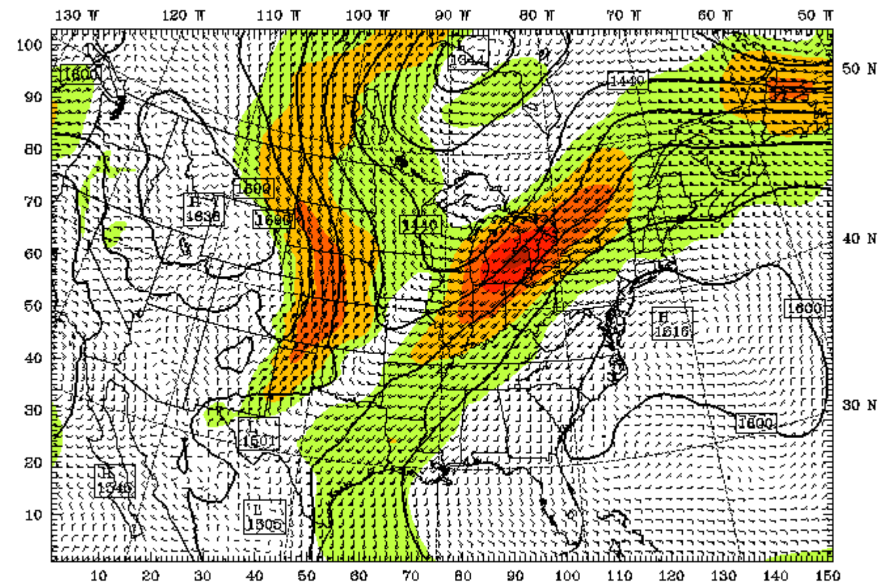
850 hPa Winds and Geopotential Height



MM5
ANALYSIS

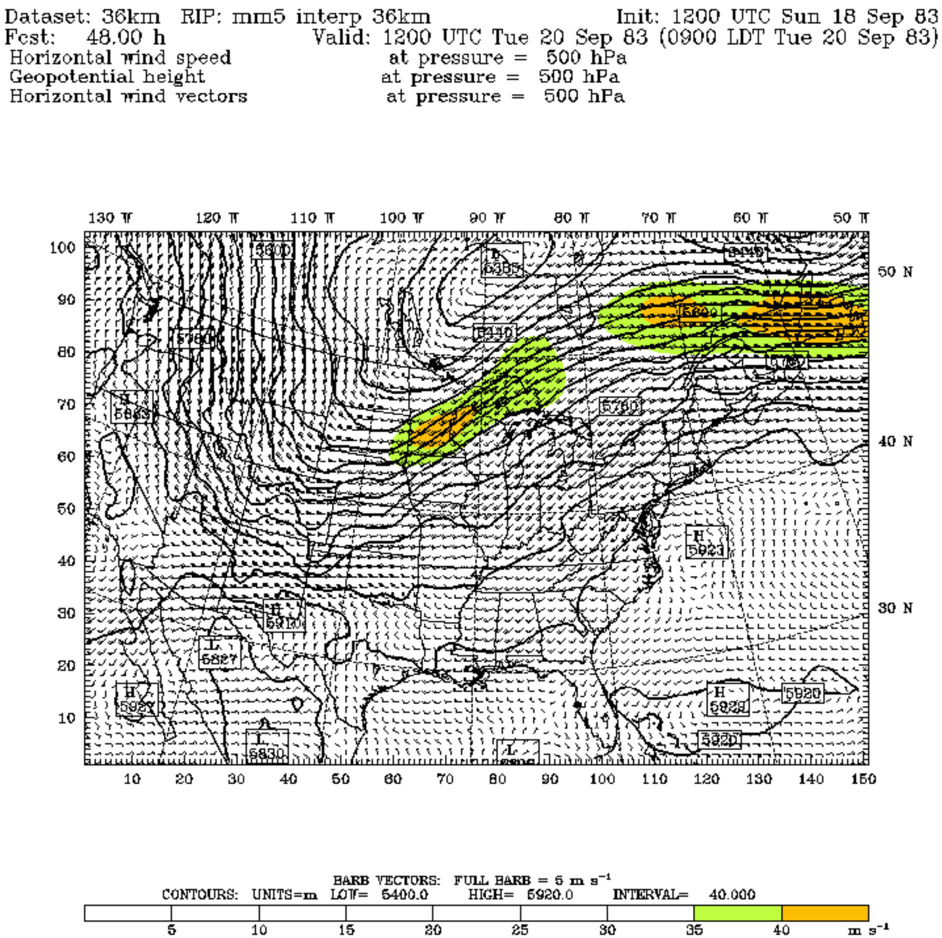


WRF NO FDDA

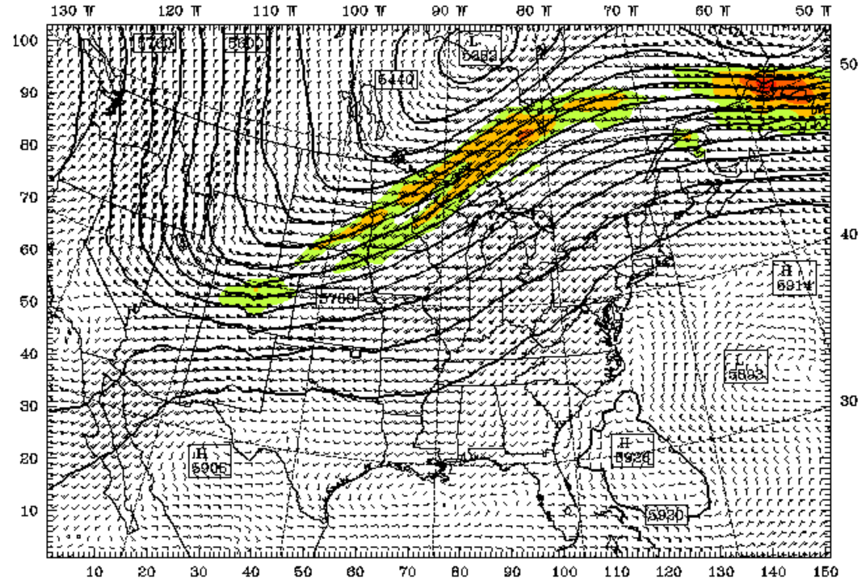


WRF FDDA

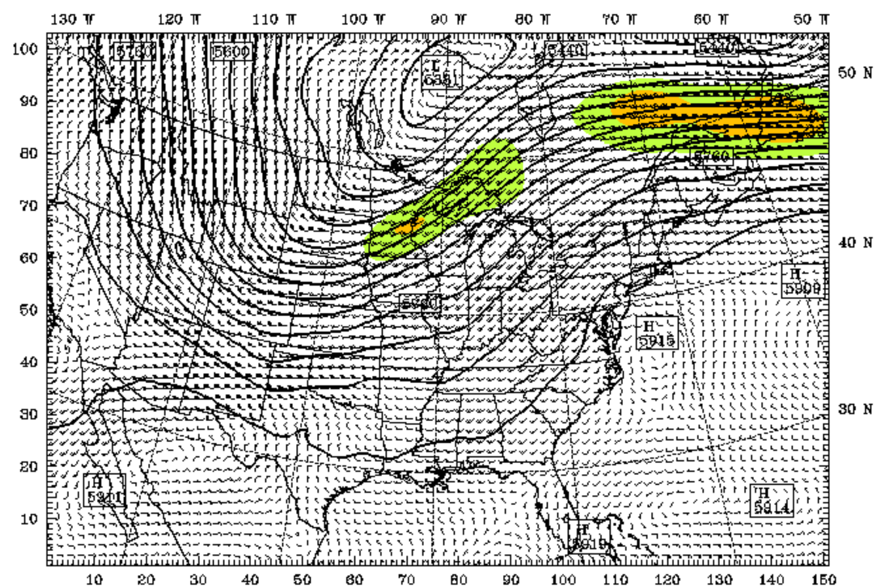
500 hPa Winds and Geopotential Height



MM5 ANALYSIS



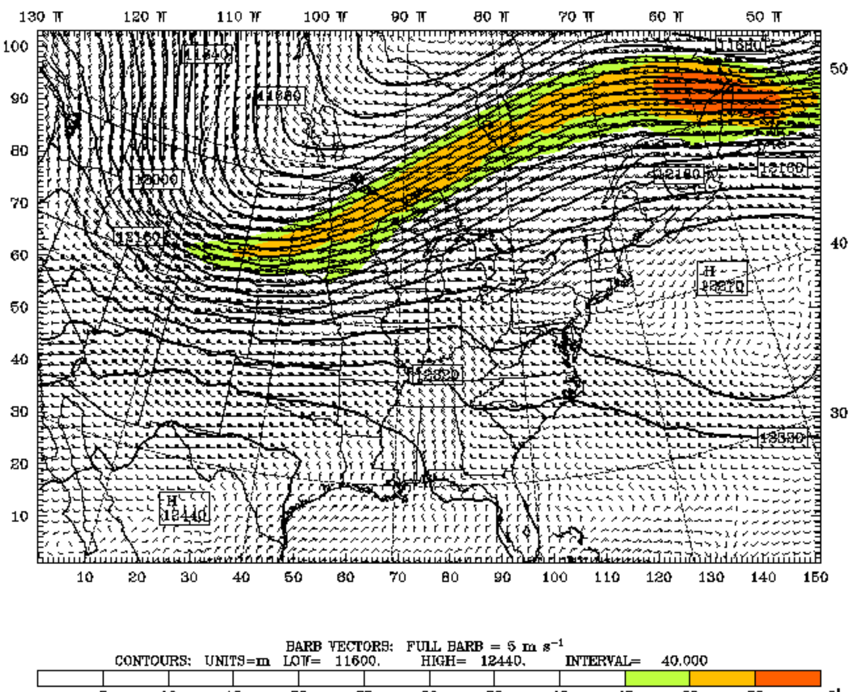
WRF NO FDDA



WRF FDDA

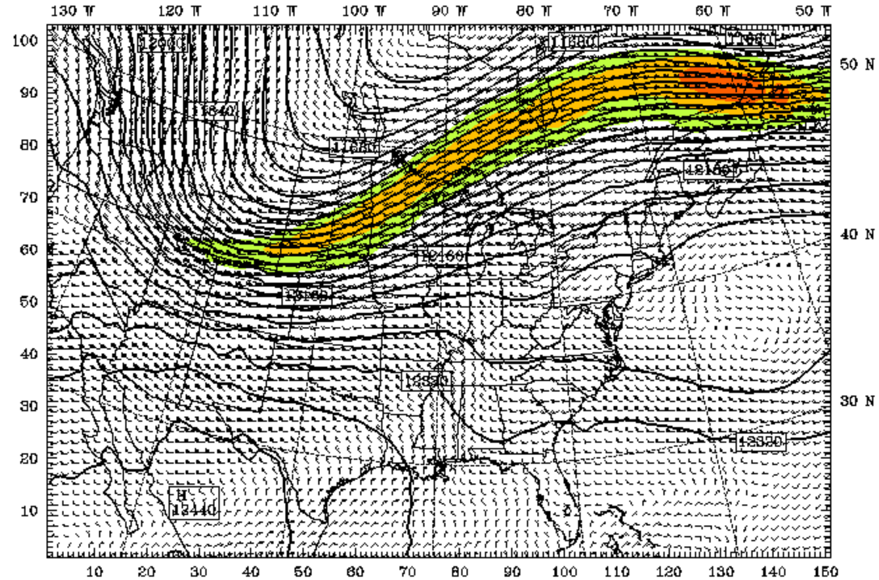
200 hPa Winds and Geopotential Height

Dataset: nofdda36 RIP: wrf wb2 mm5 36km v2.1.2 Init: 1200 UTC Sun 18 Sep 83
Fcst: 48.00 h Valid: 1200 UTC Tue 20 Sep 83 (0900 LDT Tue 20 Sep 83)
Horizontal wind speed at pressure = 200 hPa
Geopotential height at pressure = 200 hPa
Horizontal wind vectors at pressure = 200 hPa

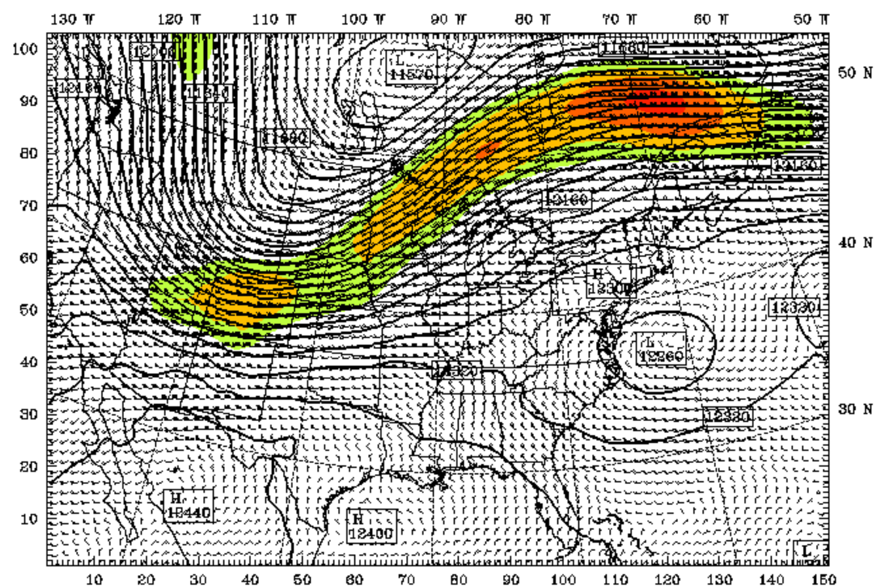


Model Info: V2.0.3.1 KF MYJ PBL WSM 3class Ther-Diff 36 km, 32 levels, 180 sec
LW: RRTM SW: Dudhia DIFF: simple KM: 2D Smagor

MM5
ANALYSIS



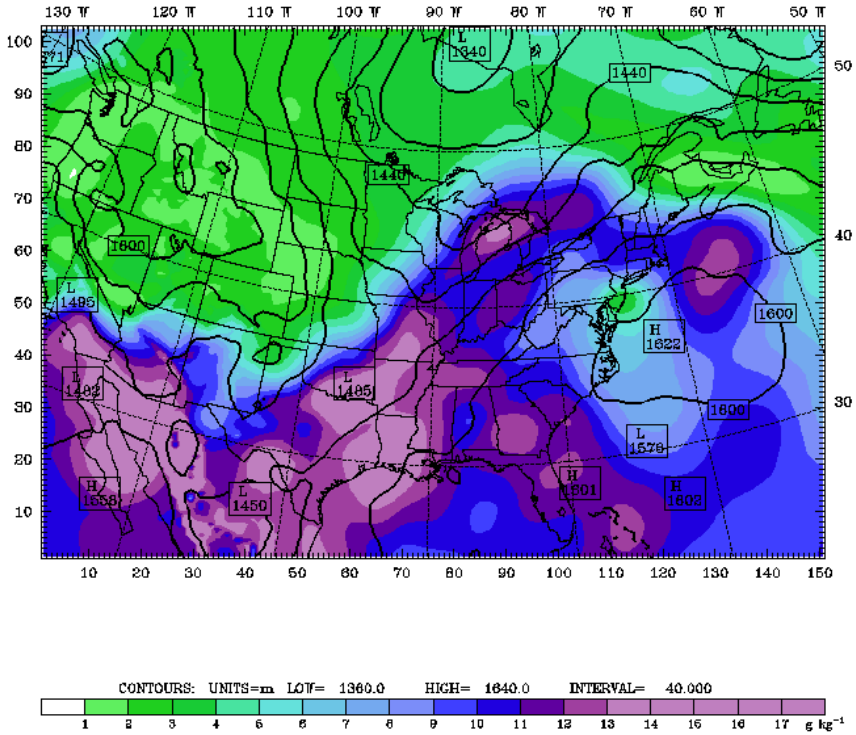
WRF NO FDDA



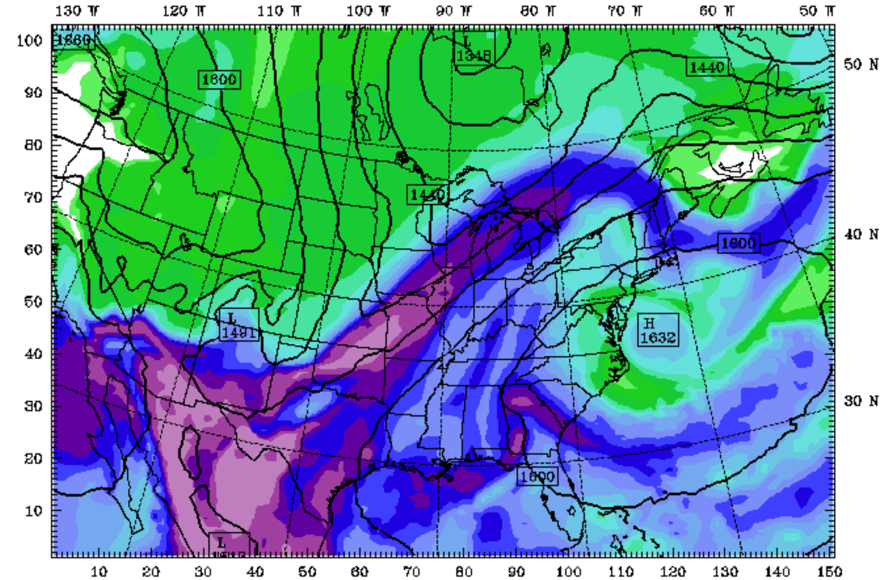
WRF FDDA

850 hPa Mixing Ratio and Geopotential Height

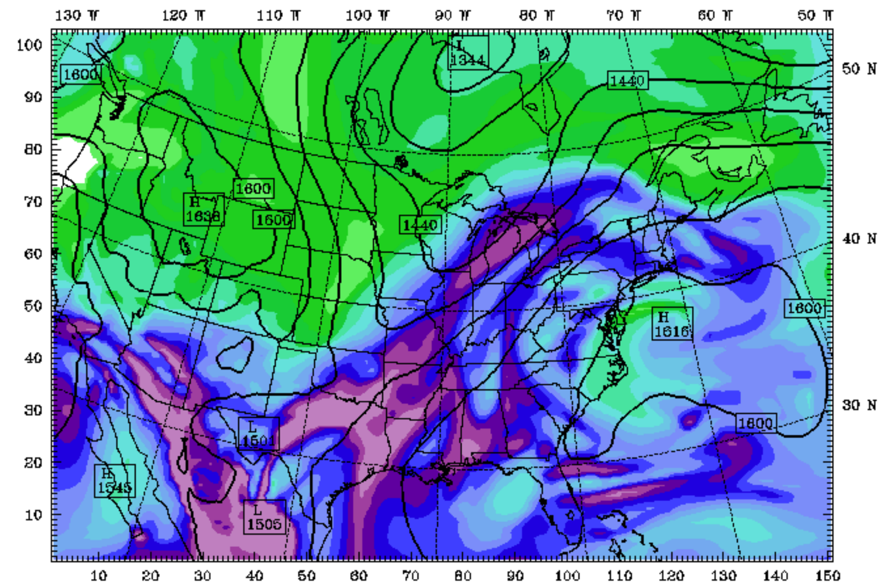
Dataset: 36km RIP: mm5 interp 36km Init: 1200 UTC Sun 18 Sep 83
Fcst: 48.00 h Valid: 1200 UTC Tue 20 Sep 83 (0900 LDT Tue 20 Sep 83)
Water vapor mixing ratio at pressure = 850 hPa
Geopotential height at pressure = 850 hPa



MM5 ANALYSIS



WRF NO FDDA



WRF FDDA

Summary and Conclusions

- Penn State has implemented a basic 3-D analysis nudging FDDA capability
  - User-specified nudging end-time and rampdown period to zero
  - User-specified strength of nudging
  - User-specified nudging within the planetary boundary layer
  - User-specified nudging in lower levels
- Testing and statistical verification on CAPTEX-83 case show that all FDDA switches work properly as designed.
- WRF simulations of weather patterns are improved by applying analysis nudging FDDA.
- Effects of analysis nudging FDDA in WRF-ARW are similar to MM5

Future Work

Penn State (with NCAR as subcontractor) has received new three-year funding from DTRA to continue the research and development of both analysis and OBS nudging for WRF.

- More general analysis nudging (e.g. including surface analysis nudging through PBL)
- The analysis and observation nudging will also be designed to better use statistical information from variational and ensemble Kalman filter methods
- Exploration of new hybrid nudging-variational-EnKF techniques, etc.
- …………………..

Nudging FDDA

$$\frac{\partial \alpha}{\partial t} = G \bullet (\alpha_{ob} - \alpha) + \ldots$$

$$\int_0^t (\ )\, dt \Rightarrow \alpha(t) = (\alpha_0 - \alpha_{ob}) \bullet e^{-Gt} + \alpha_{ob}$$

$$\alpha(t) = (\alpha_o - \alpha_{ob}) \bullet e^{-Gt} + \alpha_{ob}$$

$$\frac{1}{G} \equiv e - \textit{folding time} \quad O(1h)$$

WRF Mass-Coordinate Model Integration Procedure

Begin time step

Runge-Kutta loop (steps 1, 2, and 3)

(i) advection, p-grad, buoyancy using $(\phi^t, \phi^*, \phi^{**})$

Nudging FDDA (ii) physics if step 1, save for steps 2 and 3

(iii) mixing, other non-RK dynamics, save…

(iv) assemble dynamics tendencies

Acoustic step loop

(i) advance U,V, then μ, Θ, then w, ϕ

(ii) time-average U,V, Ω

End acoustic loop

Advance scalars using time-averaged U,V, Ω

End Runge-Kutta loop

Adjustment physics (currently microphysics)

End time step

Domains: 108, 36, 12 and 4 km