A Year-Long Gulf Coast Mesoscale Modeling Study for Improving Meteorological Inputs for Air-Quality Models

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Outline

- Study Objectives
- Development Case
- Year-Long Study
- High-Resolution Experiments for Three Selected Cases
- Summary and Conclusions
- Acknowledgments

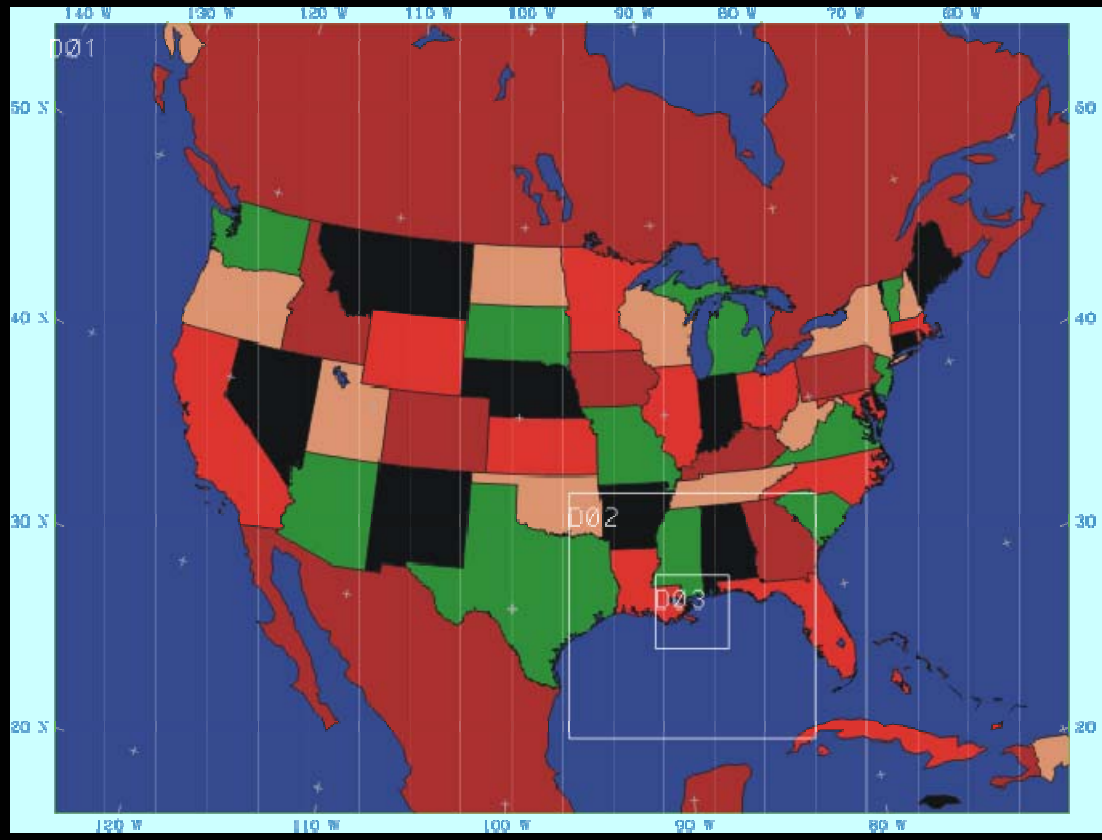
Breton National Wilderness Area

Study Objectives

- Breton National Wilderness Area air-quality (AQ) study
- One-year of 5.5-day 12-km resolution model simulations for AQ:
  - Are there monthly or seasonal trends in model performance?
  - Is this data set acceptable for AQ inputs (dynamically consistent, seamless and fit to observations)?
- Is it necessary to run the entire year of model simulations at a higher horizontal resolution?
- Can we improve upon the standard high-resolution, 4-km model results?

Mesoscale Model

- Penn State/NCAR MM5
- Three nested domains (36-km, 12-km, 4-km)
- 45 vertical sigma levels (lowest level at ~15 m AGL, and ~16 levels within the lowest 1000m)

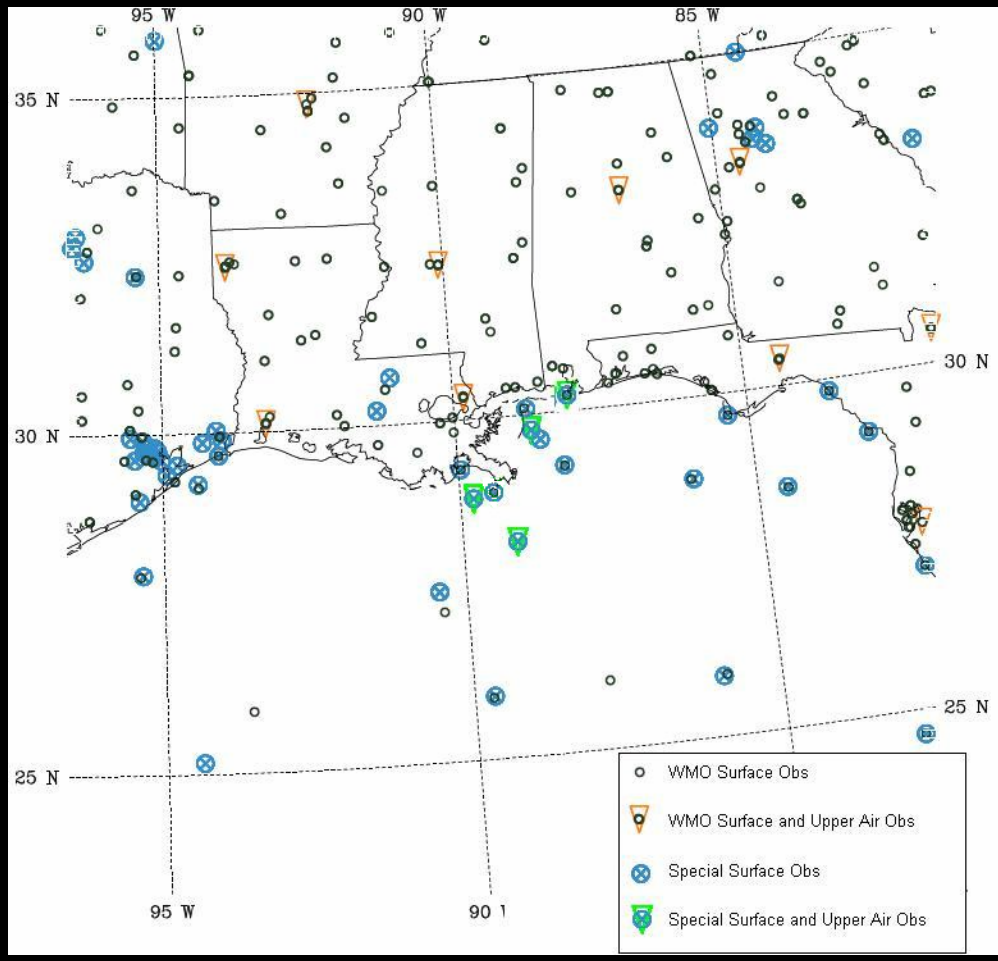


Development Case

- 10 experiments
- Four-dimensional data assimilation strategy
  - Analysis nudging
    - 12-hourly 3D (upper air) analysis nudging
    - 3-hourly surface analysis nudging within PBL
  - Observational nudging
    - Standard observational data (WMO obs)
    - Special observational data

Additional Data Sources

- Special surface observations
  - Additional land observations
  - Buoys and oil platforms
- Special upper-air observations
  - Vertical wind profilers

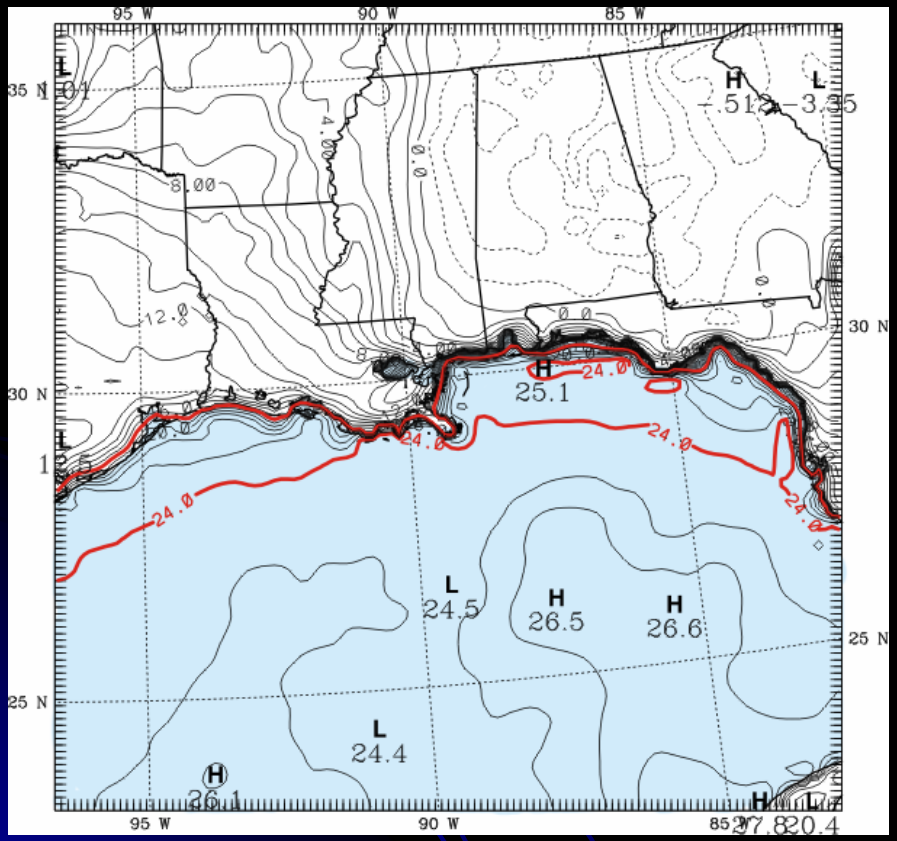


SST Products

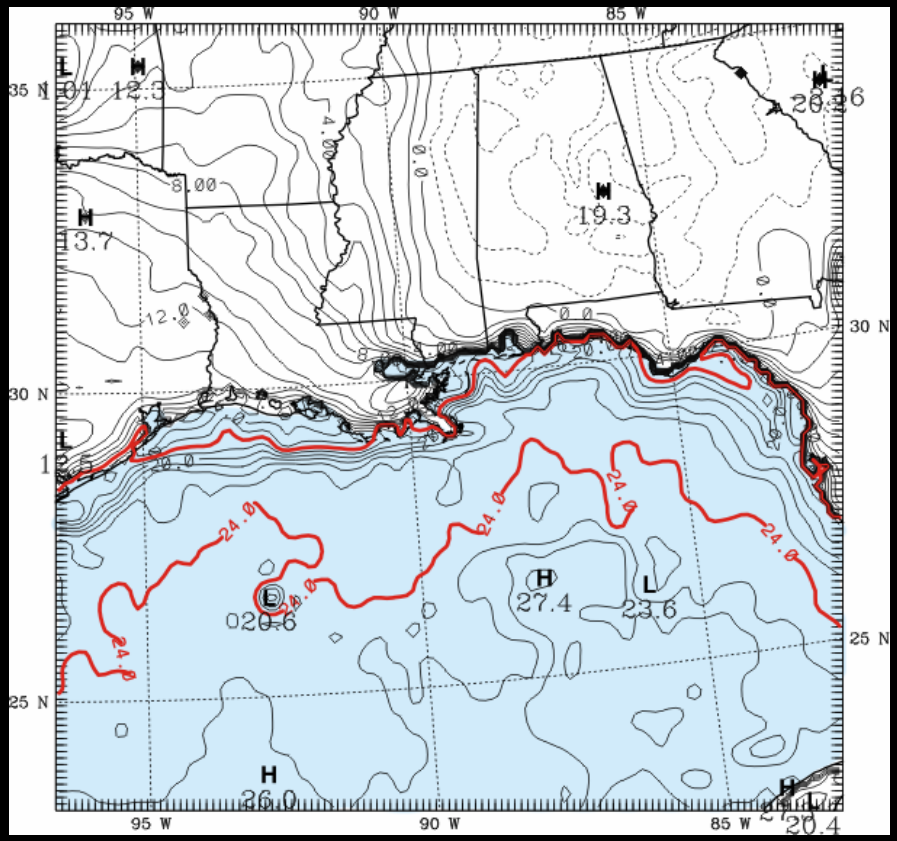
- ETA 212 Grid SST
  - 40-km resolution
  - Available standard from NCEP
- MODIS Satellite-derived SST
  - 36-km and 4-km resolution on our MM5 grids
  - Processed by Earth Tech for this one-year period

ETA and MODIS SST Fields

ETA 40-km Resolution

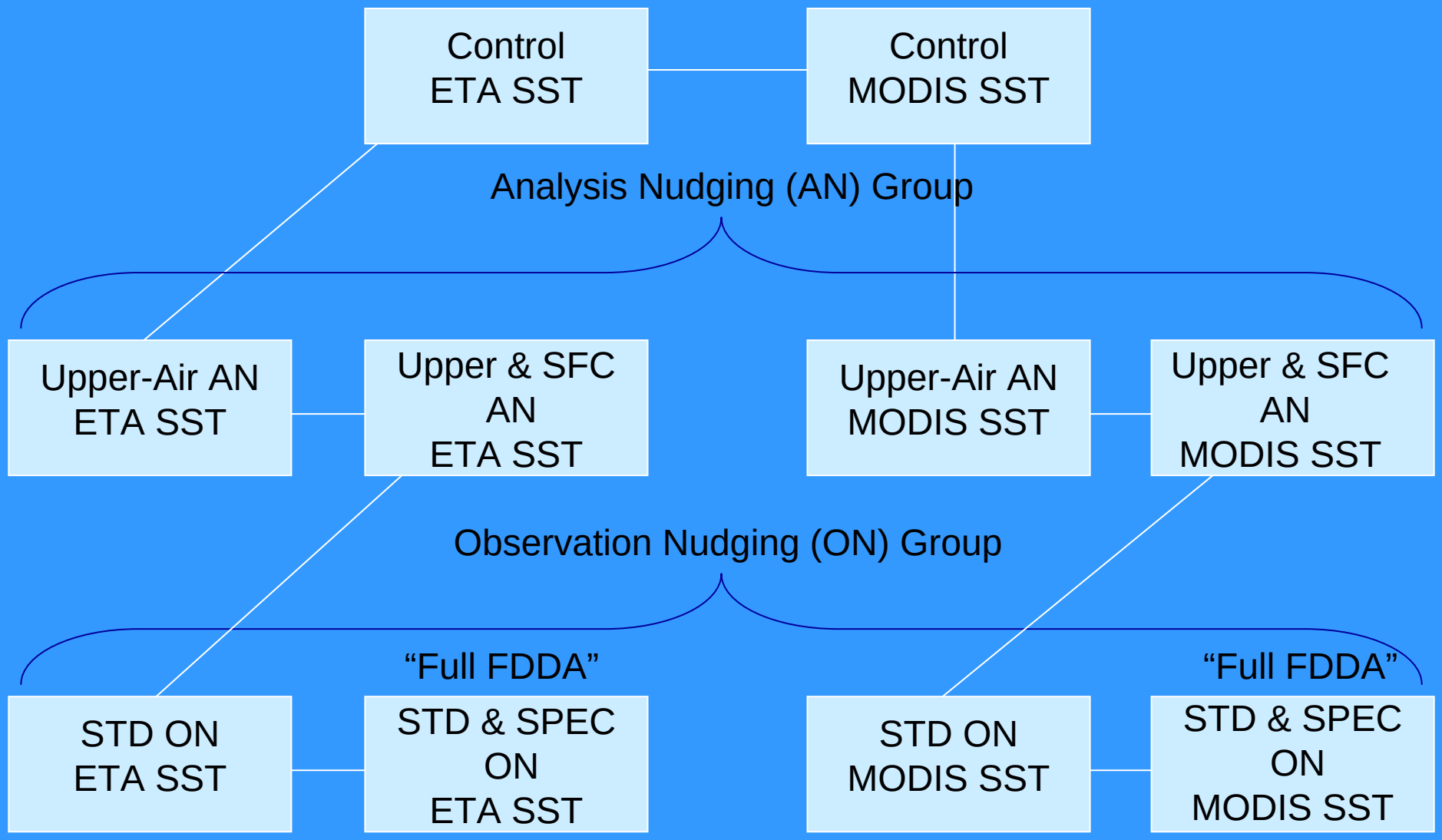


MODIS 36-km Resolution

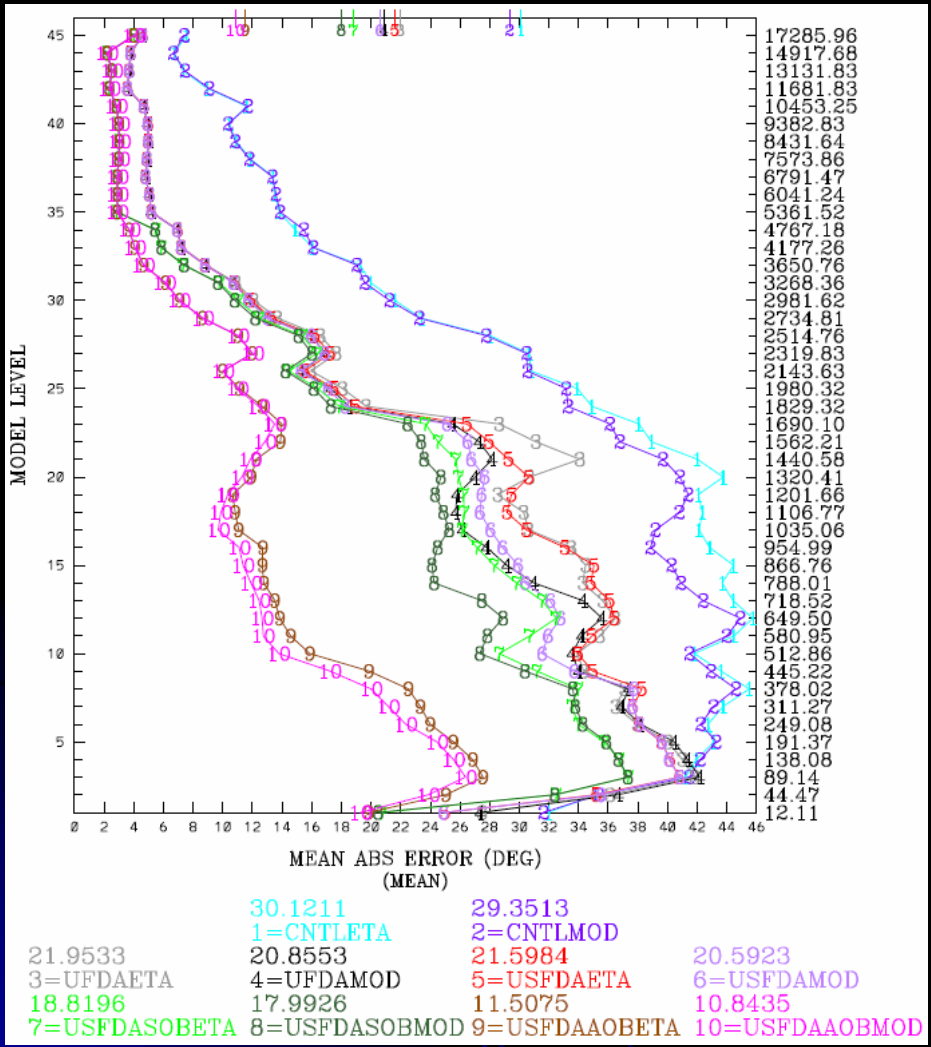


12 UTC, 1 December 2000

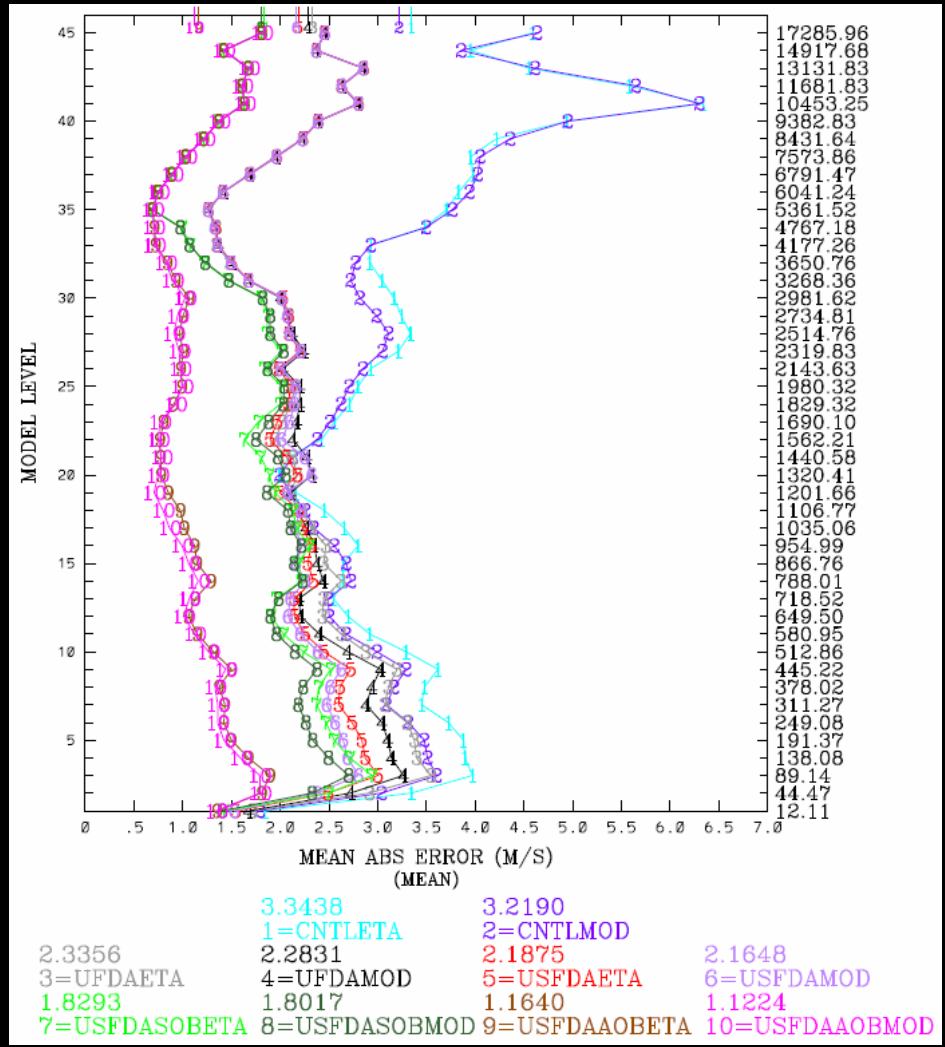
Development Case Experiments



Vertical Wind Field MAE Profiles

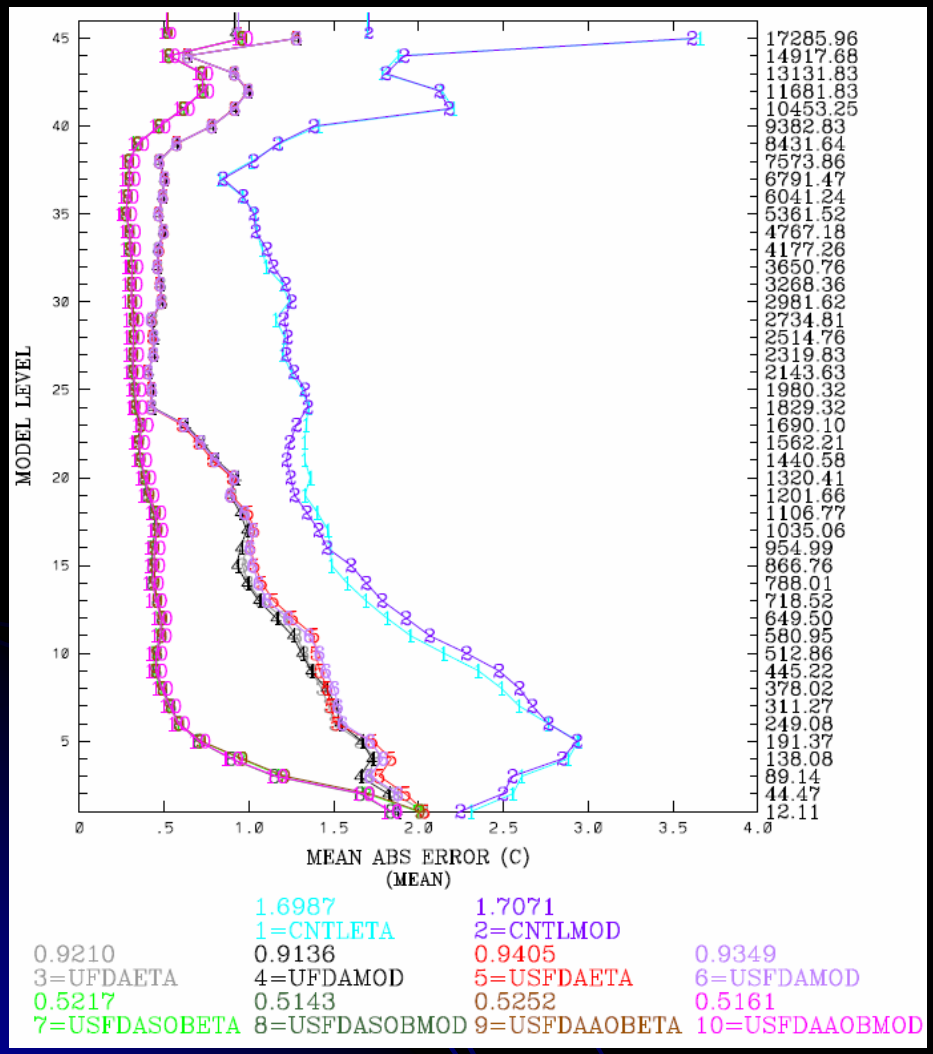


Wind Direction

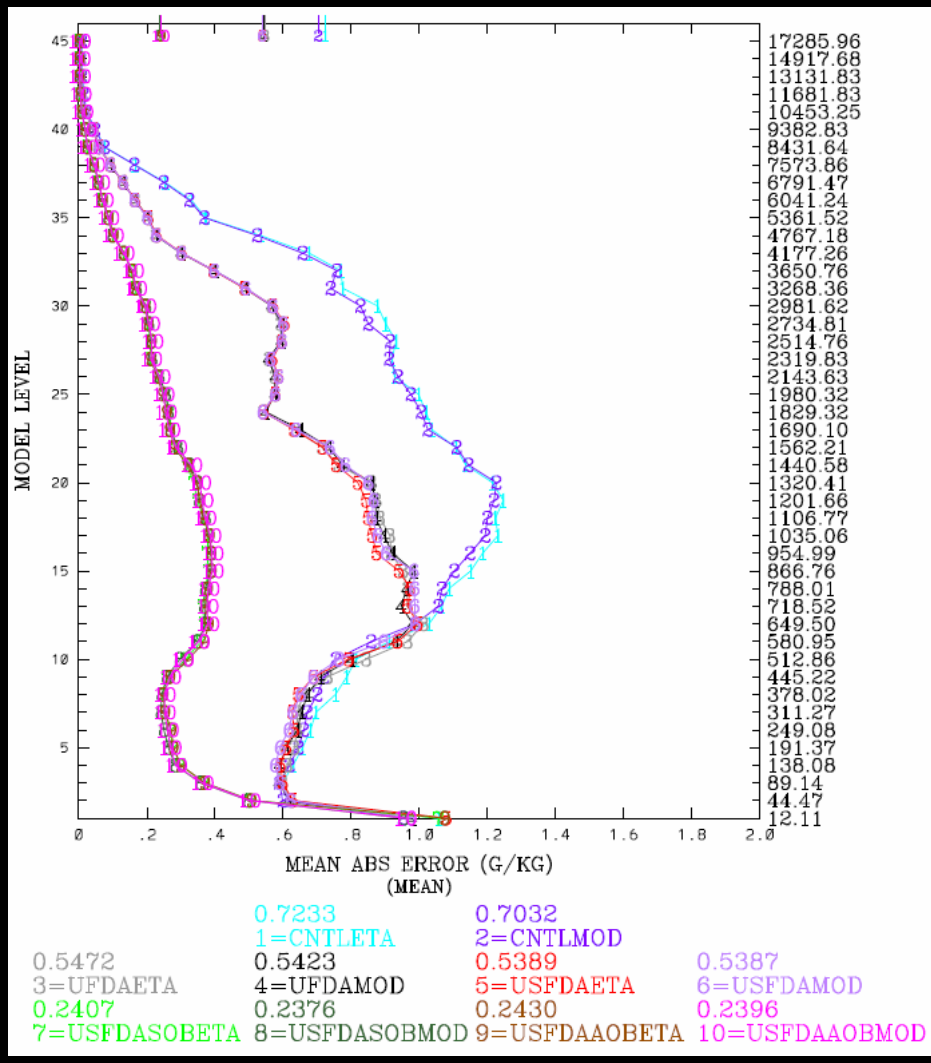


Wind Speed

Vertical Mass Field MAE Profiles



Temperature



Mixing Ratio

Conclusions from the Development Case

- Observation nudging runs produce best statistical fit to data throughout the vertical
- MODIS SST also provides some statistical benefit over the ETA SST.
- Best configuration
  - Upper-air plus surface analysis nudging within the PBL
  - Standard plus special data observation nudging
  - 36-km resolution MODIS SST

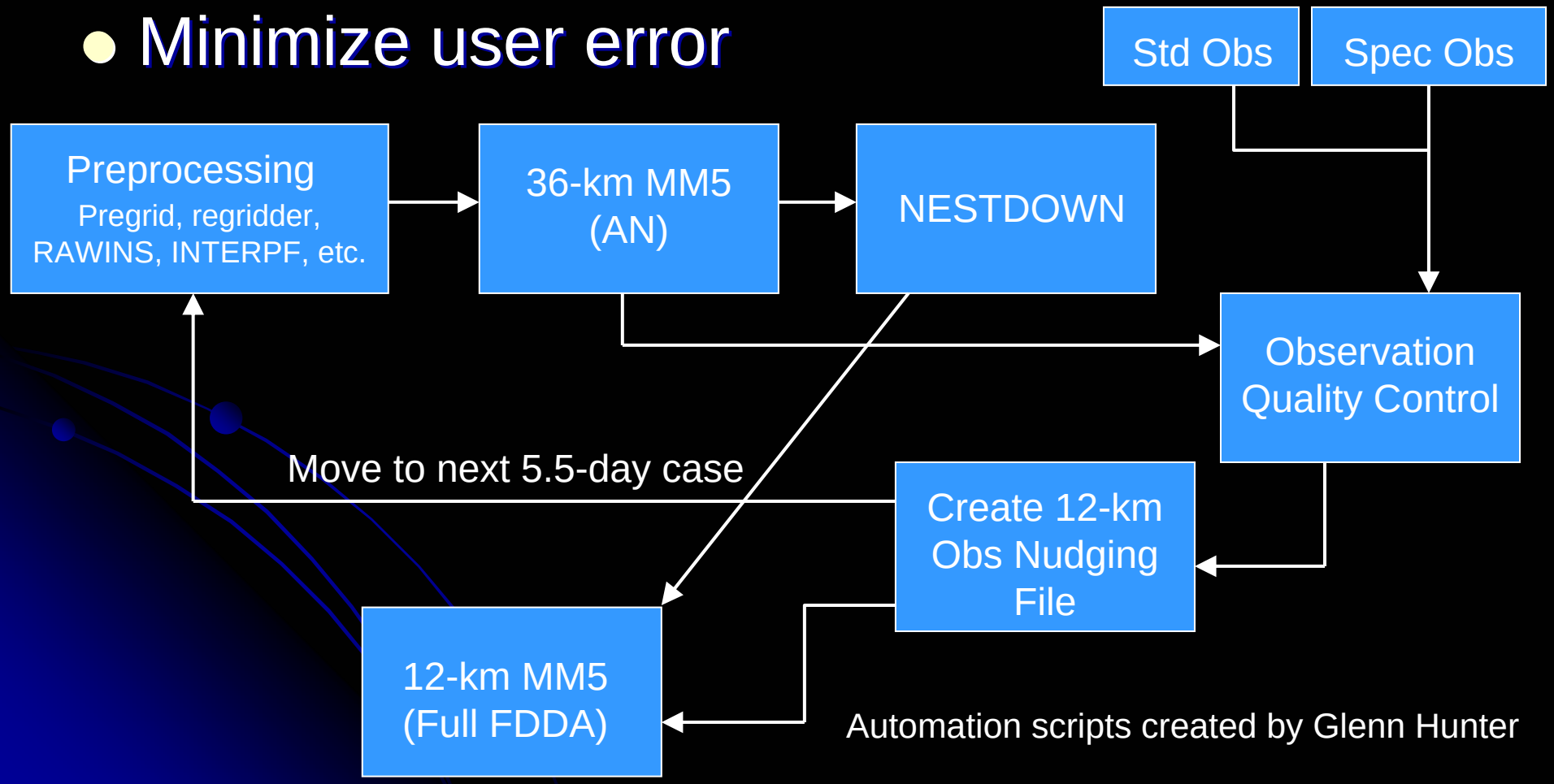
Year-Long Study

- 1 October 2000 – 30 September 2001
- 5.5-day cases, with half-day of overlap allotted for spin-up
- 6 cases designated as “episodes”*
  - 12 UTC 1 Dec 2000 to 00 UTC 7 Dec 2000
  - 12 UTC 1 Mar 2001 to 00 UTC 7 Mar 2001
  - 12 UTC 8 Jul 2001 to 00 UTC 14 Jul 2001
  - 12 UTC 7 Aug 2001 to 00 UTC 13 Jul 2001
  - 12 UTC 7 Nov 2000 to 00 UTC 13 Nov 2000
  - 12 UTC 29 Dec 2000 to 00 UTC 4 Jan 2001

* For air-quality concerns

Model Automation

- Limited timeframe to complete model runs
- Minimize user error



Automation scripts created by Glenn Hunter

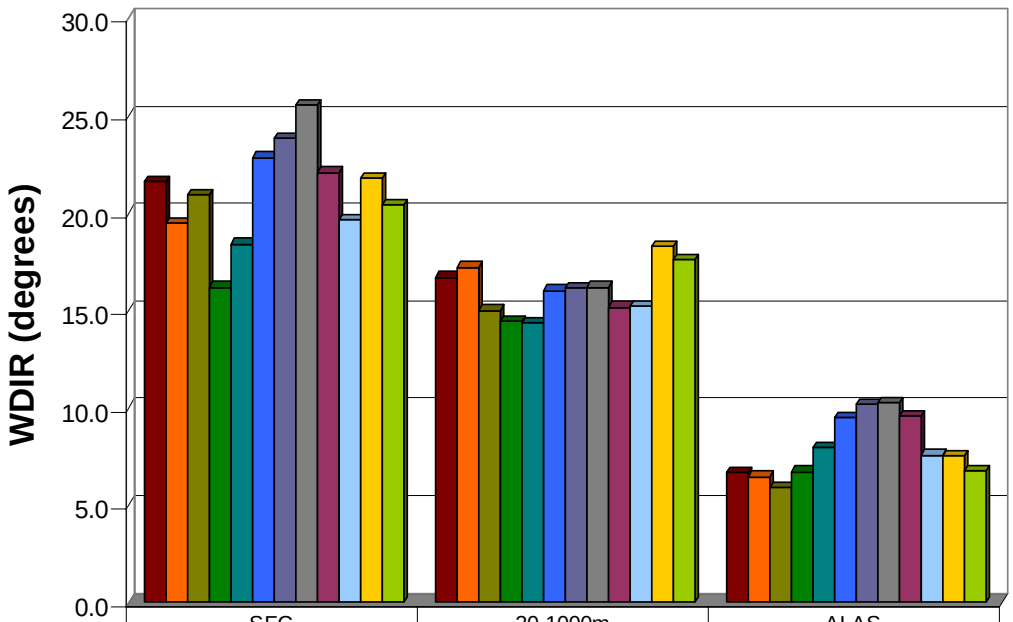
Statistical Averages

- Six-episode averages
- Year-long case-by-case averages
- Monthly averages
- Seasonal averages
- Annual averages – what can be expected?

What trends in model performance are noticeable on these timescales?

Monthly Wind Direction Error

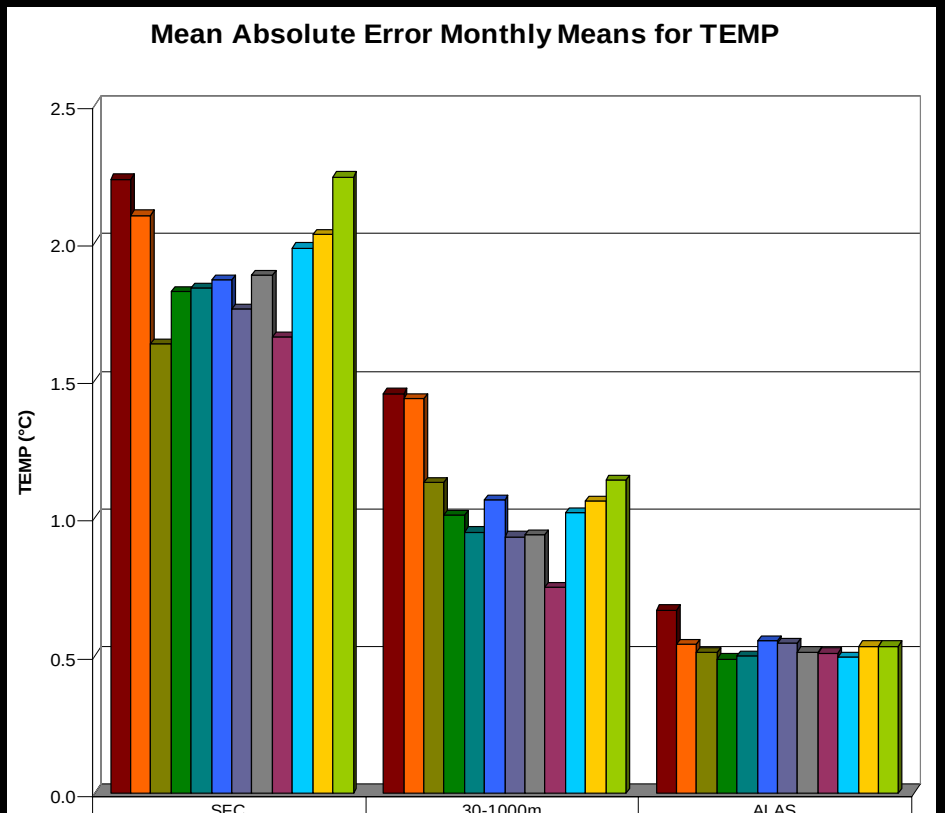
- Direction errors largest during the warm season
  - Weak synoptic forcing
  - Land/Sea interactions
  - Convective outflows
- Smallest during the cool season
  - Large-scale, synoptically-driven systems



	SFC	30-1000m	ALAS
Jan	21.6	16.7	6.7
Feb	19.5	17.2	6.5
Mar	20.9	15.0	5.9
Apr	16.2	14.4	6.7
May	18.4	14.4	8.0
Jun	22.9	16.0	9.5
Jul	23.8	16.2	10.2
Aug	25.5	16.2	10.3
Sep	22.1	15.2	9.6
Oct	19.7	15.2	7.6
Nov	21.8	18.3	7.5
Dec	20.4	17.6	6.8

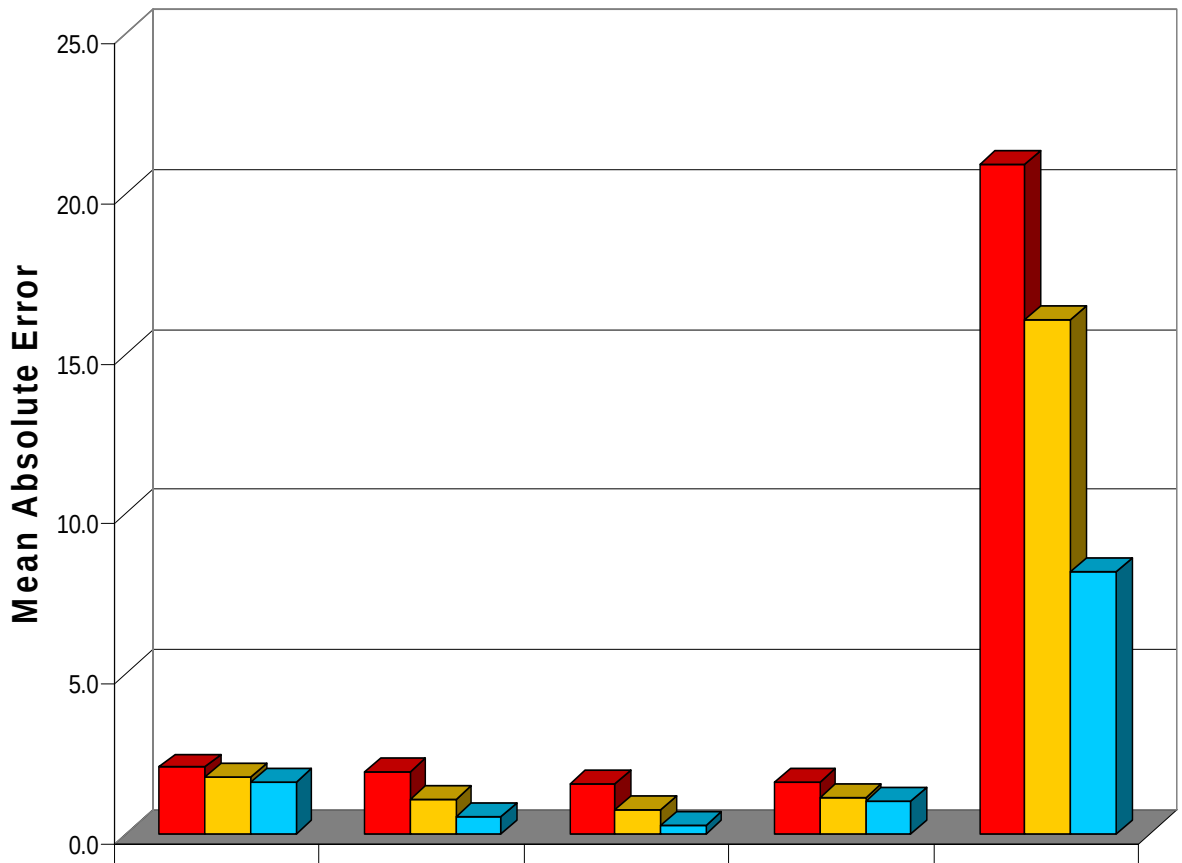
Monthly Temperature Error

- Largest temperature errors during the cold season
  - More frontal passages, stronger horizontal gradients
- Smallest temperature errors during the warm season



	SFC	30-1000m	ALAS
Jan	2.2	1.5	0.7
Feb	2.1	1.4	0.5
Mar	1.6	1.1	0.5
Apr	1.8	1.0	0.5
May	1.8	0.9	0.5
Jun	1.9	1.1	0.6
Jul	1.8	0.9	0.5
Aug	1.9	0.9	0.5
Sep	1.7	0.7	0.5
Oct	2.0	1.0	0.5
Nov	2.0	1.1	0.5
Dec	2.2	1.1	0.5

Annual Average Model Errors



	VWD (m/s)	TEMP (°C)	MIXR (g/kg)	WSPD (m/s)	WDIR (degrees)
SFC	2.1	1.9	1.5	1.6	20.9
30-1000m	1.8	1.1	0.8	1.2	16.0
ALAS	1.6	0.5	0.3	1.0	8.2

Conclusions from Year-Long Study

- Monthly and seasonal errors were as expected
  - Largest (smallest) directional errors occurred when winds were lightest (strongest)
  - Mass field errors are smallest when patterns are larger-scale
- Model performance well within the threshold criteria for specific case studies, set by previous AQ studies

High-Resolution Case Studies

High-Resolution Case Studies

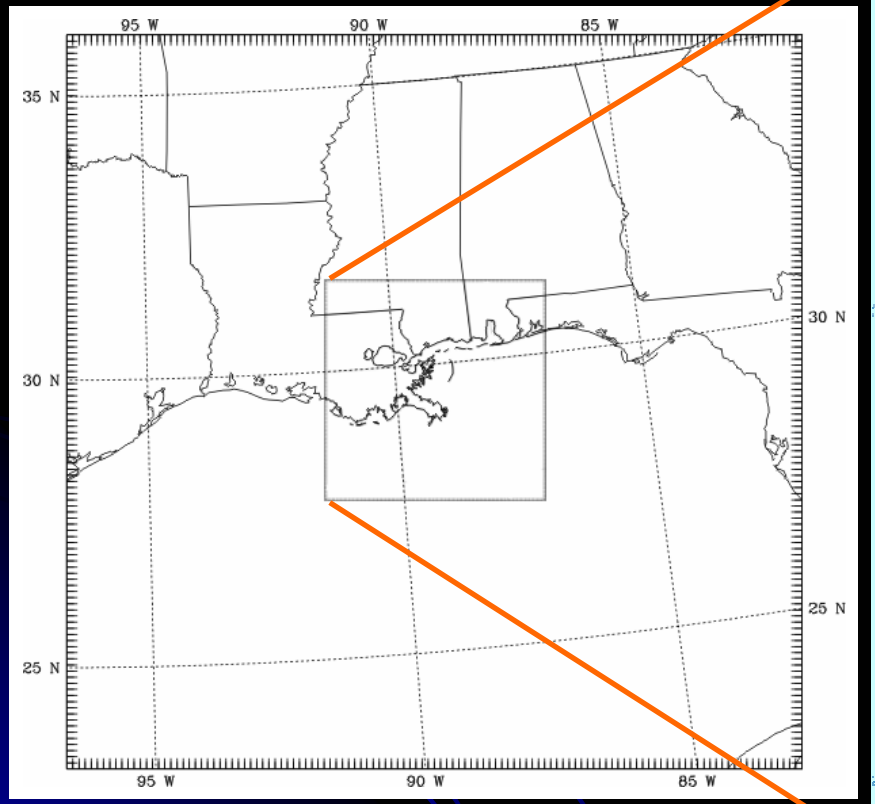
- Is there any benefit of 4-km resolution simulations over 12-km simulations?
- Is there added value for use of a convective parameterization on a 4-km domain?
- Can a high-resolution SST field improve mesoscale circulations in a coastal zone?
- What is the best model configuration for this study?

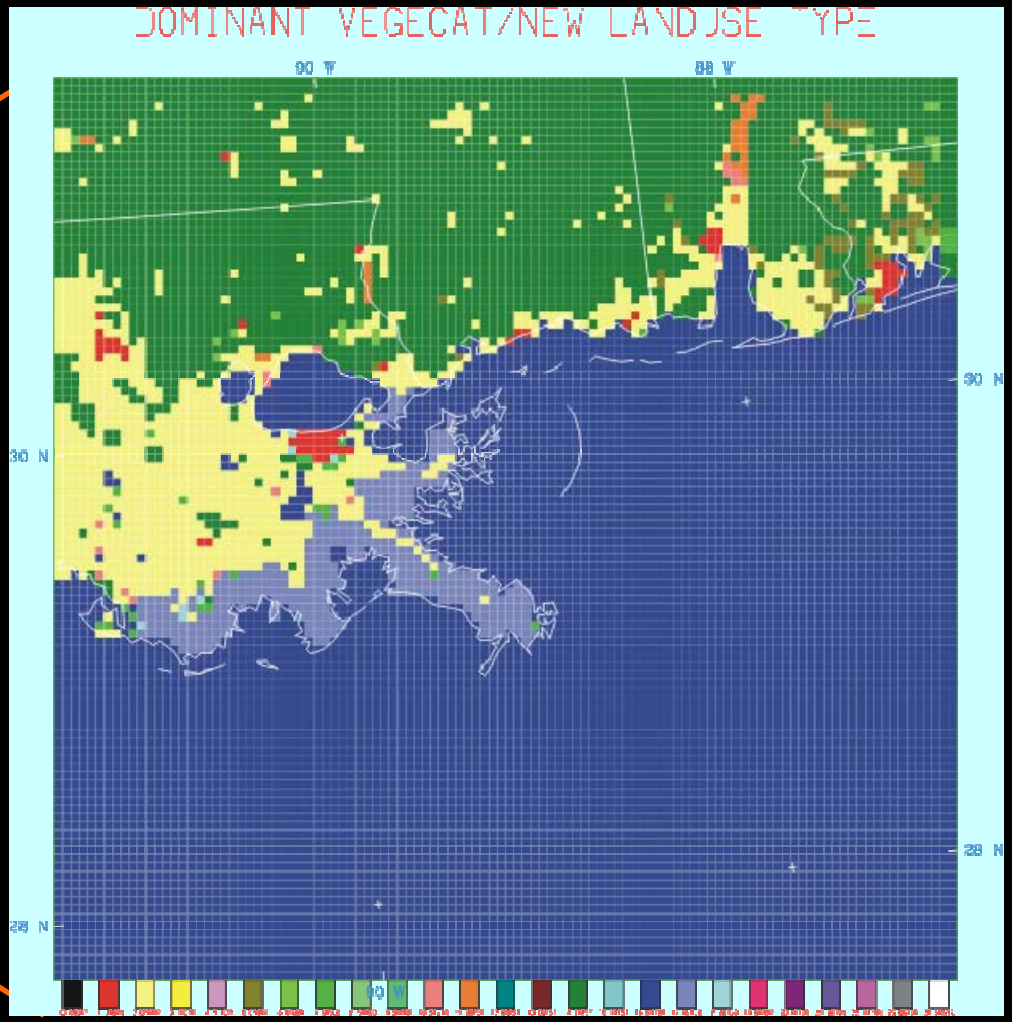
Three Selected Cases

Each case represents one of the six "episode" cases, determined by the sponsor

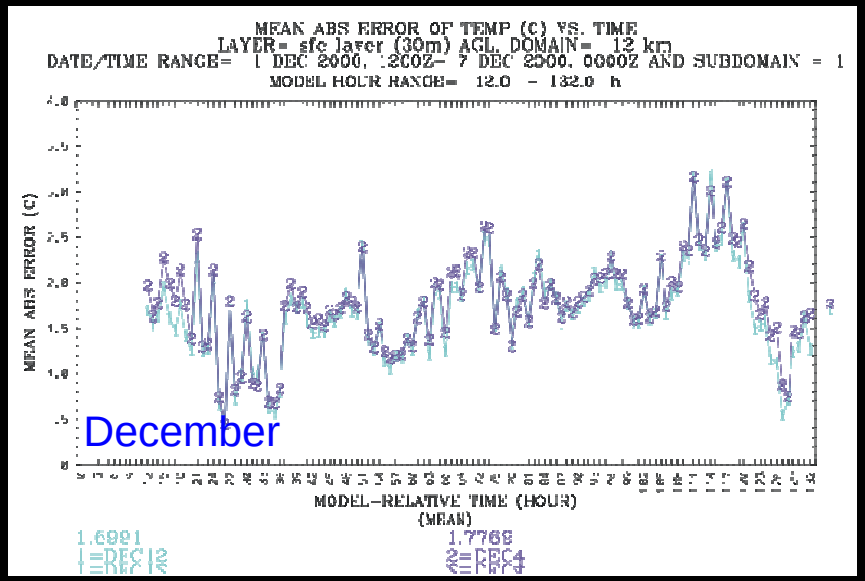
1. 12 UTC, 1 December 2000 to 00 UTC, 7 December 2000
   - Strong, offshore synoptic flow
   - Cold-frontal passage
2. 12 UTC, 1 March 2001 to 00 UTC, 7 March 2001
   - Stationary front partially inside the 4-km domain area
   - Cold front pushes through the area
   - Weak synoptic forcing at the end of the period
3. 12 UTC, 8 July 2001 to 00 UTC, 14 July 2001
   - Weak synoptic flow throughout the entire case period
   - Daily convection
   - Recurring sea-breeze circulations

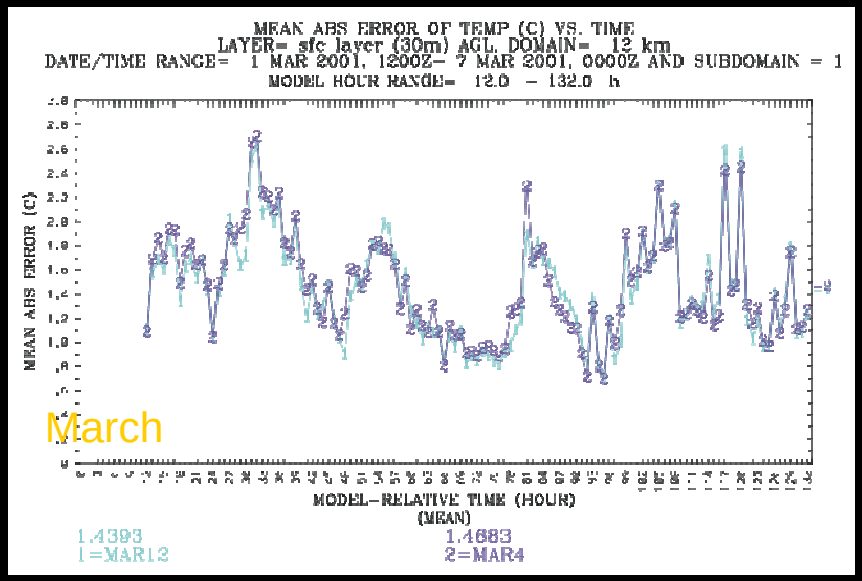
12-km and 4-km Domains

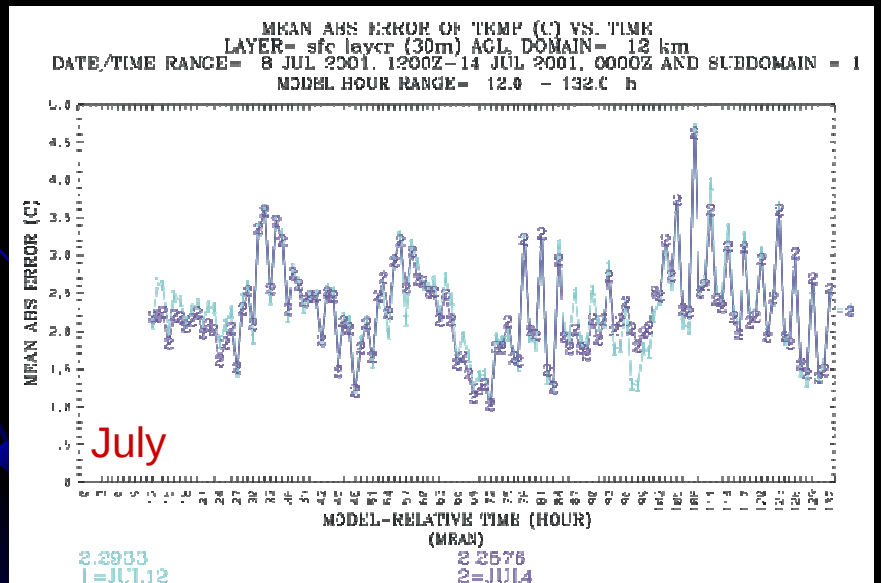




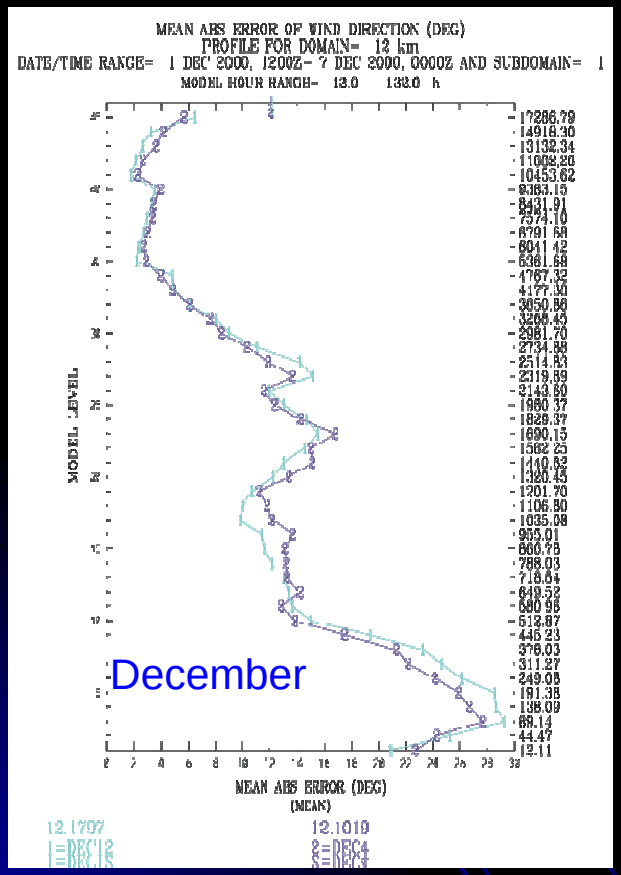
12-km vs. 4-km Surface Temp Statistics for the Three Cases

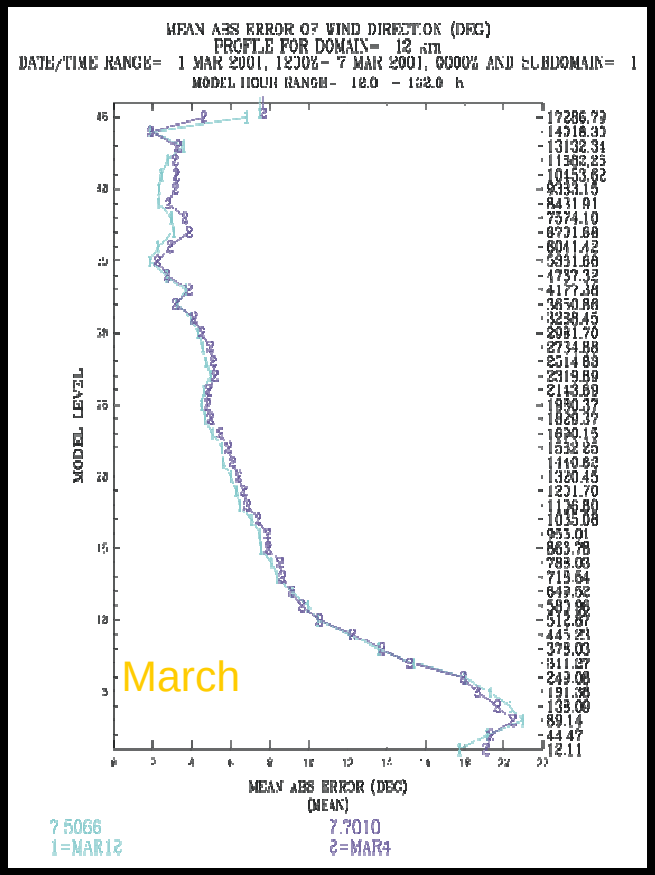


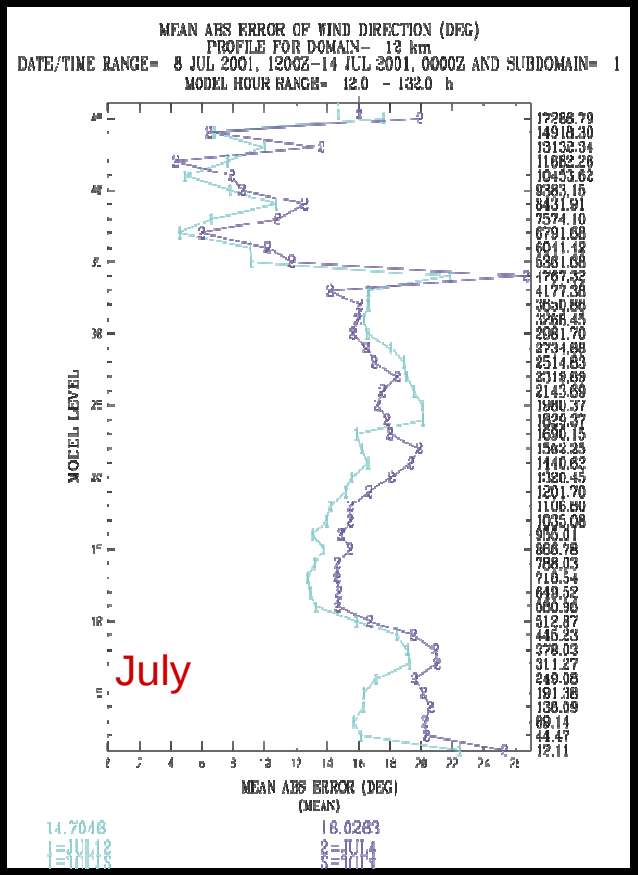




12-km vs. 4-km Vertical Profile Wind Direction Statistics







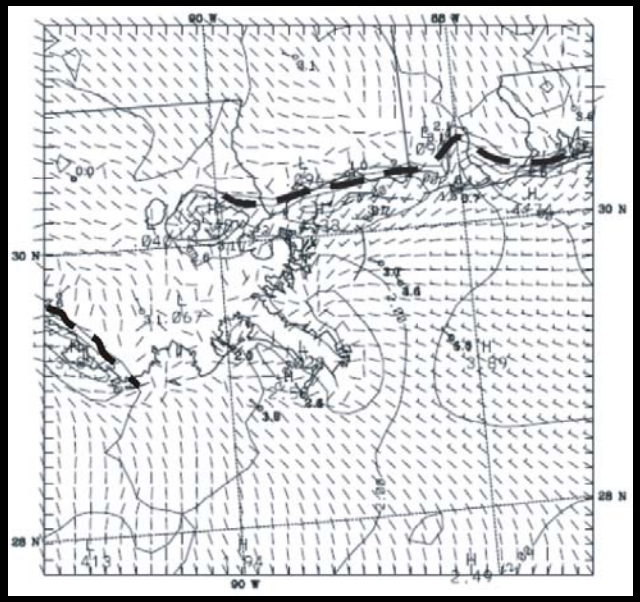
12-km vs. 4-km Statistics

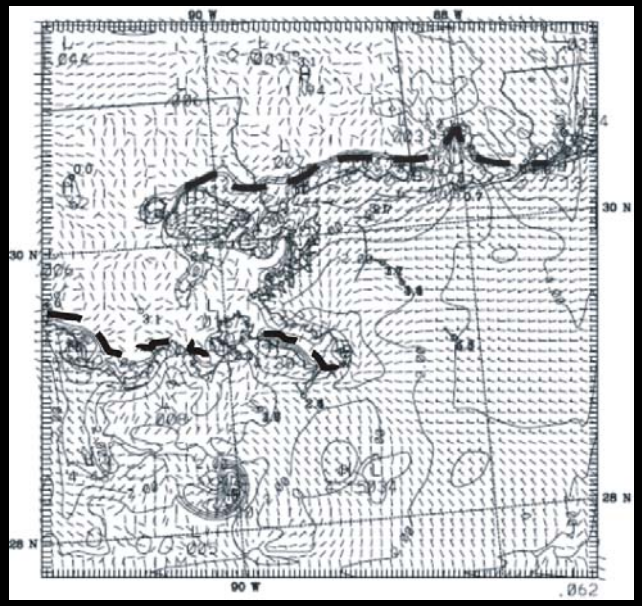
- Average error statistics tend to favor 12-km resolution, but differences small
- Notes:
  - Comparable statistical skill on 12-km vs. 4-km model grids (e.g., Schroeder et al. 2006)
  - Greater value of higher model resolution in more complex terrain (Stauffer et al. 2007)

12-km 4-km

18 UTC,

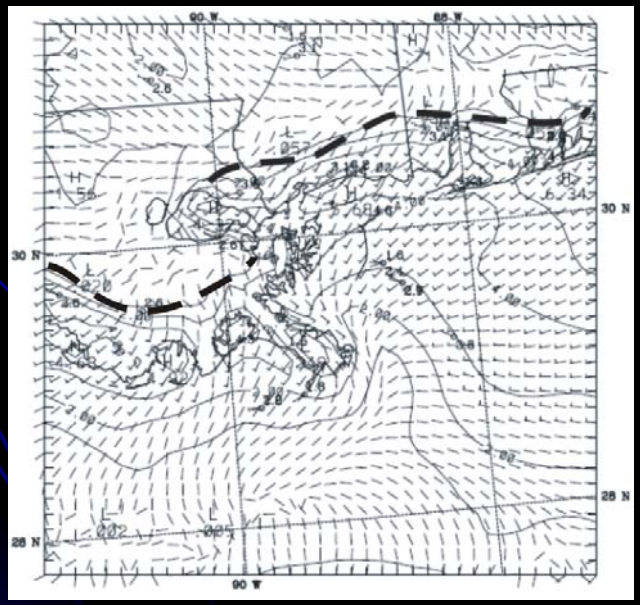
9 July 2001

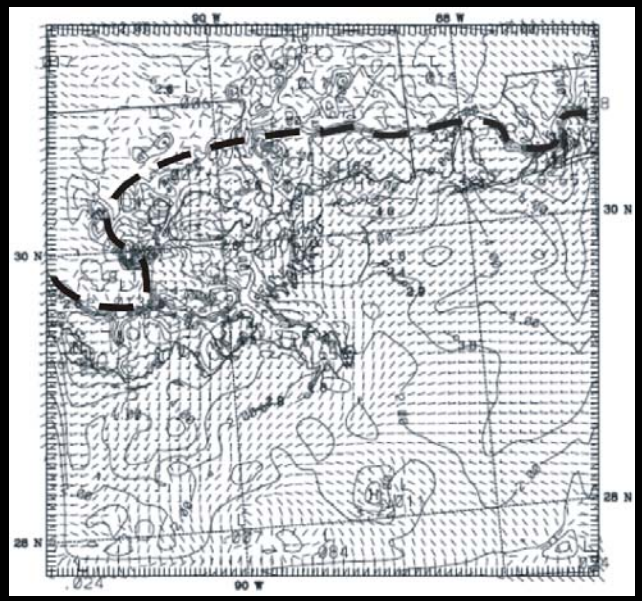




21 UTC,

9 July 2001





Summary of 12-km vs. 4-km Resolution Experiments

- Do the 4-km resolution simulations have a clear statistical benefit? Not for standard statistics and these three cases
- The benefit comes in the form of more mesoscale details
  - Differences in phasing and amplitude could hinder the statistics
  - 4-km resolution introduces more risk!
  - Extra detail could be largely beneficial to pollutant transport in air-quality models
- Running an entire year of simulations at 4-km resolution may not be justified…

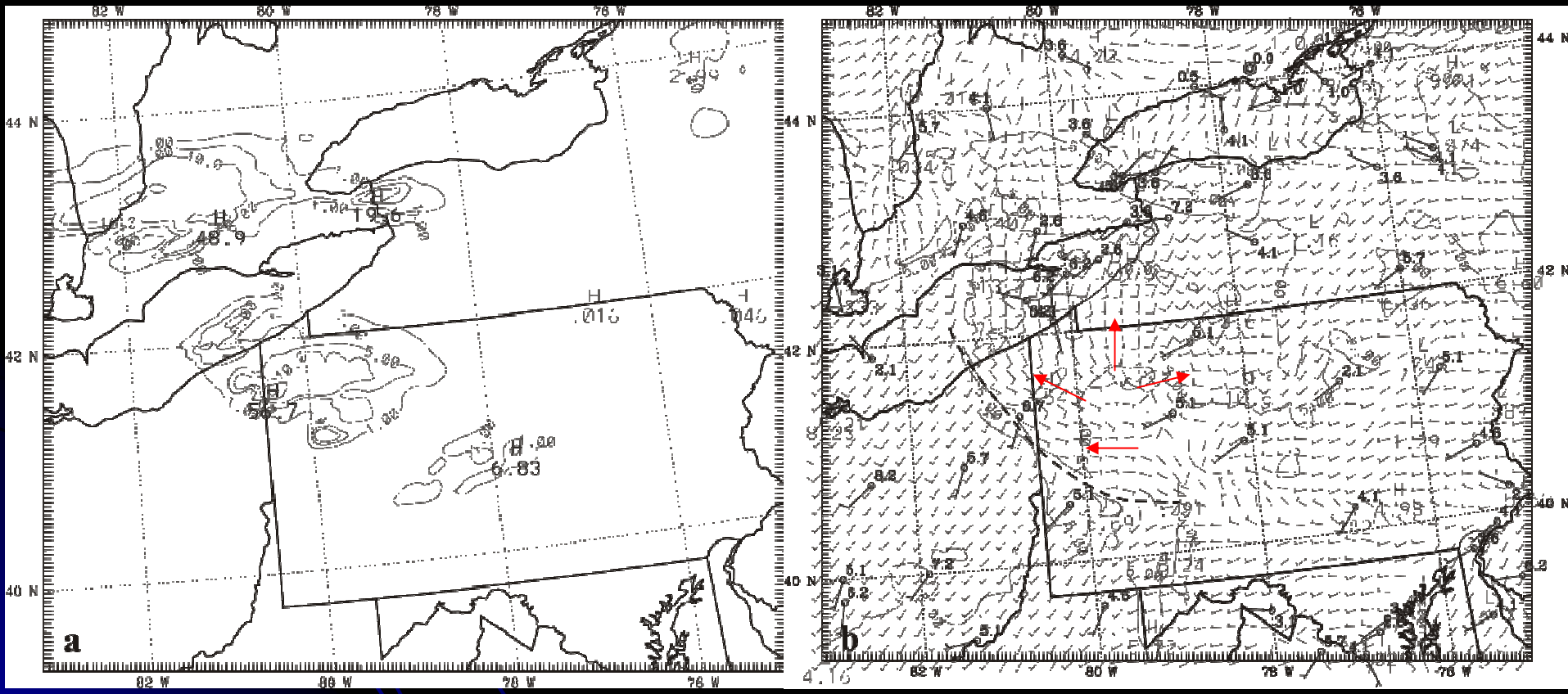
Improving on 4-km Resolution Simulations

Convective Parameterization on 4-km Grid

- This is not a typical practice
  - Scale separation
  - Explicit microphysics – 4-km updrafts?
- There may be some benefits
  - Alleviate “grid-point storms” (Deng and Stauffer 2006)
  - Create better precipitation coverage and low-level winds in convective situations

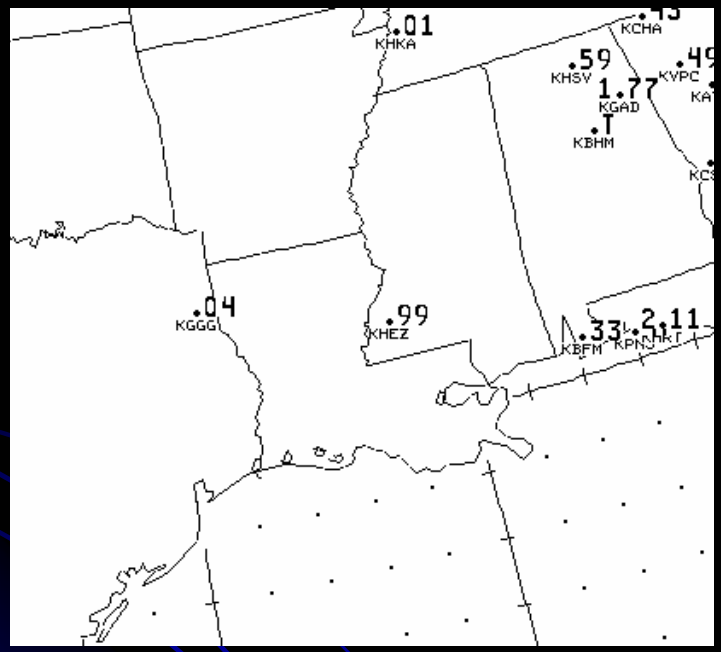
Grid-Point Storms

From Deng and Stauffer (2006)



Subjective Precipitation Results

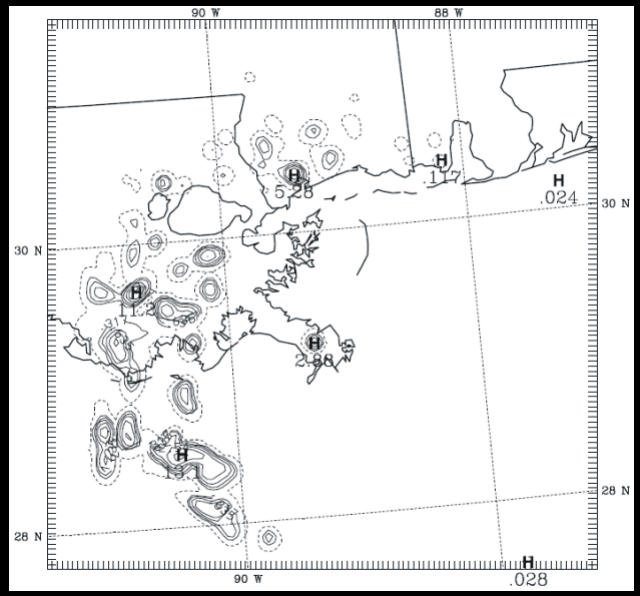
24-hr Accumulated Precipitation (inches)



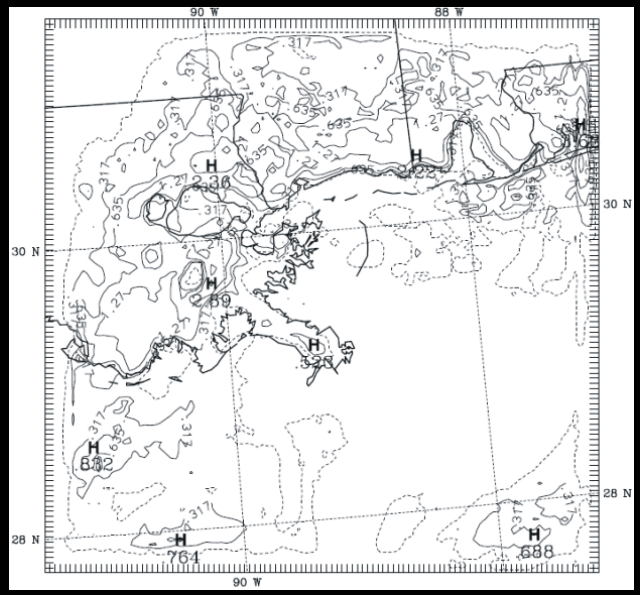
12 UTC, 9 July 2001

to

12 UTC, 10 July 2001



Explicit



Parameterized

Other Subjective Notes on use of Convective Parameterization at 4-km Resolution

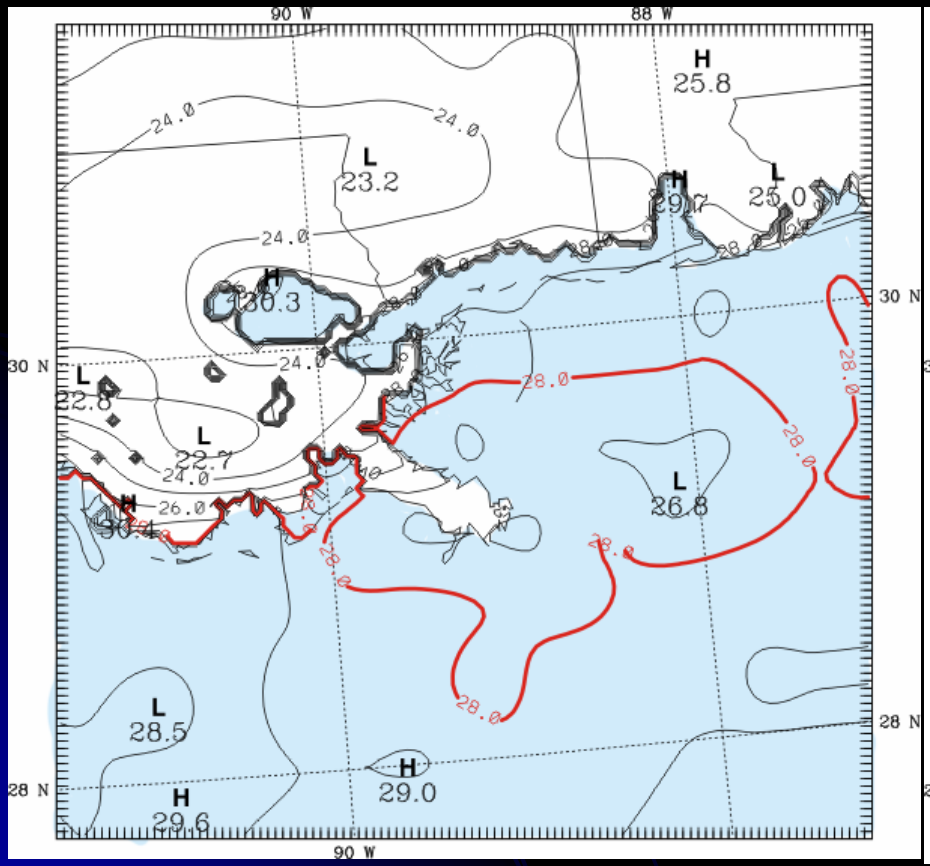
- Slight differences in the wind fields do exist when using the convective parameterization
  - Sea breeze fronts are less distinct
  - Sea breezes start later in the day (~3 hrs)
  - May be a result of additional precipitation coverage and cloud cover caused by convective parameterization

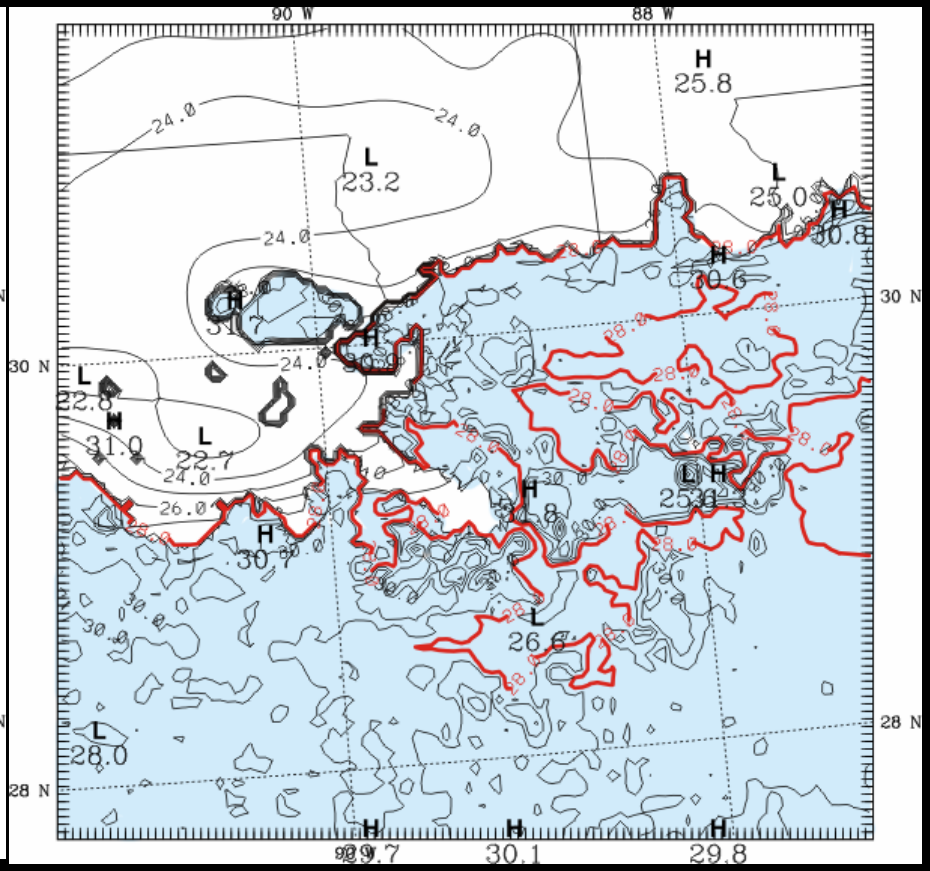
Summary of Use of Convective Parameterization at 4-km Resolution

- Use of a convective parameterization has little statistical benefit in these threes cases, but also does not hurt the results
- Greatest differences in model output are evident in the precipitation fields
  - Creates larger precipitation coverage area
  - Produces more realistic precip amounts and low-level winds in convective situations
- Note: Violates underlying assumptions of current convective parameterizations, but results better!

High Resolution SST

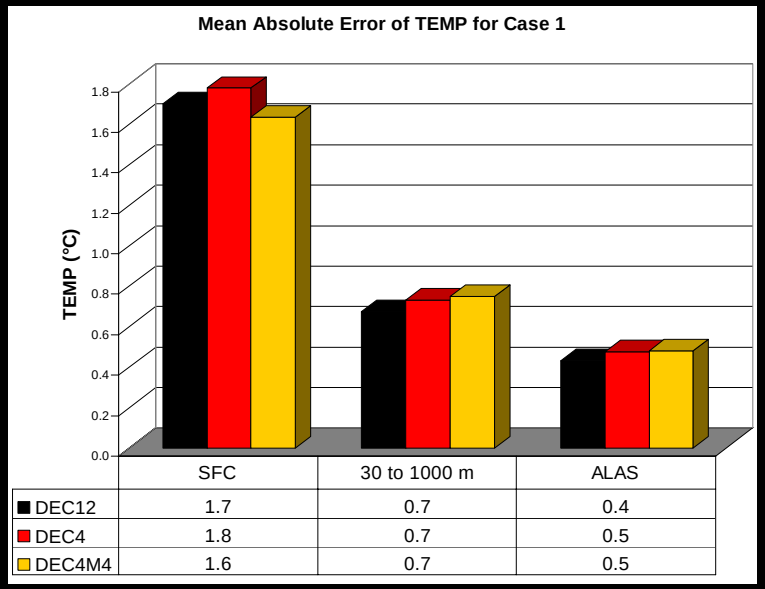
- MODIS SST data were available in 36-km and 4-km resolutions (8 July 2001).

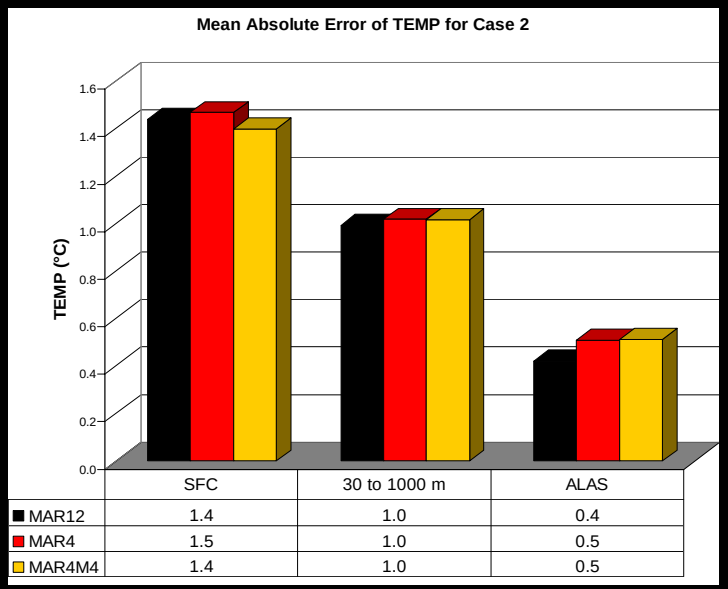




SST Experiment Temp Stats

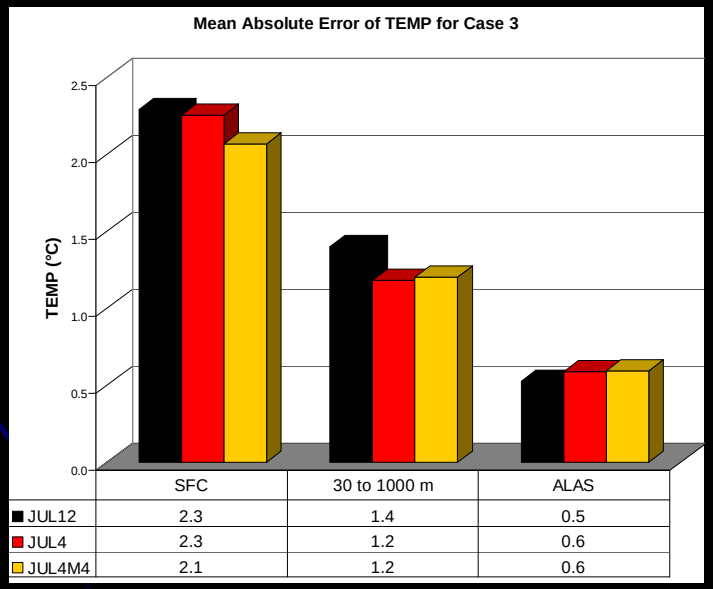
DEC





MAR

JUL



High-Resolution SST Notes

- Temperature statistics benefit from higher-res SST at low levels
- Wind direction statistics are comparable (not shown)
- Subjective differences inconclusive (not shown)

Summary of High-Resolution SST

- Use of a high-resolution SST decreased low-level temperature errors
- Improved low-level temperatures may be important for air chemistry
- Subjectively, these SST results are inconclusive

Conclusions …

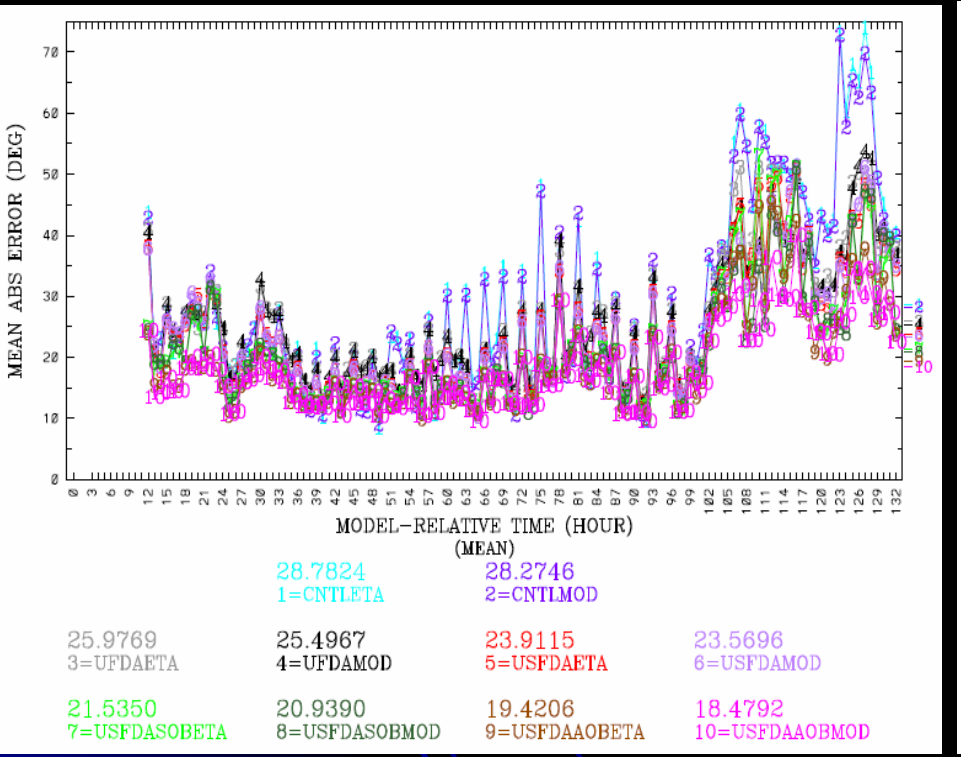
- Use of 4-km grid spacing may be beneficial on a case-by-case basis especially in complex terrain. Greater accuracy is not guaranteed and the additional computational costs may not be warranted.
- Use of a convective parameterization on the 4-km domain may be attractive as a “safety net” against grid-point storms and numerical instabilities.
- If water is a major part of your focus area, high-resolution SST data may have some benefits if the data are available.

Acknowledgments

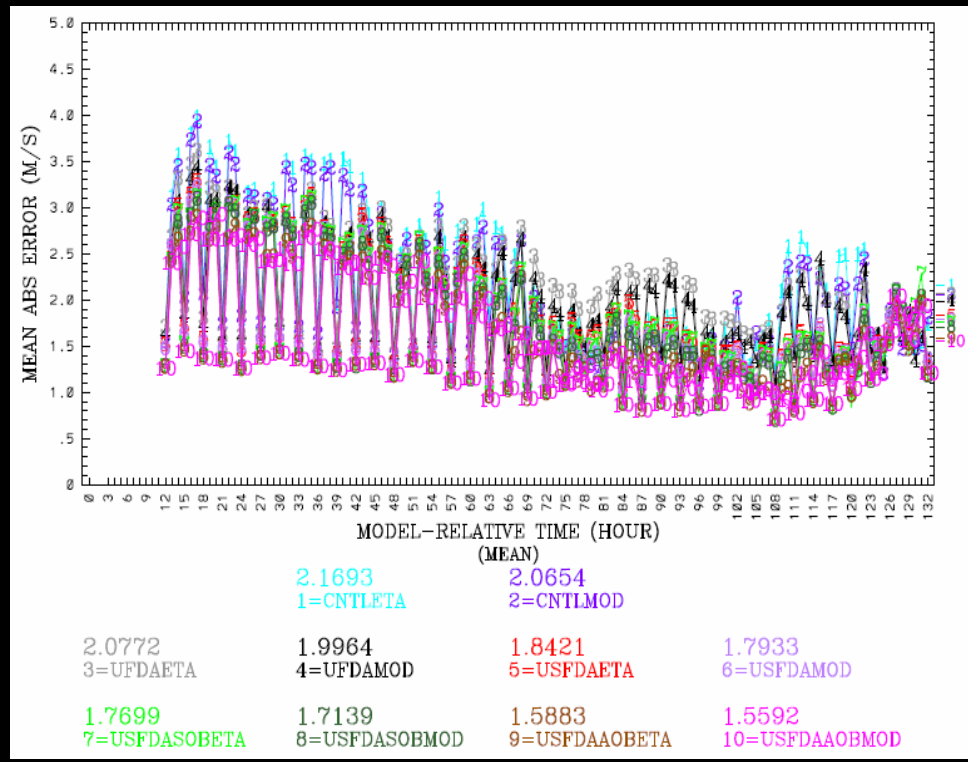
- Penn State Team Members
  - Dr. David R. Stauffer
  - Mr. Glenn Hunter
  - Dr. Aijun Deng
- Sponsors/Collaborators
  - Minerals Management Service
  - Sonoma Technologies

Supplemental Slides

Surface MAE Time Series for Wind Fields

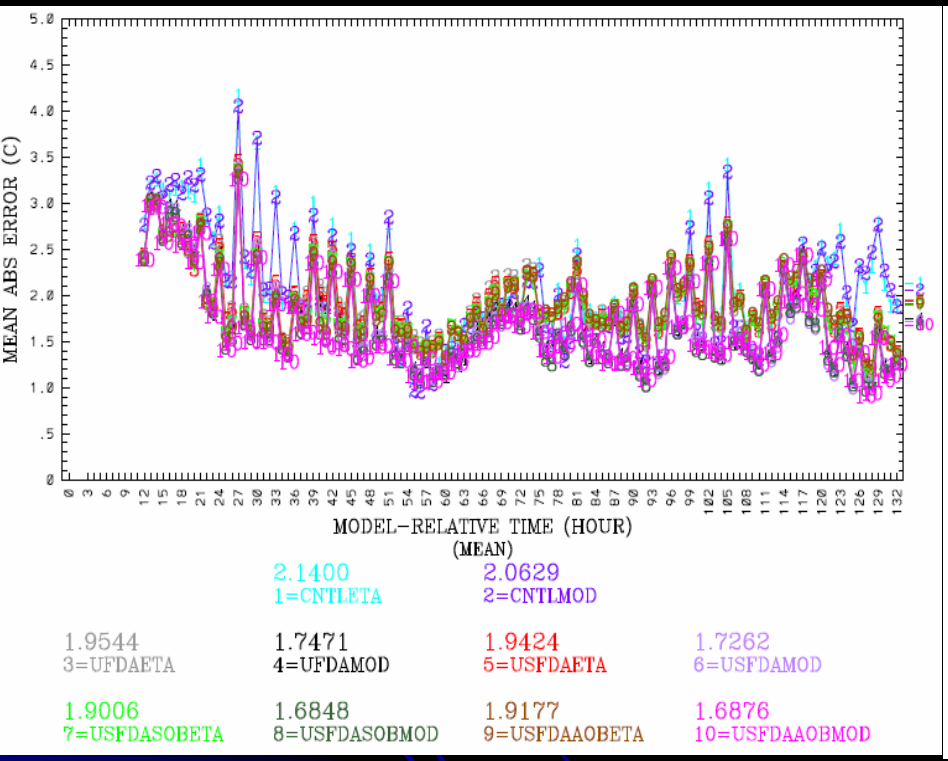


Wind Direction

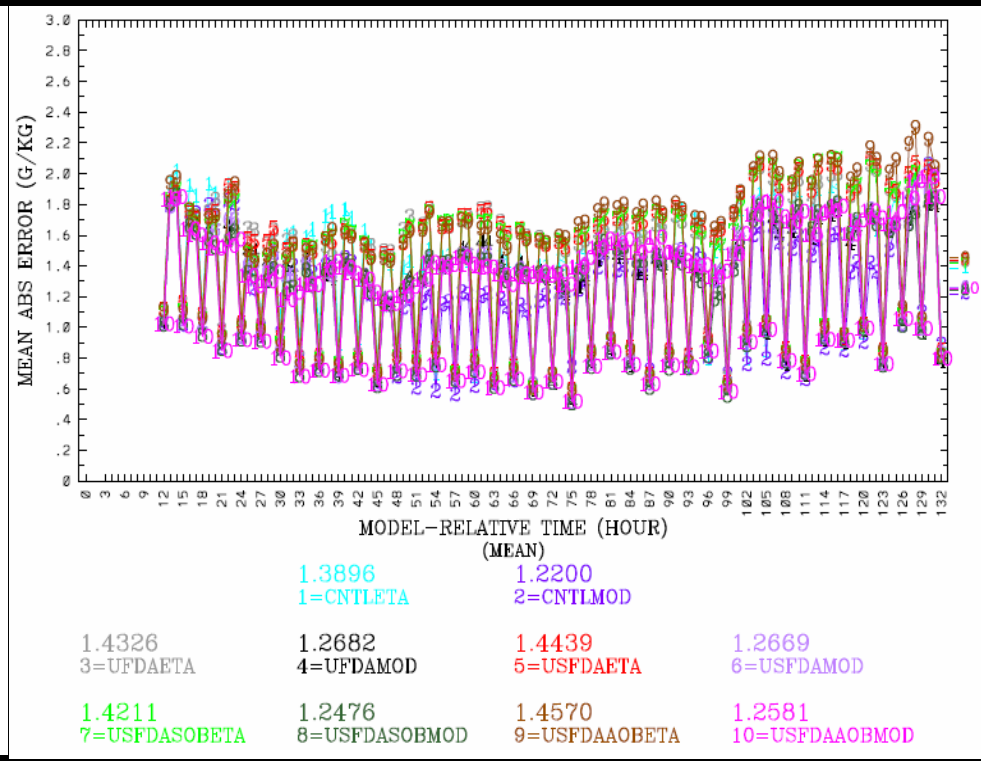


Wind Speed

Surface MAE Time Series for Mass Fields

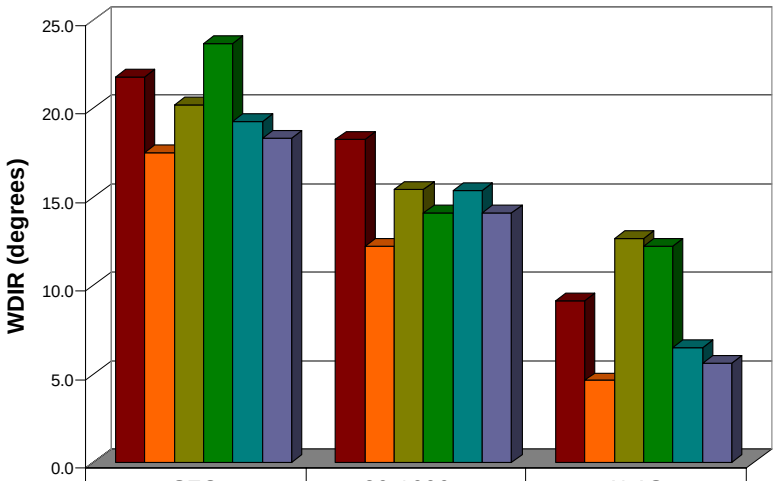


Temperature



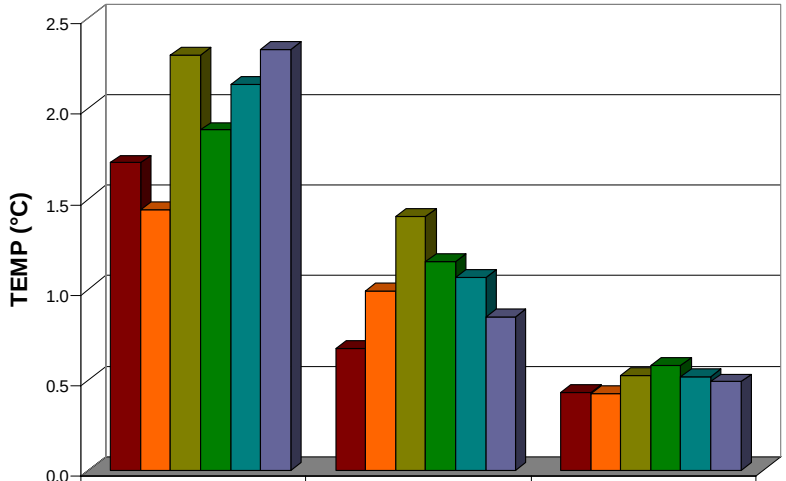
Mixing Ratio

Episodic Case Error Averages



	SFC	30-1000m	ALAS
Ep. 1 - DEC	21.8	18.3	9.1
Ep. 2 - MAR	17.5	12.2	4.6
Ep. 3 - JUL	20.2	15.4	12.7
Ep. 4 - AUG	23.7	14.1	12.2
Ep. 5 - NOV	19.3	15.3	6.5
Ep. 6 - JAN	18.3	14.1	5.6

Wind Direction

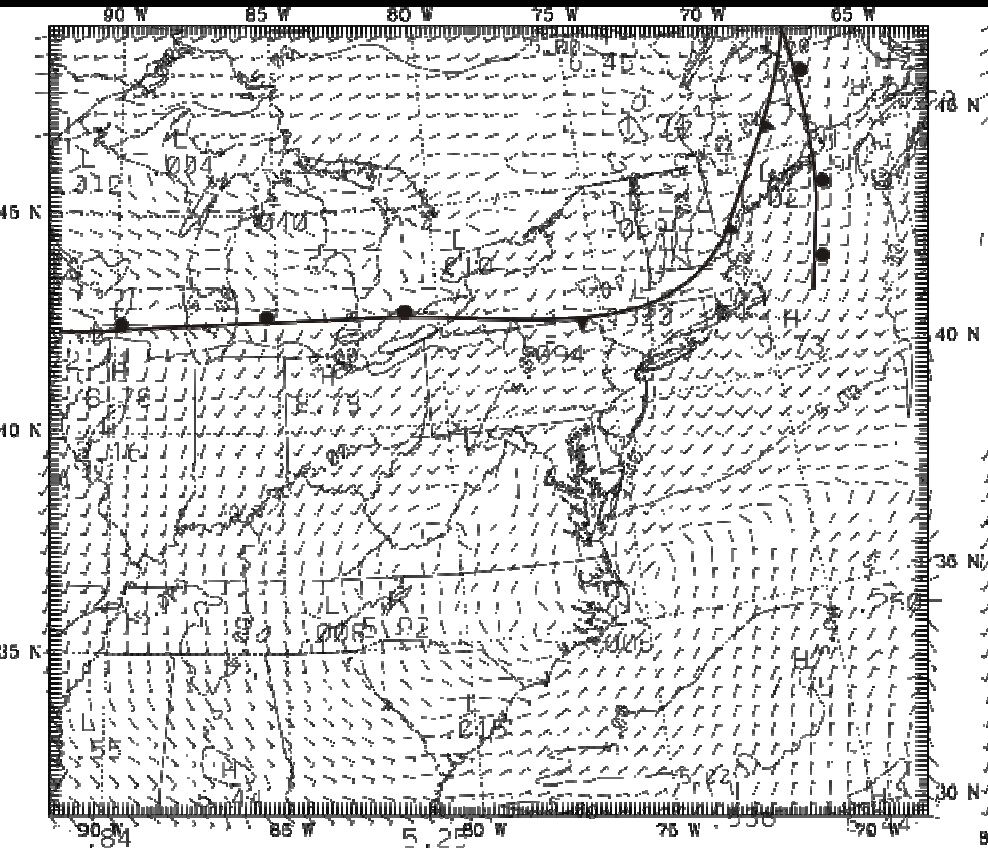


	SFC	30-1000m	ALAS
Ep. 1 - DEC	1.7	0.7	0.4
Ep. 2 - MAR	1.4	1.0	0.4
Ep. 3 - JUL	2.3	1.4	0.5
Ep. 4 - AUG	1.9	1.2	0.6
Ep. 5 - NOV	2.1	1.1	0.5
Ep. 6 - JAN	2.3	0.8	0.5

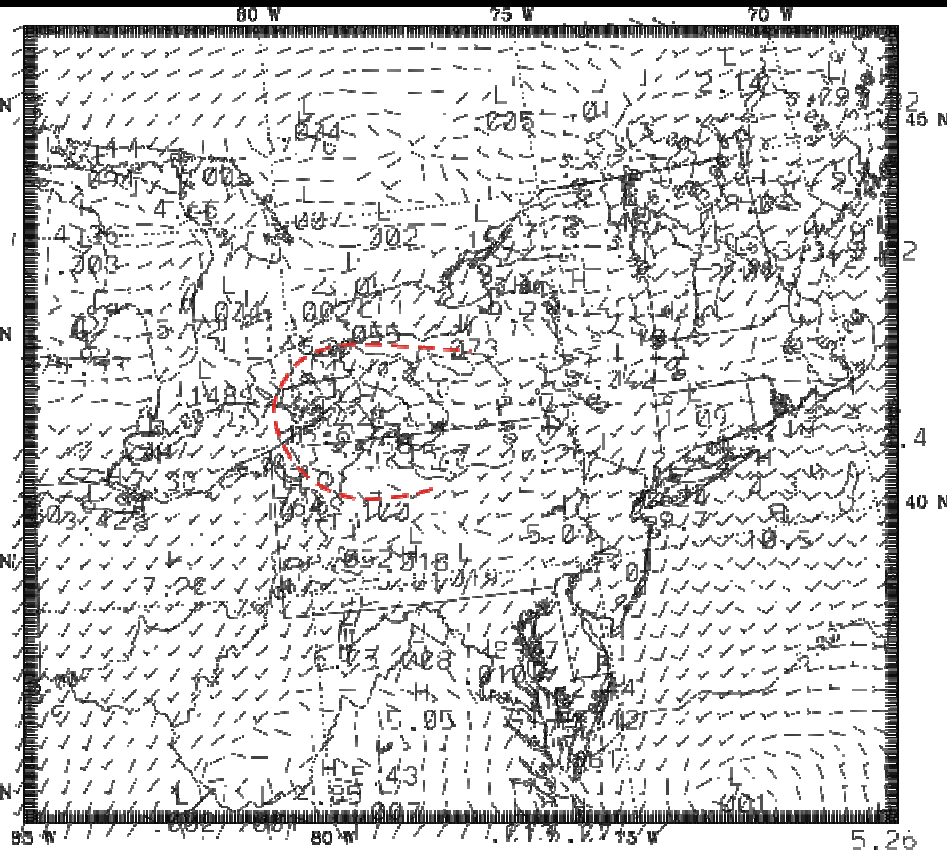
Temperature

MM5-Simulated Surface Wind Fields at 1800 UTC, 19 September 1983 (30 h)

12 km

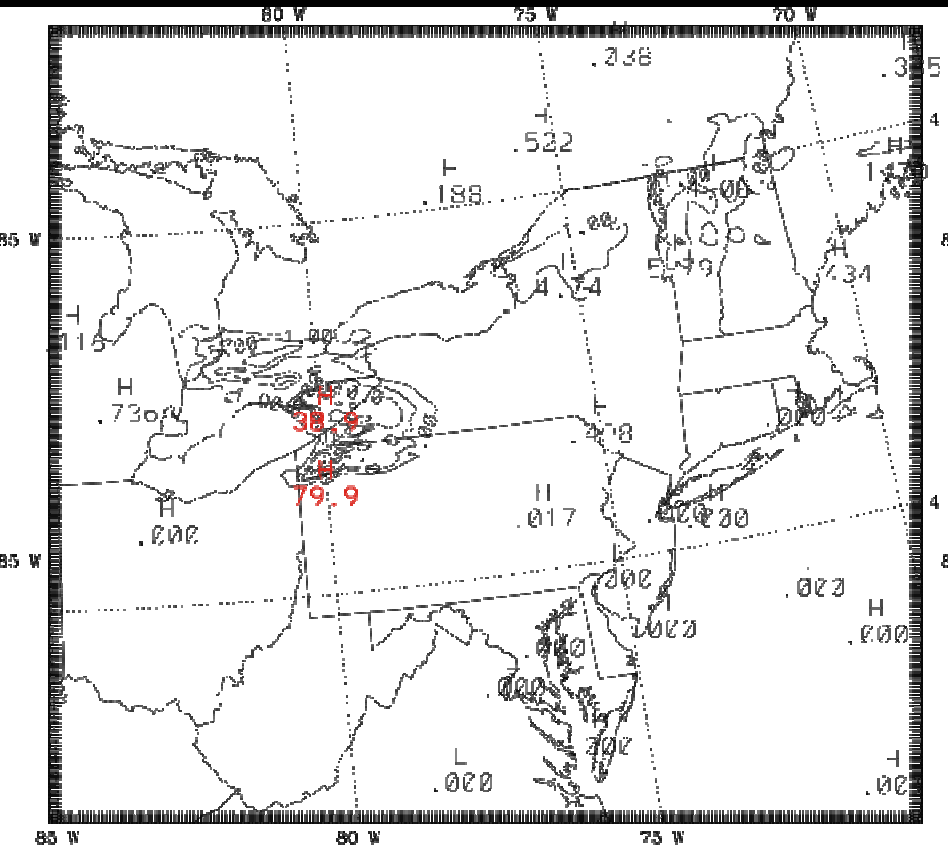


4 km



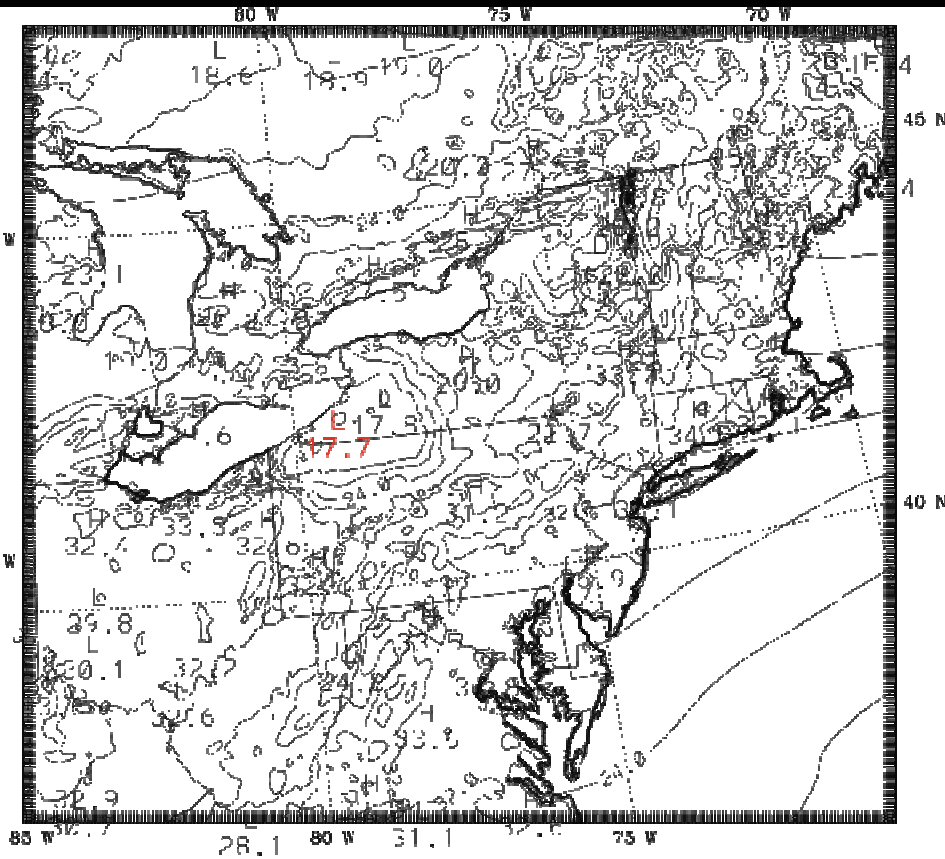
MM5 Simulation on the 4-km Domain at 1800 UTC, 19 September 1983 (30 h)

3-h Total Precipitation (mm)



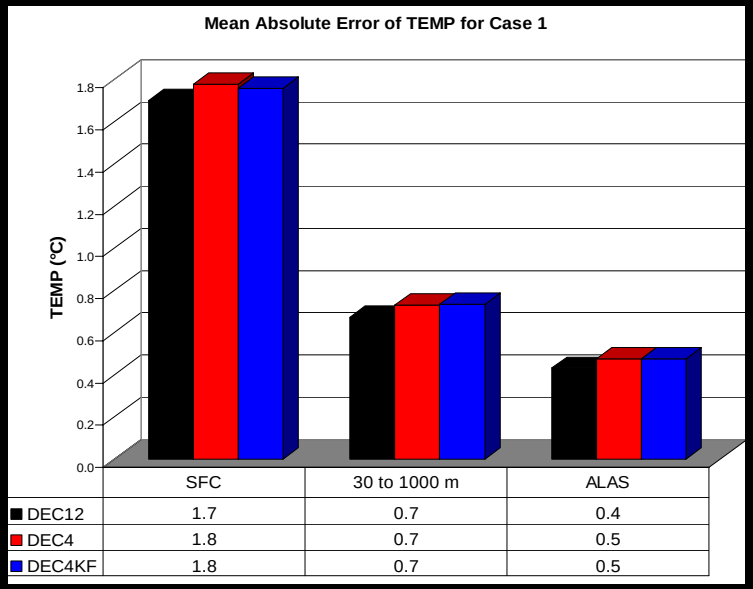
MM5V3-CAPTEX, EXP 3A, 4km

Surface Temperature (C)



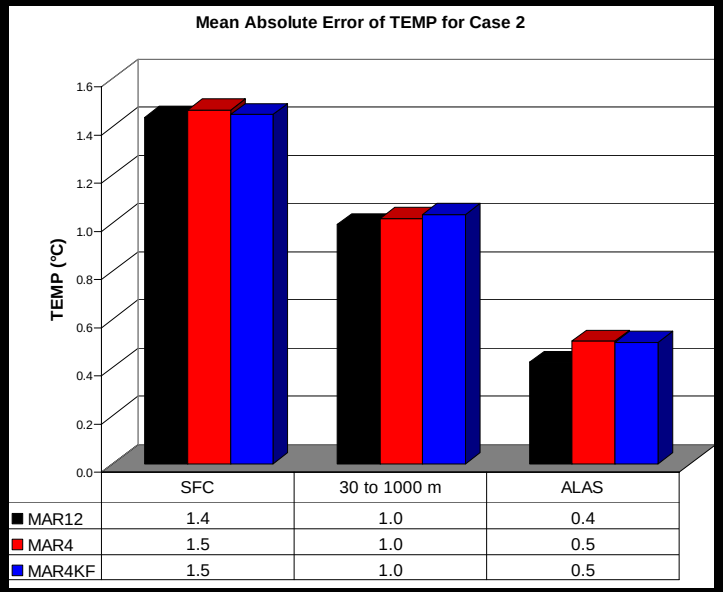
MM5V3-CAPTEX, EXP 3A, 4km

Statistical Temperature Analysis



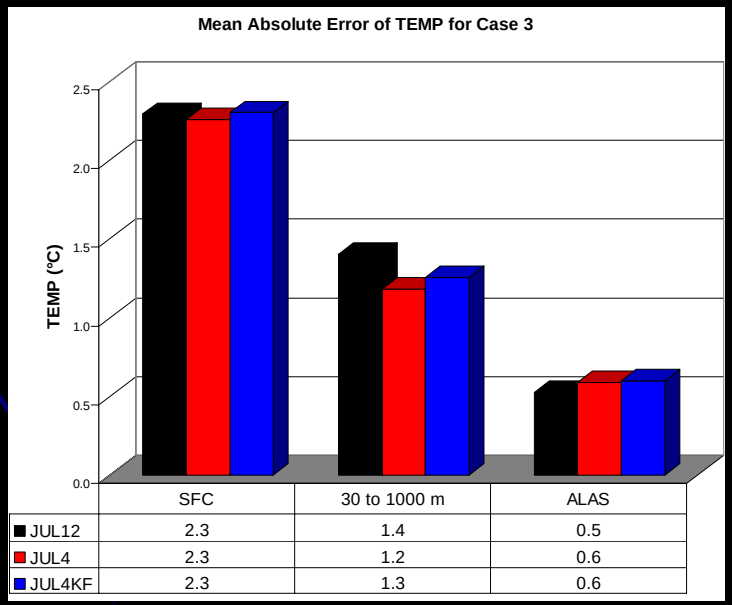
	SFC	30 to 1000 m	ALAS
DEC12	1.7	0.7	0.4
DEC4	1.8	0.7	0.5
DEC4KF	1.8	0.7	0.5

DEC



	SFC	30 to 1000 m	ALAS
MAR12	1.4	1.0	0.4
MAR4	1.5	1.0	0.5
MAR4KF	1.5	1.0	0.5

MAR

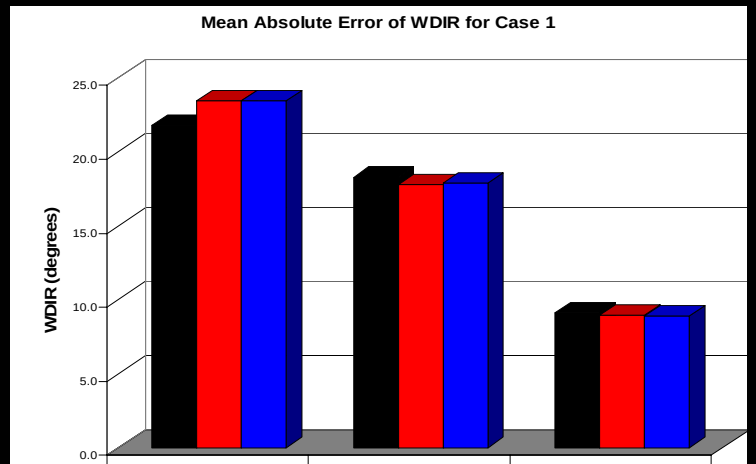


	SFC	30 to 1000 m	ALAS
JUL12	2.3	1.4	0.5
JUL4	2.3	1.2	0.6
JUL4KF	2.3	1.3	0.6

JUL

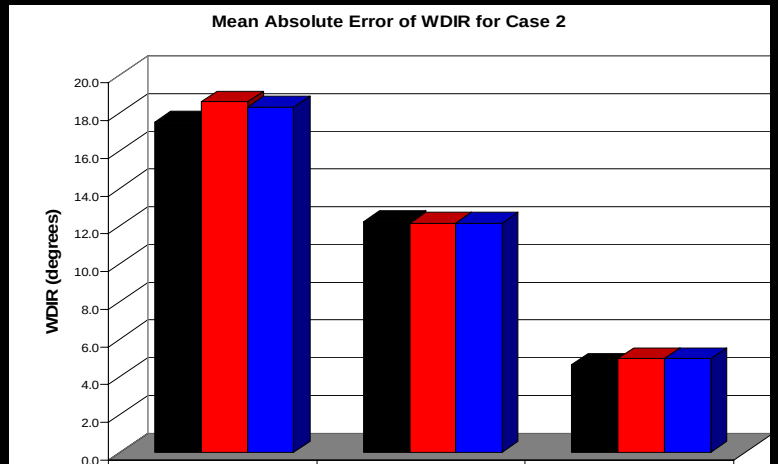
Statistical Directional Analysis

DEC



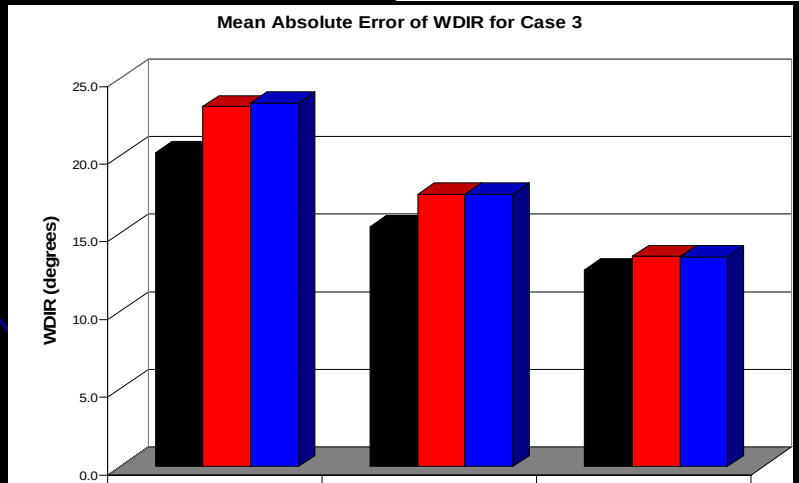
	SFC	30 to 1000 m	ALAS
DEC12	21.8	18.3	9.1
DEC4	23.4	17.7	8.9
DEC4KF	23.4	17.9	8.9

MAR



	SFC	30 to 1000 m	ALAS
MAR12	17.5	12.2	4.6
MAR4	18.6	12.1	5.0
MAR4KF	18.3	12.1	5.0

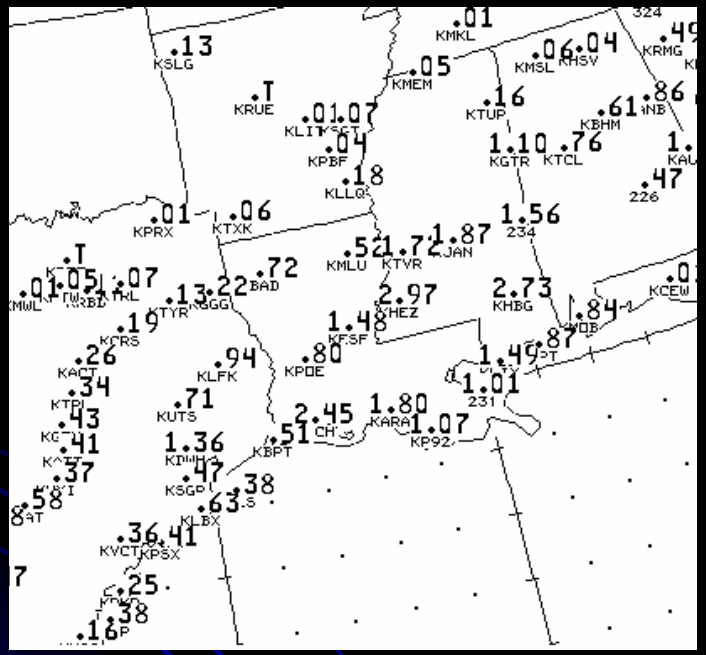
JUL



	SFC	30 to 1000 m	ALAS
JUL12	20.2	15.4	12.7
JUL4	23.2	17.5	13.5
JUL4KF	23.4	17.5	13.5

Subjective Precipitation Results

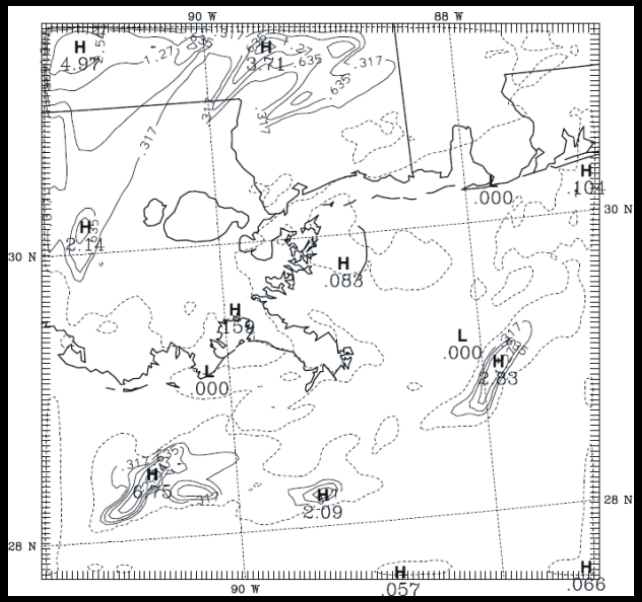
24-hr Accumulated Precipitation



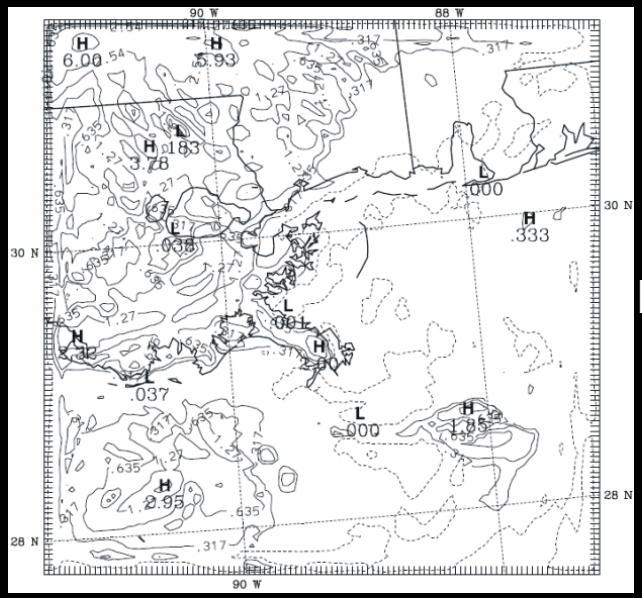
12 UTC, 2 March 2001

to

12 UTC, 3 March 2001



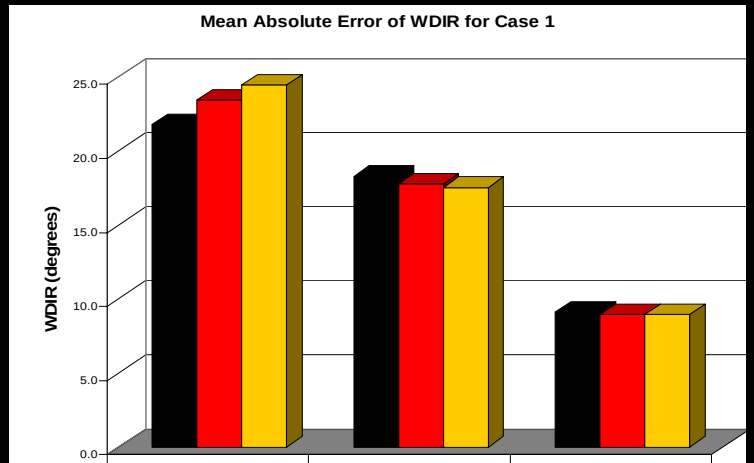
Explicit



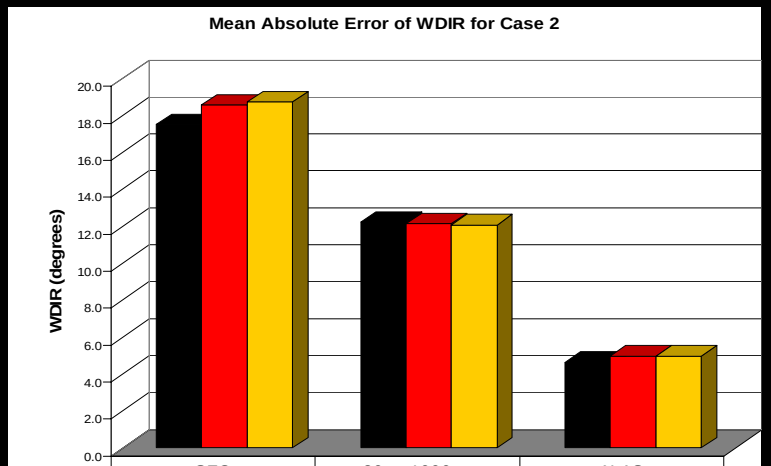
Parameterized

SST Experiment Directional Stats

DEC



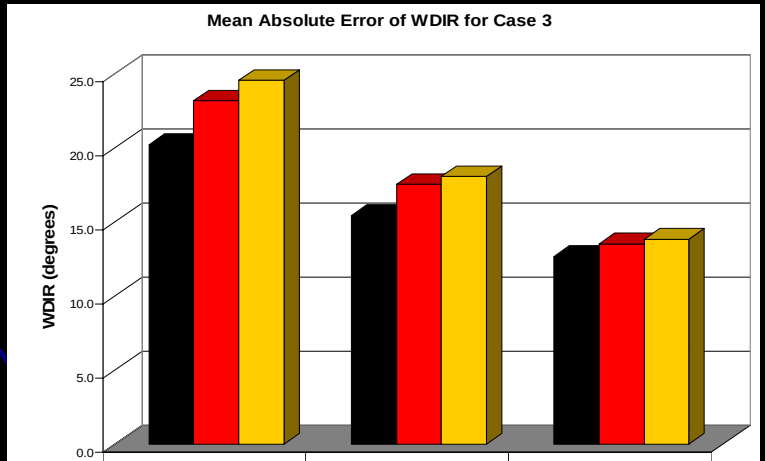
	SFC	30 to 1000 m	ALAS
DEC12	21.8	18.3	9.1
DEC4	23.4	17.7	8.9
DEC4M4	24.4	17.5	8.9



	SFC	30 to 1000 m	ALAS
MAR12	17.5	12.2	4.6
MAR4	18.6	12.1	5.0
MAR4M4	18.7	12.1	5.0

MAR

JUL



	SFC	30 to 1000 m	ALAS
JUL12	20.2	15.4	12.7
JUL4	23.2	17.5	13.5
JUL4M4	24.5	18.1	13.8

Model Configuration

Resolution	Grid Points	PBL Scheme	Cumulus Param.	Microphysics
36-km	129x165	1.5-order TKE PBL	Kain-Fritsch 2	Dudhia Simple Ice
12-km	121x121	1.5-order TKE PBL	Kain-Fritsch 2	Dudhia Simple Ice
4-km	109x109	1.5-order TKE PBL	None	Dudhia Simple Ice

Prognostic TKE Profile

CAPE Closure

No mixed-phase processes

Nudging FDDA

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

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

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

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

Observation Nudging

MM5 observation nudging equation
(Stauffer and Seaman 1994)

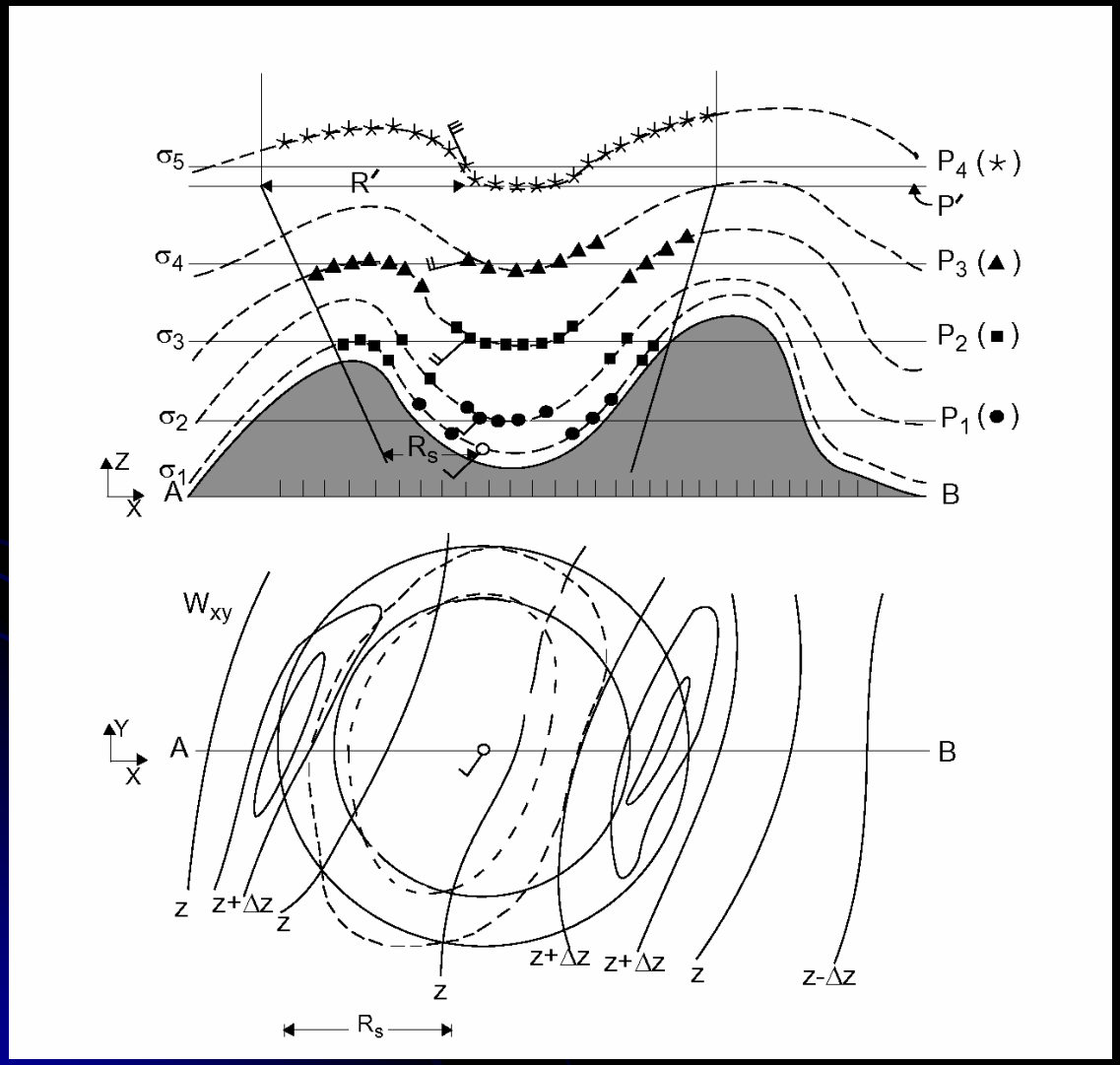
$$\frac{\partial p^* \alpha}{\partial t} = F(\alpha, \vec{x}, t) + G_\alpha \cdot p^* \frac{[\sum_{i=1}^{N} W_i^2(\vec{x}, t) \cdot \gamma_i \cdot (\alpha_0 - \alpha)_i]}{\sum_{i=1}^{N} W_i(\vec{x}, t)}$$

Four-dimensional weighting function:

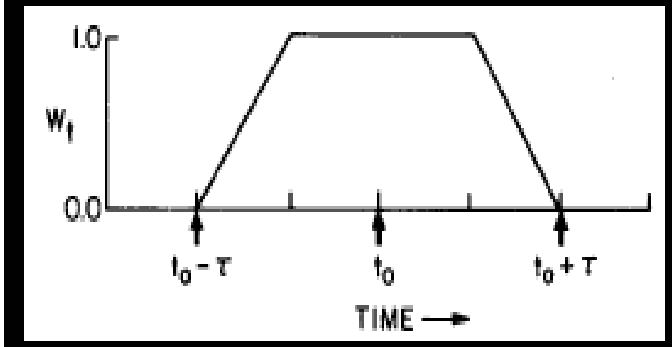
$$W(\vec{x}, t) = w_{xy} w_\sigma w_t$$

Observation Nudging Weighting Functions

w_σ

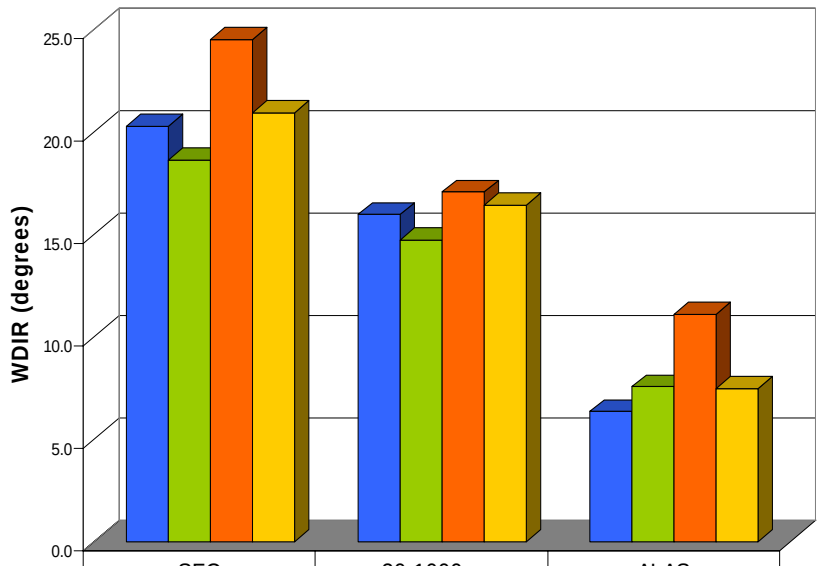


w_{xy}



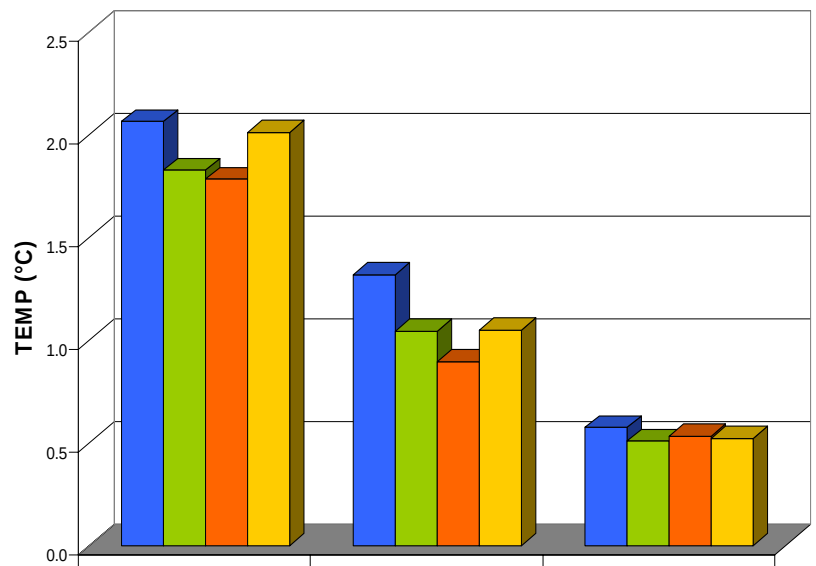
w_t

Seasonal Error Averages



	SFC	30-1000m	ALAS
Winter	20.3	16.0	6.3
Spring	18.6	14.7	7.6
Summer	24.5	17.1	11.1
Fall	20.9	16.4	7.5

Wind Direction



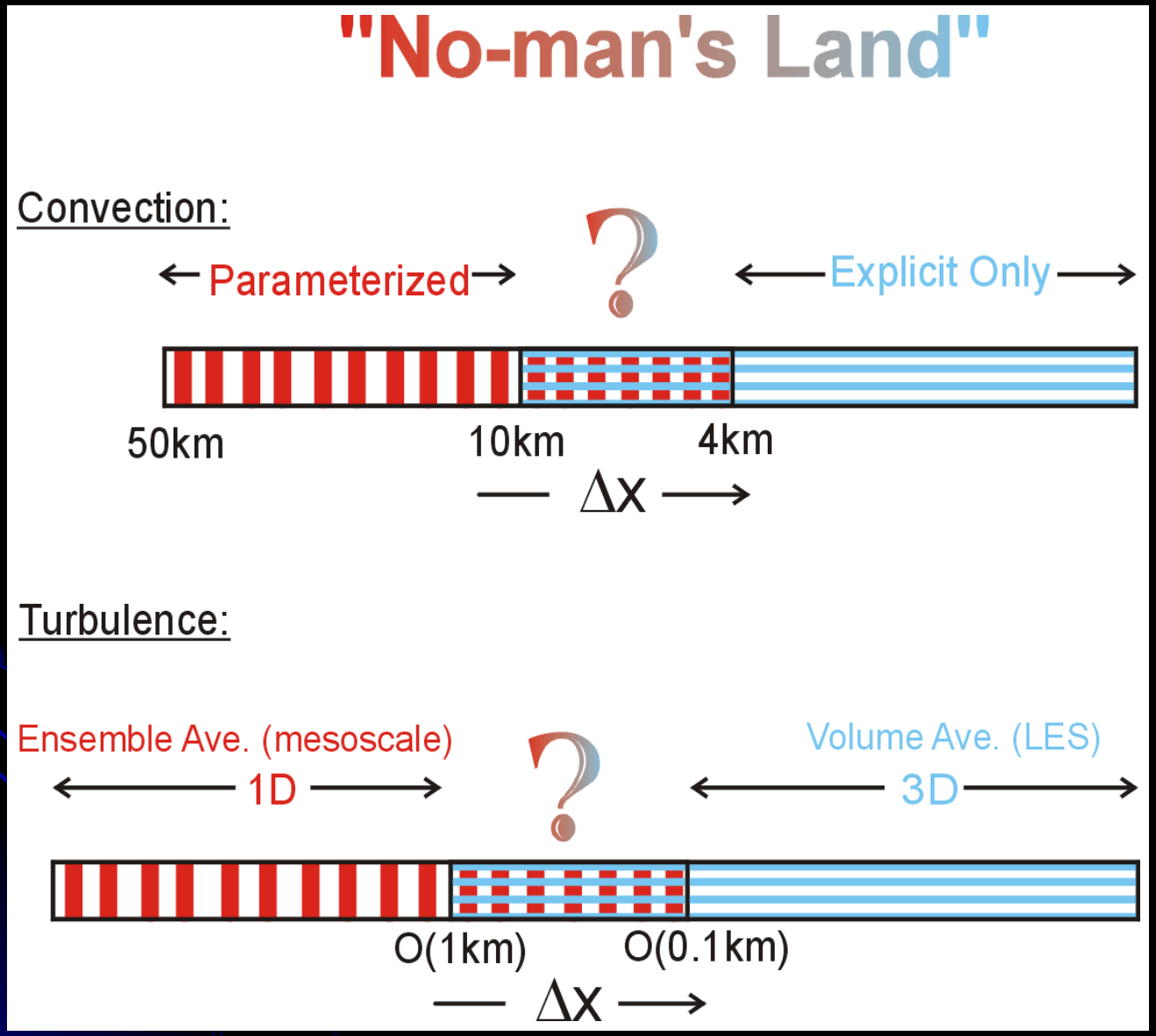
	SFC	30-1000m	ALAS
Winter	2.1	1.3	0.6
Spring	1.8	1.0	0.5
Summer	1.8	0.9	0.5
Fall	2.0	1.0	0.5

Temperature

Statistical Approach

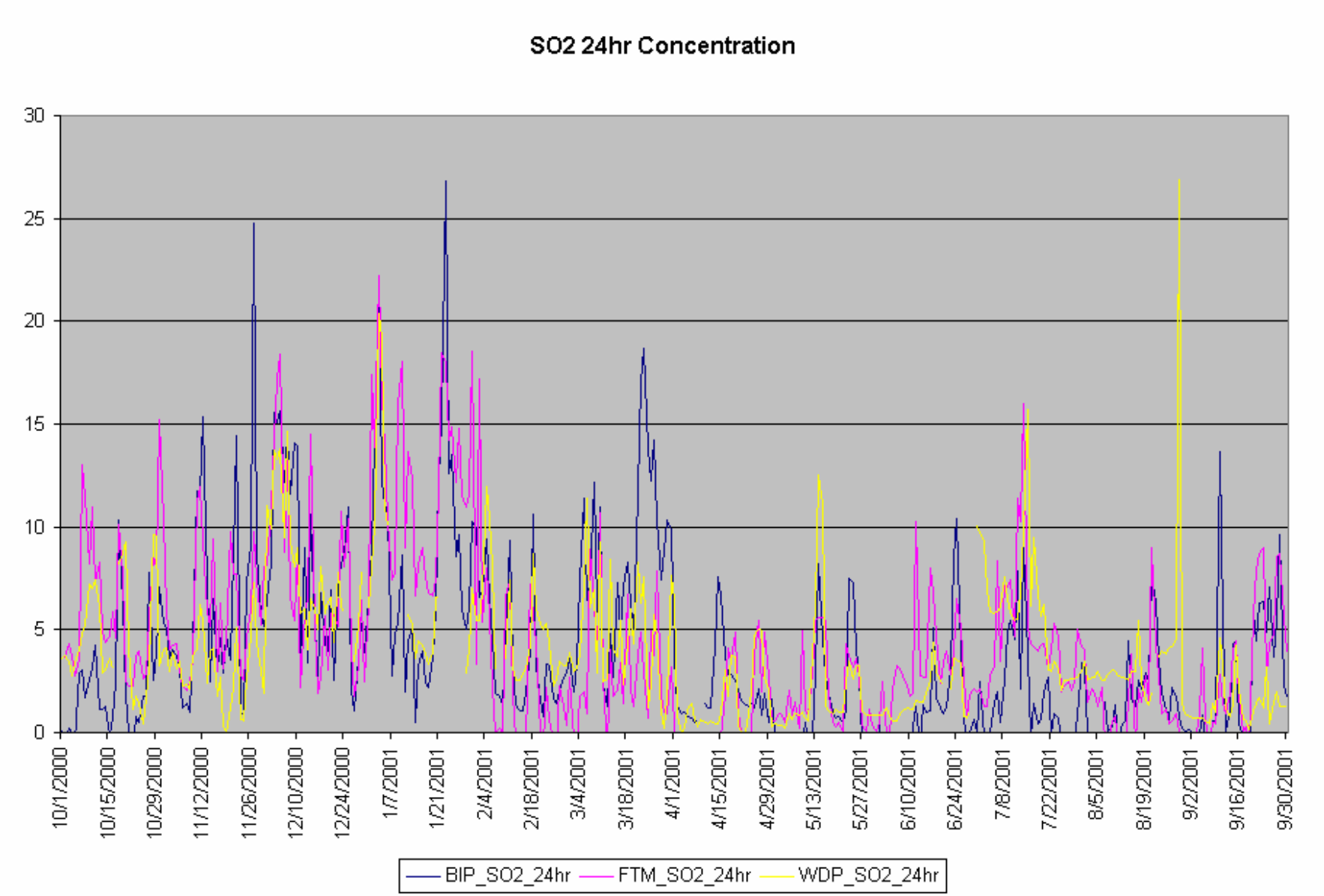
- Time series statistics mass-weighted by layer
  - SFC
  - 30-1000m (approximate PBL)
  - 1000-5000m (Lower Troposphere)
  - 5000-10000m (Upper Troposphere)
  - 10000-20000m (Stratosphere)
- Vertical profiles temporally averaged
  - All sigma levels represented
  - Weighted based on the number of observations at a particular level/time
- All statistics calculated for the 4-km subdomain region

Scale Separation



Deng and Stauffer (2006)

Motivation


SO2 24hr Concentration
30
25
20
15
10
5
0
10/1/2000
10/15/2000
10/29/2000
11/12/2000
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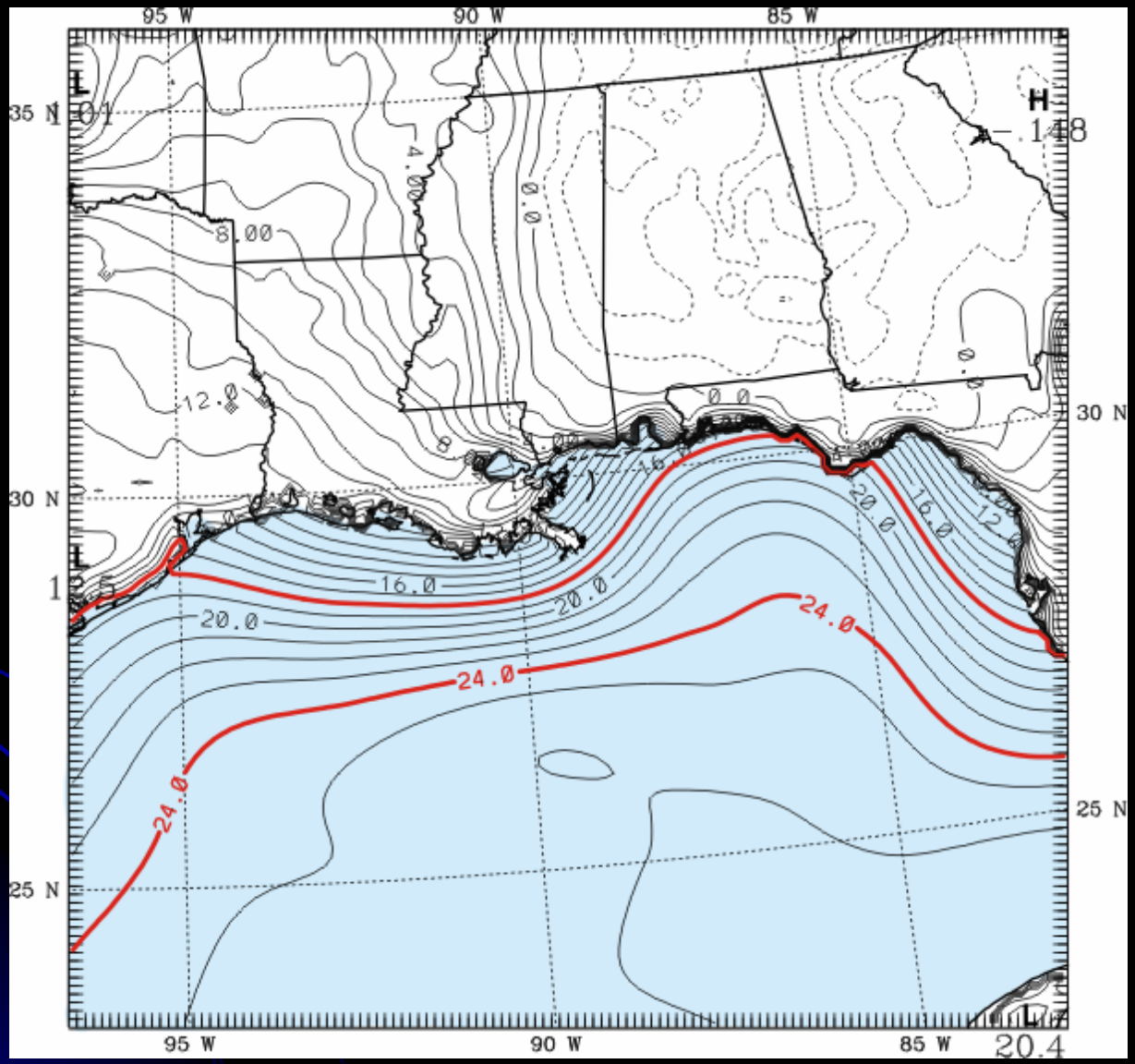
12/10/2000
12/24/2000
1/7/2001
1/21/2001
2/4/2001
2/18/2001
3/4/2001
3/18/2001
4/1/2001
4/15/2001
4/29/2001
5/13/2001
5/27/2001
6/10/2001
6/24/2001
7/8/2001
7/22/2001
8/5/2001
8/19/2001
9/2/2001
9/16/2001
9/30/2001
BIP_SO2_24hr
FTM_SO2_24hr
WDP_SO2_24hr

NCEP Reanalysis SST



12 UTC, 1 December 2000

References

Deng, A. and D.R. Stauffer. 2006. On Improving 4-km mesoscale model simulations. Journal of Applied Meteorology 45:361–381.

Schroeder, A.J., D.R. Stauffer, N.L. Seaman, A. Deng, A.M. Gibbs, G.K. Hunter, and G.S. Young. 2006. An automated high resolution, rapidly relocatable meteorological nowcasting and prediction system. Monthly Weather Review 134:1237–1265.

Stauffer, D.R, G. Hunter, A. Deng, J. Zielonka, P. Hayes, C. Kiley, and J. McQueen. 2007. On the role of atmospheric data assimilation and model resolution on meteorological accuracy and atmospheric transport and dispersion. Preprints, Chemical and Biological Information Systems Conference, Austin, TX, 8 – 11 January. 6 pp.