Tom’s Influence and Inspiration in Today’s Numerical Weather Prediction at PSU

The Warner Memorial Symposium

NCAR Foothills Lab
Boulder, CO
2 December 2011

David R. Stauffer, PSU
Outline

• Some memories of my early grad student years starting in 1981

• Some highlights of my PSU Numerical Weather Prediction (NWP) Group activities over the last ten years
  – NWP for Air Quality Modeling
  – Military-Defense-Aviation NWP Systems
    • Army, Marines, DTRA, NOAA
  – Basic and Applied Research
    • Stable Boundary Layer, Waves and AT&D
    • Model Ensembles
      – Advanced Data Assimilation
      – Uncertainty Quantification
A Numerical Study of Appalachian Cold-Air Damming and Coastal Frontogenesis

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(Manuscript received 28 March 1986, in final form 9 October 1986)

ABSTRACT

A 24-h numerical simulation is used to study features of the wedge-shaped pressure ridge and the coastal front, which occurs in eastern United States during winter and often cause substantial errors in operational models. Specifically, the Pennsylvania National Center for Atmospheric Research, Mesoscale Model (MM) is used as a diagnostic tool to investigate the mesoscale structure of these phenomena associated with the Appalachian ice-storm of 13-14 January 1986.

The MM, which used 13 vertical levels (8 below 800 mb), a 50-km horizontal mesh size, and a multi-level boundary-layer parameterization, produced a better forecast of boundary-layer temperature and sea-level pressure than that of the National Meteorological Center's operational model for this case-study period. To the east of the mountains, the MM maintained the wedge-ridge pattern and produced the low-level, northerly flow which is characteristic of the damming region. The MM also provided reasonable vertical profiles of temperature and wind, including a low-level, mountain-parallel jet which is commonly observed along mountain ridges during cold-air damming. However, despite the model's fairly sophisticated surface energy equation and moderate spatial resolution, the low-level temperature simulation was still 1-5°C too warm in some areas to the east of the mountains.

The moderate horizontal and vertical resolution did allow the MM to develop the coastal front which appeared in the Chesapeake Bay-New Jersey area by the end of the 24-h study period. Despite the small-scale nature of a coastal front, synoptic and mesoscale forcing in the model created a realistic, coastal low-pressure system. The simulated, low-level temperature gradient and convergence zone compared favorably with surface observations. The simulated coastal front, exporting extremely moist air from the cold northern flow advected diminished in strength with height and disappeared by 940 mb. In the damming region, observations suggested that the cold-air damming was a "cooled coastal front": a sloping inversion separating the trapped surface-based cold air from the warm ocean flow above. This feature appears to be at least partially responsible for the low-level jet.

Model-generated, kinematic trajectories showed the strongly sheared, three-dimensional character of the flow within the damming region. These model results and observations indicate that a relatively large number of model layers would be required below ~400 mb in order to adequately model the thermal and wind field structures.

1. Introduction

The veteran forecaster raises his brow whenever a strong surface anticyclone, tracking eastward toward New England, extends southeastward along the eastern slopes of the Appalachians as an inverted ridge in the sea-level pressure (SLP). This familiar "ridge flow," the result of cold-air damming" by the mountains, is often the harbinger of hazardous winter weather east of the Appalachian Mountain chain.

Despite the sufficient horizontal grid spacing to resolve the wedge ridge in current operational models, the incomplete treatment of the boundary-layer processes generally contributes to poor near-field and wind field forecasts in the damming region, while forecast errors are normally much smaller elsewhere on the model domain (Richwine, 1980; Bosart, 1981; Forbes et al., 1987). East of the mountains, boundary-layer temperatures are often predicted to be too warm, while surface pressures are forecast to fall too rapidly.

This wedge-shaped pressure ridge is often associated with yet another forecast challenge existing along certain parts of the east coast of the United States. Bosart et al. (1972) and Bosart (1973) have studied a shallow, penum-warm or stationary "coastal front" in New England. The observation that coastal fronts tend to be oriented more parallel to the seashore contours than to the coastline may support the hypothesis that cold-air damming enhances their intensity (Richwine, 1980). Furthermore, Bosart (1981), among others, indicates that this cold-air pressure ridge also favors coastal cyclogenesis.

This paper discusses the results of a numerical simulation, which used a mesoscale model (MM) with sophisticated boundary-layer physics and moderate horizontal and vertical resolution, to investigate the mesoscale detail of the wedge ridge and coastal front. The case studied is the Appalachian freezing-rain event of 13-14 January 1980, recently documented by Forbes et al. (1987).
the wind-field forecast at 1200 UTC 14 January verifies reasonably well against the available data. No wind data were available at this time above the surface at GSO. A strong surface wind for this time at GSO compared favorably with the observed 5 m s⁻¹ wind from the north-northeast. Observed low-level winds at IAD and AHN at this time were 3-5 m s⁻¹ from the north.

The dynamical arguments of Schwerdtfeger mentioned earlier, that attempt to explain the existence of terrain-induced jets in terms of geostrophic considerations, can be useful here. That is, the presence of the extended coastal-front inversion in the damming region may accelerate the air toward the south along the eastern Appalachian slope. Perhaps the underestimated strength of the inversion strength by the model may explain why the simulated low-level jet appeared 4-6 h after it was observed. Geostrophic forcing would be weaker and therefore more time would be required for the model to develop the jet. Forbes et al. (1987) state that the observations in this case were generally supportive of Schwerdtfeger's arguments.

Figure 19 shows a back trajectory of an air parcel which was embedded in the jet core at 950 mb at 24 h in the numerical simulation. This trajectory and those presented later were calculated from the three-dimensional wind fields defined at 15-min intervals by the 24-h model simulation. The dark dots in Fig. 19 show the parcel's position at 2-oh intervals with the total wind T, geostrophic wind G and geostrophic wind G plotted every 4 h. The pressure level and pressure height of the parcel above the surface are in millibars and enclosed in parentheses. The parcel's mean speed for each 2-h interval is in meters per second and is encircled.

The parcel, which originated in the low levels over the ocean surface, initially accelerates and then turns westward after 8 h (2000 UTC 13 January). Near the coast, its motion is largely geostrophic. At this time (2000 UTC 14 January), the coastal front has not developed yet; but the parcel still rises and decelerates as it moves further inland over the cold air. As it ascends, it passes through different pressure-gradient regimes. After 18 h, owing to the stability of the air, the parcel is deflected to the left (south) as predicted by Schwerdtfeger's argument. The local pressure gradient force is directed normal to and away from the mountains. During the next few hours, Coriolis effects become important enough to support the geostrophic-type flow of the northerly jet. Analysis of other trajectories in the region of the jet at 24 h produced similar results. Examination of the low-level wind simulation in the region of this trajectory shows reasonable agreement with available observations. Therefore, its general characteristics should be representative of the true atmosphere.

d. The coastal front

The initial surface-layer temperature field at 1200 UTC 13 January was shown in Fig. 7 to have isotherms oriented nearly east-west in the coastal states; little or no low-level convergence existed in the initial model winds at this time along the coast. By 0400 UTC 14 January, the model produced a weak convergence zone in the Chesapeake Bay-New Jersey area (Fig. 10), where the coastal front was just beginning to develop. By 1200 UTC, a mesoscale temperature gradient and a strong convergence zone were well developed in this
Current and Recent NWP and Process Studies for Air Quality Applications...

- Alaska PM2.5: EPA and Alaska Department of Environmental Conservation (ADEC), Gaudet
- California Ozone and PM2.5: Bay Area Air Quality Management District (BAAQMD), Deng and Rogers
Alaska Domains:

- 12 km: Synoptic scale
- 4 km: Central AK region
- 1.33 km: Tanana Basin

401 x 301 \( \Delta t = 24 \) s
202 x 202 \( \Delta t = 8 \) s
202 x 202 \( \Delta t = 4 \) s

39 vertical levels, to 4 m grid spacing near surface
California Summer Case - Ozone

WRF Streamlines with Terrain Shaded
Daytime: 0000UTC 30 July 2000

Schematic Diagram of Typical Regional Daytime Flow

Multiscale FDDA – Analysis nudging on 36- and 12-km domains, obs nudging on 12- and 4-km domains

After Bao et al. (2008), Stauffer (1995)
Multiscale FDDA – Analysis nudging on 36- and 12-km domains, obs nudging on 12- and 4-km domains

After Bao et al. (2008), Stauffer (1995)
Military-Defense:

U.S. Army MMS-Profiler Nowcast
AN/TMQ-52 MMS-Profiler Overview

- Provides **MET support for artillery**
  - Collect meteorological data from satellite, upper air radio soundings, and local surface conditions
  - Use meteorological data as input to weather forecast model to provide a snapshot of battlefield weather conditions
  - Communicate with fire support via tactical voice/data radios.

Smiths Detection
• Comprised of MET sensors and a mesoscale modeling system running locally on the battlefield with continuous data assimilation to provide timely and accurate MET for use in correcting standard firing tables to accurately engage targets throughout the battlespace.

• Fielded to active Army units in early 2005, approved for full rate production in June 2005 with full 108-unit production cycle completed in 2010.

• Provides Local and Target Area ARTY MET messages every 15-30 minutes

• Provides as a minimum the MET Parameters
  – Temperature, Humidity, Pressure
  – Wind Speed, Wind Direction
  – Target Area: Ceiling, Visibility, Precip Rate, Precip Type
Army MMS-Profiler system with its crew, armed and wearing desert camouflage
USMC METMF(R) NEXGEN

Meteorological Mobile Facility Replacement - Next Generation
In-House Relocatable On-demand Forecast System (ROFS)

- Based on full-physics MM5/WRF
- Flexible or scheduled start and end times
- User-defined domains, sizes and horizontal/vertical resolutions
- Runs in real time and historical event modes
- Runs on massively parallel computing platforms (MPI)
- Continuous multi-scale four-dimensional data assimilation (FDDA) capability for improved model initialization (dynamic initialization)
DTRA Connect article...

DTRA Team models wind, weather in support of Winter Olympics

Dr. David Hashman, USEC Senior Scientist, is known for his research on wind and snow impacts and for his work on the Torino Winter Olympics. His team models wind and weather conditions in support of the Olympics.

The team used the National Center for Atmospheric Research's (NCAR) Weather Research and Forecasting (WRF) model to predict wind and snow conditions. The model was validated against data from the Torino Olympics.

PSU 1.3 km ROFS winds (Feb. 22/14 UTC) and HPAC/SCIPUFF predictions (Feb. 22/13-17 UTC)
Beijing Summer Olympics 2008

Chinese monsoon and complex terrain / coastal-zone sea-breeze effects at 06 UTC (1400 LST), midpoint of 12-h SCIPUFF surface dosage forecast.

Black=WMO obs
Red=supplementary obs
The use of a 1.3-km domain allowed for an accurate forecast of a surface wind confluence line at 03 UTC (2000 LST) along the front range of the Rockies.
Vancouver Winter Olympics 2010

Surface Slice
C7F14 at 17-Feb-10 12:00Z (16.0 hrs)

UNCLASSIFIED
UNCLASSIFIED

Fukushima 2011

PSU / DTRA Reachback Forensic Analysis of Fukushima
Aviation:

Interim Progress Report on
A NextGen Airport Forecast System (NGAFS)

Cooperative Agreement between
NOAA/NWS/OST and Penn State Univ.

Silver Spring, MD
20 July 2011

David R. Stauffer, P.I., PSU
NGAFS Motivation

Objective: Build, test and evaluate a local-data assimilating, high-resolution numerical / statistical airport forecast system to dynamically downscale operational numerical products, yielding more detailed and accurate aviation forecast parameters.
Cooperative Approach

- Penn State will build a numerical modeling system with overall characteristics similar to the experimental HRRR model under development at NOAA/OAR/GSD.
  - ARW dynamical core; RUC-like physics.
  - ICs and LBCs from RR; RUC LSM at lower boundary.
  - 1-h cycling of 6-h to 12-h forecasts.
  - Partial-cycling data assimilation of local observations.
  - Highest grid resolution ~ 1 km.

- NOAA/NWS/OST/MDL will use Penn State ARW products as an input to a LAMP-like system to forecast aviation-sensitive Wx parameters in the vicinity of major airports.
  - Hourly observations and analyses.
  - GFS/LAMP-based MOS updated with PSU ARW 1-km forecasts.
PSU Realtime Systems

• Central PA Centered WRF
  • http://www.meteo.psu.edu/~wfrt/

• NGAFS WRF
  • http://www.meteo.psu.edu/~ngafs/

• Stable Boundary Layer WRF
  • http://www.meteo.psu.edu/~wfrt1/
Improved Understanding and Prediction of the Stable Boundary Layer to Better Predict the Fate of Airborne Toxics Released by WMDs

HDTRA1-10-0033

David R. Stauffer, PI
Professor, Penn State University
Defense Threat Reduction Agency (DTRA)
Project Objective

• To understand and predict the structure and variability of stable boundary layers (SBLs) to improve predictions of atmospheric transport and dispersion (AT&D) of airborne toxic materials from accidents or WMDs.
Combined modeling and observation study

WRF smallest domain (0.444 km horizontal resolution)

Observation Network

UNCLASSIFIED
WRF-ARW Model Configuration

- WRF uses nested domains with 12-, 4-, 1.33, and 0.44-km horizontal grid spacing. Sub-kilometer horizontal resolution to resolve fine-scale terrain important for shallow SBL flows and AT&D.

- Very high vertical resolution near the surface to resolve shallow SBL and gravity-driven slope flows (10 layers in lowest 50 m AGL).

- 12-hour forecasts from 00 to 12 UTC (7PM to 7AM EST)

- Model output, saved every 12 minutes, is used to represent submeso fluctuations in trajectories and AT&D predictions
WRF MYJMod PBL Physics Model and Observed Surface Winds
Conceptual Model of Nocturnal Flow Regimes
For Valleys with Weak Down-valley Terrain Slopes

Internal waves and other submeso motions cause intermittent turbulence near the surface.

Shallow gravity-driven drainage flow overrides coldest air on valley floor, gradually filling Nittany Valley.

Very light omni-directional winds in cold pool.

55 °C/°K boundary layer diagonal cross-section - interpolated to terrain.

Internal gravity waves
Cold, shallow SBL in Nittany Valley

Accelerating Drainage Wind

Transition

BOT 900 m

MID 325 m

UP
Wave structures are captured by the observing network (Josh Hoover, Scott Richardson)

Wave-like pattern in wind speed and vertical motion

Periodic fluctuations of 3-m temperature over several hours
Positive temperature fluctuation is associated with the passage of the wave crest and the underlying rotor. As the wave propagates upstream, the rotor-induced circulation causes the surface cold pool to erode between 0600-0630 UTC and brings higher potential temperature air to the surface.

WRF model produces structures that are consistent with observations.

**Loca7on of Site 9**
Vertical Velocity

Dataset: CTRL. RIP: w zoom
Init: 0000 UTC Thu 14 Apr 11
Pest: 0000 h
Valid: 0000 UTC Thu 14 Apr 11

Vertical velocity

- XY: 2.0, 148.0 to 148.0, 2.0

Potential temperature

- XY: 2.0, 148.0 to 148.0, 2.0

10 km scale
Hovmoller Diagram for Vertical Motion

Height: 1km

Distance (km)

Allegheny Mts.  Tussey Ridge
5-m Releases at Site 9

(a) 0500-0700 UTC

(b) 0600-0800 UTC

(c) 0700-0900 UTC

(d) 0500-0700 UTC

(e) 0600-0800 UTC

(f) 0700-0900 UTC
SCIPUFF Surface Dosage and Concentration of 5-m Release at Site 9

a) SFC dosage 0500-0700 UTC

b) SFC dosage 0600-0800 UTC

c) SFC dosage 0700-0900 UTC

d) Concentration at 0620 UTC

e) Concentration at 0720 UTC

f) Concentration at 0820 UTC
Terrain-induced gravity waves were found to have an impact on AT&D.

- Small changes in the location of the wave crest and underlying rotor result in significantly different transport and dispersion patterns.
- Rotors can also transport harmful materials suspended above ground level to the surface or circulate surface releases over the same location.
- Terrain-induced gravity waves can also affect the downstream transport of harmful materials.

Additional cases are needed in order to test the sensitivity of AT&D to the presence of internal-gravity waves and the ability of the model to forecast non-wave cases versus stationary and non-stationary wave events. More R&D is also needed to improve the model physics for these weak wind, stable conditions.
Nudging:

\[
\frac{d\bar{x}}{dt} = \cdots + G \cdot w_s \cdot w_t \cdot (\bar{x}^o \square \bar{x})
\]

EnKF:

\[
\bar{x}_a = \bar{x}_b + K (\bar{x}^o - \bar{x}_b)
\]

Hybrid Nudging - EnKF:

\[
\frac{d\bar{x}}{dt} = \cdots + f(K, w_t) \cdot (\bar{x}^o \square \bar{x})
\]

• The hybrid nudging coefficients:

\[
G \cdot w_s = \frac{1}{\sum_t w_t \cdot \Delta t} \cdot K
\]
Cannot say enough about judicious use of knowledge gained from the shallow water equations...
The 2D shallow water equations... and hybrid nudging terms:

\[
\begin{align*}
\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} - f v &= \frac{\partial}{\partial x} \left( g \frac{\partial h}{\partial x} \right) + \kappa \nabla^2 u + G_{uu} \cdot \mathbf{w}_t \cdot (u^o - u) + G_{uv} \cdot \mathbf{w}_t \cdot \left( \frac{\partial}{\partial x} v \right) + G_{uh} \cdot \mathbf{w}_t \cdot \left( \frac{\partial}{\partial x} h \right) \\
\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + f u &= - \frac{\partial}{\partial y} \left( g \frac{\partial h}{\partial y} \right) + \kappa \nabla^2 v + G_{vu} \cdot \mathbf{w}_t \cdot \left( \frac{\partial}{\partial y} u \right) + G_{vv} \cdot \mathbf{w}_t \cdot (v^o - v) + G_{vh} \cdot \mathbf{w}_t \cdot \left( \frac{\partial}{\partial y} h \right) \\
\frac{\partial h}{\partial t} + u \frac{\partial h}{\partial x} + v \frac{\partial h}{\partial y} &= - h \left( \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right) + \kappa \nabla^2 h + G_{hu} \cdot \mathbf{w}_t \cdot (u^o - u) + G_{hv} \cdot \mathbf{w}_t \cdot (v^o - v) + G_{hh} \cdot \mathbf{w}_t \cdot (h^o - h)
\end{align*}
\]

Diagonal \textcolor{red}{(red)} terms: traditional nudging
Hybrid Nudging - EnKF:
- Continuous Data Assimilation

2D Shallow Water Model (SWM) Results
(Lei and Stauffer 2009)

Quasi-Stationary Wave Case

Moving Vortex Case

Extend Lorenz and SWM hybrid nudging – EnKF to 3D WRF / DART…
Methodology for the HNEEnKF

Ensemble state

EnKF

G(K, t_w)

X_{nudging}^a

Nudging

obs

EnKF

G(K, t_w)

X_{nudging}^a

Nudging

obs

EnKF

G(K, t_w)

X_{nudging}^a

Nudging

obs
WRF/DART Ensemble Configurations

- **IC ensemble**: contains perturbations of the ICs and LBCs.
  - Adding perturbations, which are drawn from a multivariate normal distribution by use of the WRF-3DVAR, to the ICs and LBCs.
  - Ensemble size is 24 or 48

- **ICPH ensemble**: contains multi-physics members in addition to the perturbed ICs and LBCs members
  - Eight physics configurations are used
  - Ensemble size is 24 or 48

<table>
<thead>
<tr>
<th>Physics configuration</th>
<th>Microphysics</th>
<th>Convective</th>
<th>PBL</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>WSM-3</td>
<td>Kain-Fritsch</td>
<td>MYJ</td>
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<tr>
<td>2</td>
<td>Lin et al.</td>
<td>Kain-Fritsch</td>
<td>MYJ</td>
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<tr>
<td>3</td>
<td>WSM-3</td>
<td>Betts-Miller-Janjic</td>
<td>MYJ</td>
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<tr>
<td>4</td>
<td>WSM-3</td>
<td>Kain-Fritsch</td>
<td>YSU</td>
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<tr>
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<td>Lin et al.</td>
<td>Betts-Miller-Janjic</td>
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<td>Betts-Miller-Janjic</td>
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<tr>
<td>8</td>
<td>Lin et al.</td>
<td>Betts-Miller-Janjic</td>
<td>YSU</td>
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</table>

(Lei and Stauffer 2011)
## Experimental design

<table>
<thead>
<tr>
<th>Exp. Name</th>
<th>Exp. Description</th>
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<tbody>
<tr>
<td>CTRL</td>
<td>Assimilate no observations</td>
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<tr>
<td>FDDA</td>
<td>Assimilate observations by observation nudging</td>
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<tr>
<td>EnKFIC24</td>
<td>Assimilate observations by EnKF with IC ensemble and 24 ensemble members</td>
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<tr>
<td>EnKFIC48</td>
<td>Assimilate observations by EnKF with IC ensemble and 48 ensemble members</td>
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<tr>
<td>EnKFICPH24</td>
<td>Assimilate observations by EnKF with ICPH ensemble and 24 ensemble members</td>
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<td>EnKFICPH48</td>
<td>Assimilate observations by EnKF with ICPH ensemble and 48 ensemble members</td>
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<tr>
<td>HNEnKFICPH24</td>
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</tr>
<tr>
<td>HNEnKFICPH48</td>
<td>Assimilate observations by HNEnKF with ICPH ensemble and 48 ensemble members</td>
</tr>
</tbody>
</table>
Overview of the 18-20 September 1983 CAPTEX-83 (tracer) case

(a) 2200 UTC 18 September

(b) 0400 UTC 19 September

(c) 1000 UTC 19 September

(d) 1600 UTC 19 September

(After Deng et al. 2004)
Evaluation of temporal smoothness and insertion noise for IC ensemble

![Graph showing surface pressure tendency over model time](image)
Evaluation of temporal smoothness and insertion noise for IC and ICPH ensembles

EnKF

HNEEnKF
### Evaluation using independent surface tracer data

<table>
<thead>
<tr>
<th>Ordinal ranking</th>
<th>Experiment</th>
<th>Sum of misses and false alarms</th>
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<tbody>
<tr>
<td>1</td>
<td>FDDA</td>
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<td>HNEEnKFICPH48</td>
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<td>7</td>
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<tr>
<td>7</td>
<td>EnKFICPH48</td>
<td>31</td>
</tr>
<tr>
<td>7</td>
<td>CTRL</td>
<td>31</td>
</tr>
</tbody>
</table>
• Meteorological (MET) errors have important implications to many weather applications (e.g., AT&D, TDAs)
• Ensemble of AT&D models attractive but not practical for operations
• Efficient way to compute MET uncertainty from an NWP ensemble for input into a single AT&D model solution (HPAC/SCIPUFF wind variance matrices, UUE, VVE, UVE)
• NWP-ensemble variance (spread) is at best an approximate measure of actual uncertainty/error variance...
Motivation

• Can a single AT&D prediction using NWP-ensemble derived MET fields and wind variances (uncalibrated or calibrated) approximate and improve upon an AT&D prediction based on an explicit AT&D ensemble?

• Can we develop a simple calibration that will better predict the actual error variance?
Linear Variance Calibration (LVC) Methodology

Binned Variance Relation for 10m_AGL_U

\[ y = mx + b \]

Error Var of Bin \((\text{m/s})^2\)

Mean Ens Variance of Bin \((\text{m/s})^2\)
Daily MET-SCIPUFF
Ensemble Testbed Overview

- Use 21 NCEP 32-km SREF members (ARW, NMM, ETA, RSM) over suitably long periods (~ 1 year)
- Run 21 SCIPUFF dispersion calculations
  - Combine dosage statistics (explicit ensemble)
- Run SCIPUFF using 4-km MM5 FDDA to generate “ground truth” dispersion
- Process SREF outputs for mean ensemble MET and MET uncertainty (wind variances)
- Run single 24-h 32-km SCIPUFF with ensemble MET uncertainty wind variances (SREF hazard prediction)
- Compare single-SCIPUFF SREF hazard prediction with 32-km explicit SCIPUFF ensemble using probabilistic verification and “ground truth” dispersion calculations
SREF Member Mean Dosages

ETA
RSM
NMM
ARW
Mean Dosage and Comparison

SREF Ensemble Average

Surface Dosage
TRACER at 07-May-10 18:00Z (24.0 hrs)

MM5 Truth (color) + SREF Ensemble Probability > 1.0E-9

Surface Dosage
TRACER at 07-May-10 15:00Z (24.0 hrs)

10%  40%
Sample Reliability

June-June Reliability Diagram, MM5 (t_avg = default)
Ensemble Simulations with Coupled Atmospheric Dynamic and Dispersion Models: Illustrating Uncertainties in Dosage Simulations

THOMAS T. WARNER,*# RONG-SHYANG SHEU,* JAMES F. BOWERS,† R. IAN SYKES,‡ GREGORY C. DODD,** AND DOUGLAS S. HENN&

*National Center for Atmospheric Research, + Boulder, Colorado  
#Program in Atmospheric and Oceanic Sciences, University of Colorado, Boulder, Colorado  
†U.S. Army West Desert Test Center, Dugway, Utah  
&ARAP Group, Titan Research & Technology, Princeton, New Jersey  
**H.E. Cramer Co., Inc., Sandy, Utah

(Manuscript received 20 March 2001, in final form 31 October 2001)
Ensemble Variance Calibration for Representing Meteorological Uncertainty for Atmospheric Transport and Dispersion Modeling

WALTER C. KOLCZYNSKI JR., DAVID R. STAUFFER, SUE ELLEN HAUPT, AND AIJUN DENG

Department of Meteorology, The Pennsylvania State University, University Park, Pennsylvania

(Manuscript received 17 June 2008, in final form 22 January 2009)
Investigation of Ensemble Variance as a Measure of True Forecast Variance

Walter C. Kolczynski, Jr.¹*, David R. Stauffer¹, Sue Ellen Haupt¹, Naomi S. Altman²

and Aijun Deng¹

The Pennsylvania State University
University Park, PA 16802

¹ Department of Meteorology
² Department of Statistics

For Submission to Monthly Weather Review

December 2010
Revised May 2011

*Corresponding author: phone: 814-863-1036, e-mail: wek122@psu.edu
Mean Absolute Reliability Error (MARE)
Concentration (~100 cases, min 20 forecasts)
Thank-you !!!
Supplementary Slides
Methodology for the HNEEnKF

Model equation with additional nudging terms:

\[
\frac{dx}{dt} = f(x) + G \cdot w_s \cdot w_t \cdot (y^o - Hx)
\]

Hybrid nudging coefficients:

\[
G \cdot w_s = \frac{1}{\left( \sum_{t=\tau_{N}}^{t^o} w_t \cdot \Delta t \right)} \mathbf{K}
\]

- The hybrid nudging coefficients come directly from the EnKF gain matrix \( \mathbf{K} \) that contains information from the flow-dependent background error covariances computed from an ensemble forecast.
- Thus there is no need to specify the nudging strength or the spatial nudging weighting coefficient in either the horizontal or vertical directions.
- The hybrid nudging terms include not only the standard diagonal terms (i.e., \( u \) correction in \( u \)-equation, \( v \) correction in \( v \)-equation, etc.) in the nudging magnitude matrix \( \mathbf{G} \), but also the off-diagonal terms (i.e., inter-variable influence).
- This statistical inter-variable influence is included in the model’s relaxation terms to gradually and continuously force the model towards the observations.
- Thus the error spikes and dynamic imbalances often produced by intermittent EnKF are reduced.
## Experiment design – parameters

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Nudging strength</th>
<th>Horizontal radius of influence</th>
<th>Surface data vertical radius of influence (stable PBL)</th>
<th>Surface data vertical radius of influence (unstable PBL)</th>
<th>Half-period of nudging time window</th>
<th>Horizontal error covariance localization</th>
<th>Vertical error covariance localization</th>
<th>Error covariance inflation</th>
</tr>
</thead>
<tbody>
<tr>
<td>FDDA</td>
<td>$4 \times 10^{-4}$ s$^{-1}$</td>
<td>67-200 km</td>
<td>100 m</td>
<td>PBL top plus 50m</td>
<td>1-2 h</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>EnKF</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>533 km</td>
<td>150 hPa</td>
<td>Adaptive inflation</td>
</tr>
<tr>
<td>HNEnKF</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>1-2 h</td>
<td>533 km</td>
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</tr>
</tbody>
</table>
Observations Research Progress: 
Characteristics vs. Speed; 
6-hr Ave, Spring, Summer, Fall 2009

Note the weak correlation between \( w \) and \( T \) and large kurtosis for wind speeds less than 1 \( \text{ms}^{-1} \).
Probability Distribution of One-minute Averages of 5-s Heat Fluxes at Rock Springs for the Very Weak Wind, Highly Stable Regime

- 98% of data (nearly 40,000 events) carries near-zero flux.
- Important non-zero flux events are rare.
- The rare high-flux events lead to a high kurtosis = 175, skewness = -6.
- Conclusion: It is inherently difficult to parameterize the most important events.
One Min. Averaged $\sigma_w$ and Scaled $\sigma_w$ for Near-calm Nights with Strong Averaged Stratification (Black) and Weaker Stratification (Red) as a Function of $R_b$

![Graphs showing $\sigma_w$ and $\sigma_w/N$ as functions of $\log(R_b)$ with annotations for strong stratification and similarity theory validity.]

- Similarity Theory Valid for Weak Stability
- Similarity Theory Fails for Stronger Stability
Sensitivity of Parcel Trajectories to Model Resolution & PBL Physics

Trajectory Sensitivity:

• Reduced mixing in modified PBL physics allows more sub-meso motions and inter-parcel variability.

• Lower 1.3-km horizontal resolution produces larger speed bias.

• Lower standard vertical resolution suppresses gravity-driven slope flows.

Time: 0800 – 1112 UTC
Case: 7 Oct. 2007

Exp. Baseline
Exp. LrgDZ
Exp. Modified PBL Physics
Exp. LrgDX
Exp. LrgDZ
Surface Dosage at 3 h Following Release and Valid at 11 UTC

SCIPUFF Sensitivity:

• Reduced mixing in MYJ-mod allows more sub-meso motions and greater dispersion.

• Lower horizontal resolution produces larger speed bias, less-resolved drainage flow and less lateral (cross-plume) dispersion.

• Lower vertical resolution suppresses gravity-driven slope flows and produces a plume more parallel to the mountain.
The effect of terrain-induced gravity waves on hazard prediction is investigated using a **combined observation and modeling study** over the complex terrain of Central Pennsylvania.
Regions of wave reflection

Vertical Velocities (shaded) and $\theta$ (contoured) at 0836 UTC

Regions where wave reflection is predicted by linear theory
Evaluation using independent surface tracer data

The composite statistics (hits, misses and false alarms) through the 24-h period