Spring Colloquium on 'Regional Weather Predictability and Modeling'
April 11 - 22, 2005

1) Workshop on Design and Use of Regional Weather Prediction Models, April 11 - 19

2) Conference on Current Efforts Toward Advancing the Skill of Regional Weather Prediction. Challenges and Outlook, April 20 - 22

The Eta Model Numerical Design.
Vertical coordinate

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The Eta Model Numerical Design.
Vertical coordinate

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Spring Colloquium
“Regional Weather Predictability and Modeling”
Abdus Salam ICTP, Miramare, Trieste, 11-22 April 2005
Vertical coordinate issues:

The Earth has topography!
Domain and topography used for NCEP Reg. Reanalysis:
Vertical coordinate choices:

$\ z, p: \text{ problems with coordinate surfaces intersecting topography;}$

N. Phillips (1957) “sigma”:

$$\sigma = \frac{p}{p_S} \quad (\text{Or, later,} \quad \sigma = \frac{p - p_T}{p_S - p_T})$$

Isentropic:

attractive, but problems with topography not addressed;

Problems with sigma (PGF, and others, later), thus,


$$\eta = \frac{p - p_T}{p_S - p_T} \eta_S, \quad \eta_S = \frac{p_{rf}(z_S) - p_T}{p_{rf}(0) - p_T}$$

Note: can be used as a switch, eta/ sigma
FIG. 1. Schematic representation of a vertical cross section in the eta coordinate using step-like representation of mountains. Symbols $u$, $T$ and $p_s$ represent the $u$ component of velocity, temperature and surface pressure, respectively. $N$ is the maximum number of the eta layers. The step-mountains are indicated by shading.
Equations:

Generalization of Simmons, Burridge (1981); just as simple;

Moreover:

- Conservation of angular momentum (PGF), as done in Simmons, Burridge, doable;
- Conservation of energy in transformation between potential and kinetic ("\(\omega_\alpha\)) doable as well

(Both, Mesinger 1984 in 2D,
  energy: Dushka Zupanski, Appendix of Mesinger et al. 1988, 3D)
The very first result, 1984, using the switch $\sigma$/$\eta$.

Fig. 6, 300 mb geopotential heights (upper panels) and temperatures (lower panels) obtained in 48 h simulations using the sigma system (left-hand panels) and the eta system (right-hand panels). Contour interval is 80 m for geopotential height and 2.5 K for temperature.
In NCEP’s “Eta Model“, eta did extremely well: tests during the early nineties using the eta/sigma switch, on cases, and samples of forecasts, very favorable for the eta, e.g.:
However, a 10-km Eta in 1998 did a poor job on a case of so-called Wasatch downslope windstorm, while a sigma system MM5 did well;

**Eta:** bad press ever since: 

“ill suited for high resolution prediction models”

more ??

Is sigma a good way to go after all?  
Let us just look at what the sigma problem is, and at some recent results!
PGF/resolution: in hydrostatic systems

\[ \phi = \phi_S - R_d \int_{p_S}^p T_v d \ln p \]  \hfill (1)

Thus: PGF depends only on variables from the ground up to the considered \( p=\text{const} \) surface!

From this point of view, all PGF/hydrostatic equation sigma system schemes, three groups:

a. Those with hydrostatic eq. analog that relates geopotentials used for PGF to temperatures both below and \textit{above} the considered level;

b. “Level schemes”: geopotentials used for PGF obtained by vertical integration of temperatures from the ground \textit{only up to the considered coordinate surface} (e.g., straightforward isentropic coordinate schemes);

c. “Layer schemes”: using layer temperatures to define geopotential increments through layers (\textit{best} from the point of view of (1))
Continuous case:
PGF should depend on, and only on, variables from the ground up to the \( p = \text{const} \) surface

The best type of scheme:
will depend on \( T_{j+1/2,k+1} \), which \textit{it should not};
will \textit{not} depend on \( T_{j-1/2,k-1} \), which \textit{it should}.

The problem \textbf{aggravates with resolution}!!
Thus, PGF problem of terrain-following coordinates:

Not one of “two large terms”

\[-\nabla_p \phi \rightarrow -\nabla_\sigma \phi - RT \nabla \ln p_S\]

(Easy to make them much smaller, subtract “reference” atmosphere” while having the error the same or about the same)

Not one of the “truncation error”;

The error is likely to increase with increased Taylor-series accuracy;

It is likely to increase with increased resolution
Any signs of an impact?

One experiment: Eta (left), 22 km, switched to use sigma (center), 48 h position error of a major low increased from 215 to 315 km
Recent performance results

Three-model precipitation scores, on NMM ConUS domains ("East", ..., "West"), available since Sep. 2002

• Operational Eta: 12 km, driven by 6 h old GFS forecasts;
• NMM: “Nonhydrostatic Mesoscale Model” nonhydrostatic, 8 km, most other features same or similar to Eta, but switched back to \textit{sigma}, driven by the Eta;
• GFS (Global Forecasting System) as of the end of Oct. 2002 T254 (55 km) resolution, \textit{sigma}
6 h old GFS LBCs?

250 mb wind rms fits to raobs, m/s, Nov 2003-Apr 2004

“Cold Season”

Forecast hour
Back to the three models:

NOAA-wide e-mail of 19 July 2002
announcing the operational implementation of the NMM,
referring to the choice of the vertical coordinate:

"This choice will avoid the problems encountered at high resolution (10 km or finer)
with the step-mountain coordinate
with strong downslope winds
and will improve
 placement of precipitation in mountainous terrain".

Did this indeed happen?
Five "high-res windows"
However:
How can we tell how good is “placement of precipitation”?

Are there any performance measures (precip scores) that tell us how good was specifically the placement of precipitation?

A 2 x 2 problem: forecast: yes, no
  event occurred: yes, no

Two kinds of correct forecasts: yes, yes, and no, no

First papers: 1884! (Murphy, MWR 1996)
A very large number of performance measures! However: are any of them “equitable”, in the sense of Gandin and Murphy (MWR 1992)? (No reward for over- or underforecasting the event!)

Equitable threat score:
- equitable with respect to random forecasting;
- not in the sense of Gandin and Murphy :-(

Marzban (WF 1998):
- looked at 14 measures and found none equitable!

Of these, two:

- Odds ratio skill score;
- Heidke skill score;

[1926; originally proposed by Doolittle (1988)]

symmetric with respect to two types of correct forecast:

- Equitable threat score, and Threat score

emphasize correct forecasts of rain (yes, yes)

more than correct forecasts of no rain (no, no)

But neither of them is equitable :-(
BIAS NORMALIZED PRECIPITATION SCORES

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Motivation

- **Equitable threat scores**: commonly used to assess the performance of model precipitation forecasts. Purpose (hoped for): access placement of precipitation

- However: sensitive to bias

- E.g.: Common wisdom has it that bias somewhat greater than 1 tends to benefit equitable threat score.

  - Thus: can we “normalize” the equitable threat score, to remove the impact of bias? (Also, standard threat score. Acknowledgment: Joe Schaefer).
Two Methods of Bias Normalization

1. \( \frac{dH}{dF} \) method: Assume the incremental change in hits per incremental change in bias is proportional to the “unhit” area, O-H

2. Odds Ratio method: Assume that the odds ratio remains unchanged as the hit and forecast areas are changed to satisfy the condition bias = 1
dH/dF Method

Assumption: \( \frac{dH}{dF} = a(O - H), \quad a = \text{const.} \) \hspace{1cm} (1)

Solve (1) to get \( H(F) = b e^{-aF} + O, \quad b = \text{const.} \) \hspace{1cm} (2)

Since \( H=0 \) for \( F=0 \): \( b = -O \rightarrow H(F) = O(1 - e^{-aF}) \) \hspace{1cm} (3)

Solve for \( a \) to get \( a = -\frac{1}{F} \ln \left(1 - \frac{H(F)}{O}\right) \) \hspace{1cm} (4)

If \( H_b \) and \( F_b \) are known values of \( H \) and \( F \) with \( O \) given, \( a = -\frac{1}{F_b} \ln \left(1 - \frac{H_b}{O}\right) \) \hspace{1cm} (5)

Insert (5) into (3) to get \( H(F) = O \left[1 - \left(\frac{O - H_b}{O}\right)^{\frac{F}{F_b}}\right] \) \hspace{1cm} (6)

Bias = 1 implies \( F = O \), and adjusted \( H, H_a \) is given by \( H_a = O \left[1 - \left(\frac{O - H}{O}\right)^{\frac{O}{F}}\right] \) \hspace{1cm} (7)

Note that the subscript \( b \) has been dropped from (7) as the distinction is no longer needed as it is in (6).
What has happened since?

“Odds ratio method”:
declared not to have a valid basis

(Manuscript on only one method about to be submitted/in internal review)
Bias normalized eq. threats
dH/dF BN Eq Threat, Western Nest, Sep 2002–Aug 2003

(Five very heavy el Niño precip events)
Bias Normalized Eq. Threat, Eastern Nest, Feb 04-Jan 05

Observation counts:
3449866 2017237 1265655 676161 386399 232222 88759 38209 11784

Threshold (Inches)
Bias Normalized Eq. Threat, Western Nest, Feb 04-Jan 05

Observation counts:

Threshold (Inches)
**Eta vs NMM:**
East, no major topography: 12-km Eta about the same as the 8-km NMM, even a tiny bit better; West, complex topography: 12-km Eta **much better** than the 8-km (sigma system) NMM !

**GFS vs Eta:**
East: **GFS** (when corrected for bias) uniformly better; West: **Eta much** better (overcoming handicaps of the 6 h lateral boundary error, and less successful data assimilation)!
Thus, summary of performance results:
Very strong indication that the eta works extremely well!

But what about its downslope windstorm problem?
The Eta Problem:
Flow separation on the lee side (à la Gallus and Klemp 2000)
Flow from left: from the box 1 the flow enters box 2 to the right of it. When conditioned to move downward, it will move downward via the interface between boxes 2 and 5. Some of the air that entered box 2 will continue to move horizontally into box 3.

Missing: the flow directly from box 1 into 5! (It would have existed had the discretization accounted for the terrain slope!) As a result: some of the air which should have moved slantwise from box 1 directly into 5 gets deflected horizontally into box 3.
Refined (sloping steps) eta

(Mesinger and Jović)

Discretization accounting for slopes. Continuity equation (at non-zero points):\[ \frac{\partial p_s}{\partial t} = -\int_0^{\eta_s} \nabla \cdot \left( \mathbf{v} \frac{\partial p}{\partial \eta} \right) d\eta - \left( \frac{\eta}{p} \frac{\partial p}{\partial \eta} \right)_s \] (3)

Approach:

Define slopes at \( \mathbf{v} \) points, based on four surrounding \( h \) points. Slopes discrete, valid on halves of the sides of \( h \) points, and halves of the eta layers. Slantwise transports calculated within the 1st term on the right of (3), and in other equations as appropriate.

Other possibilities available. However: keep the eta feature of having cells in horizontal of about equal volume (difference compared to Adcroft et al. 1997, shaved cells)! This makes Arakawa-type conservation schemes, used in the Eta, very nearly finite-volume schemes. Also, robust in the CFL sense.
The sloping steps, vertical grid

The central $v$ box exchanges momentum, on its right side, with $v$ boxes of two layers:
Horizontal treatment, 3D

Example #1: topography of box 1 is higher than those of 2, 3, and 4;
“Slope 1”

Inside the central \( v \) box, topography descends from the center of \( T_1 \) box down by one layer thickness, linearly, to the centers of \( T_2, T_3 \) and \( T_4 \)
Slantwise advection of mass, momentum, and temperature, and “$\omega\alpha$”:

Velocity at the ground immediately behind the mountain increased from between 1 and 2, to between 4 and 5 m/s. “lee-slope separation” removed. Zig-zag features in isentropes at the upslope side removed.
Conclusions (re eta)

12-km Eta: excellent QPF performance over complex topography! Better than the sigma system 8-km NMM, and better than the GFS;

The Eta downslope windstorm problem: correctible/corrected, while keeping favorable Eta features:
- quasi horizontal coordinates (PGF !);
- very nearly finite-volume;
- robustness in the CFL sense.
Some of the references made
