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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*

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The Eta Model Numerical Design. Vertical coordinate

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The Eta Model Numerical Design.

Vertical coordinate

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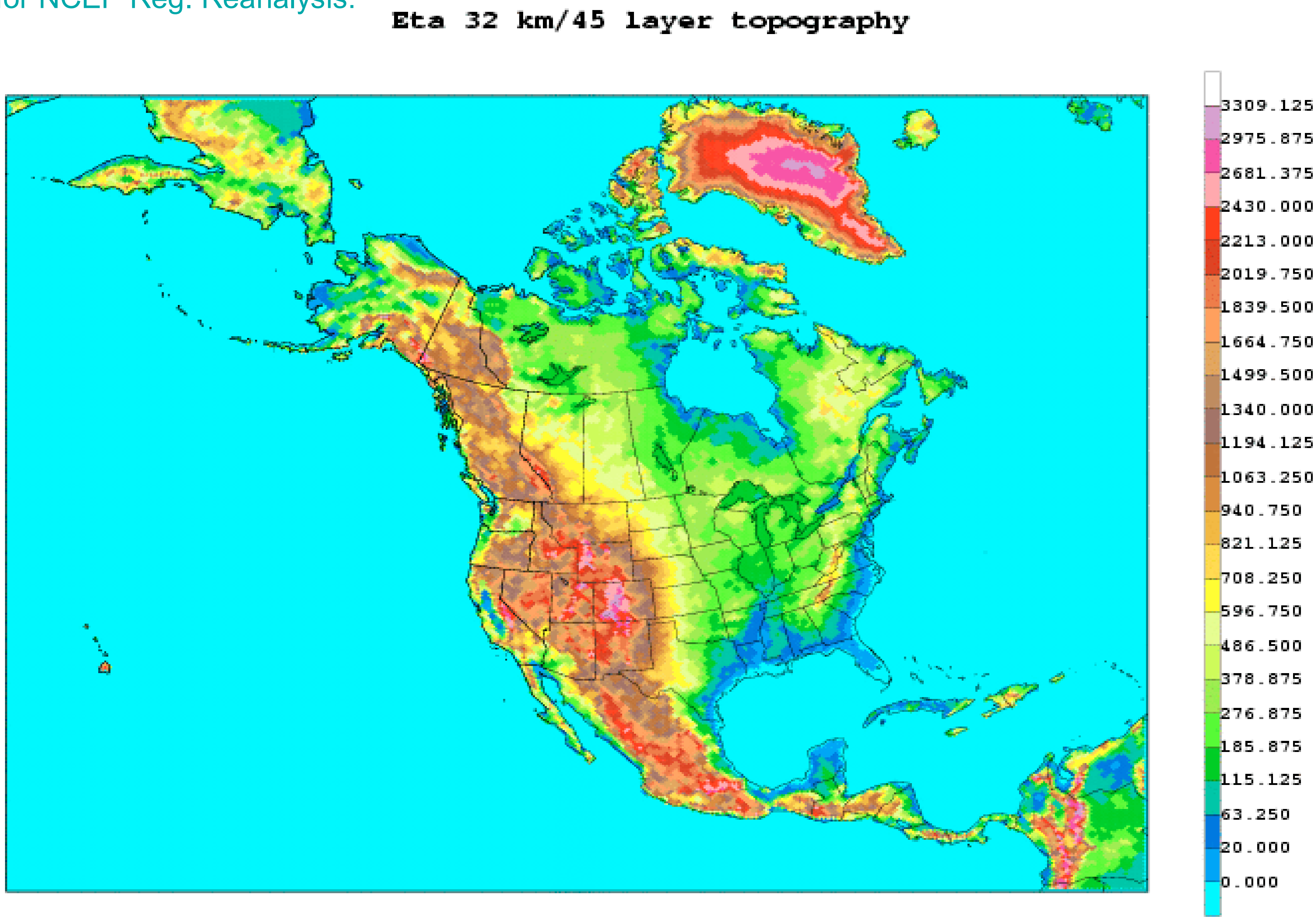
“Regional Weather Predictability and Modeling”
Abdus Salam ICTP, Miramare, Trieste, 11-22 April 2005

Vertical coordinate issues:

The Earth has topography !

Domain and topography used for NCEP Reg. Reanalysis:



Vertical coordinate choices:

z, p: problems with coordinate surfaces intersecting topography;

N. Phillips (1957) "sigma":

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

Isentropic:

attractive, but problems with topography not addressed;

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

Mesinger (1984) "eta":

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

Note: can be used as a switch, eta/ sigma

Step-topography discretization (Mesinger 1984):

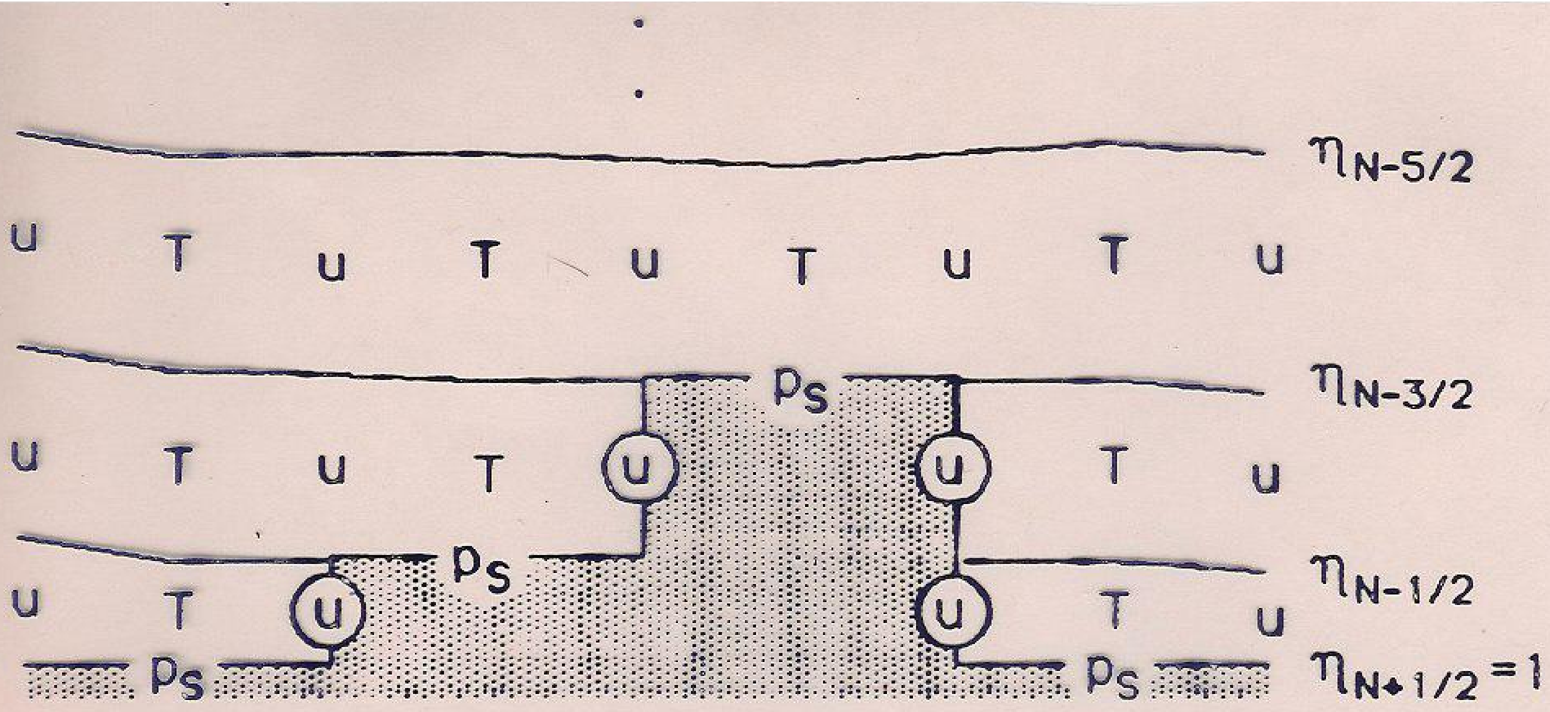


FIG. 1. Schematic representation of a vertical cross section in the eta coordinate using step-like representation of mountains. Symbols u, T and p_s represent the u component of velocity, temperature and surface pressure, respectively. N is the maximum number of the eta layers. The step-mountains are 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 (“ωα□□”) 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 eta/ sigma:

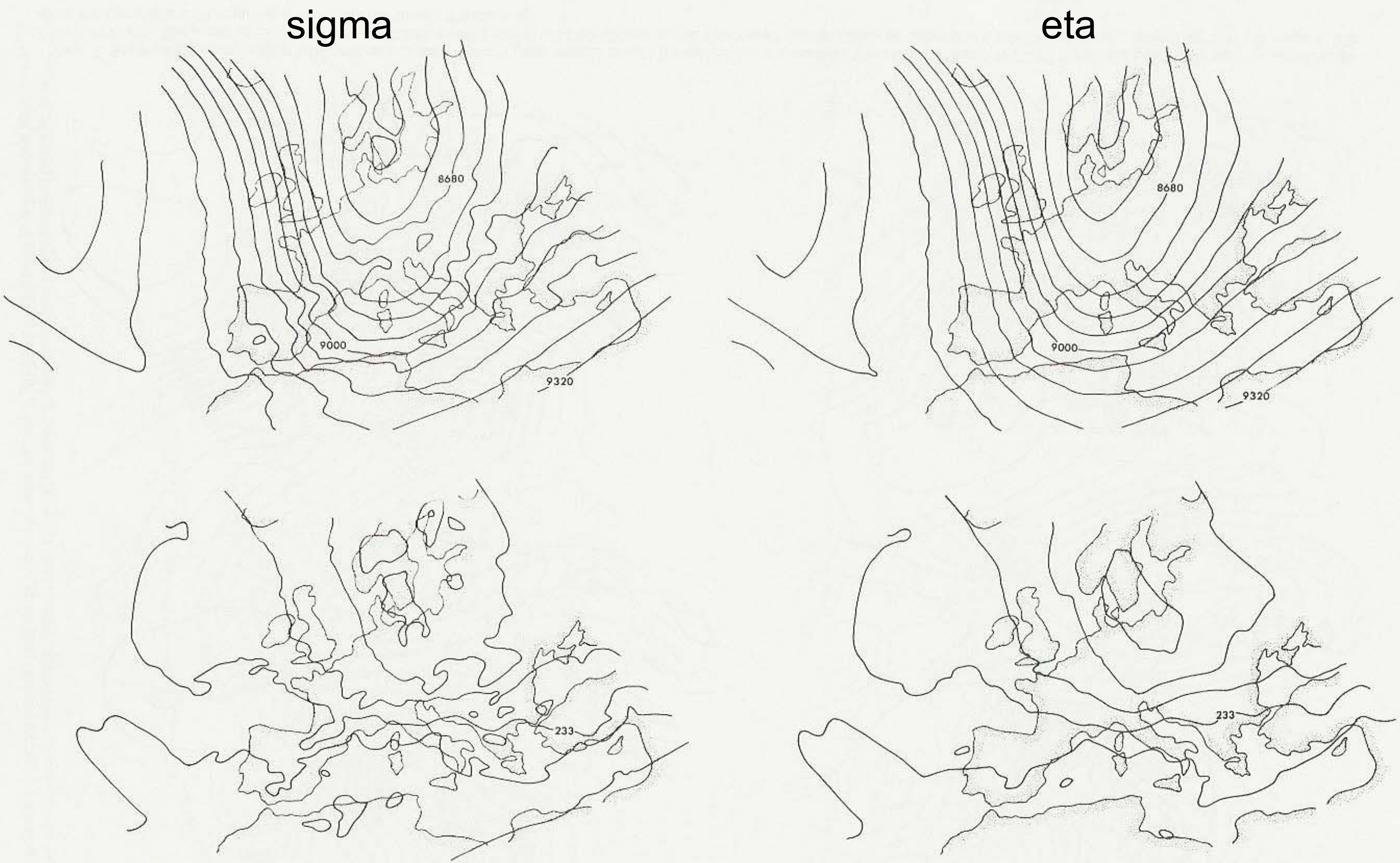


FIG. 6. 300 mb geopotential heights (upper panels) and temperatures (lower panels) obtained in 48 h simulations using the sigma system (left-hand panels) and the eta system (right-hand panels). Contour interval is 80 m for geopotential height and 2.5 K for temperature.

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.:

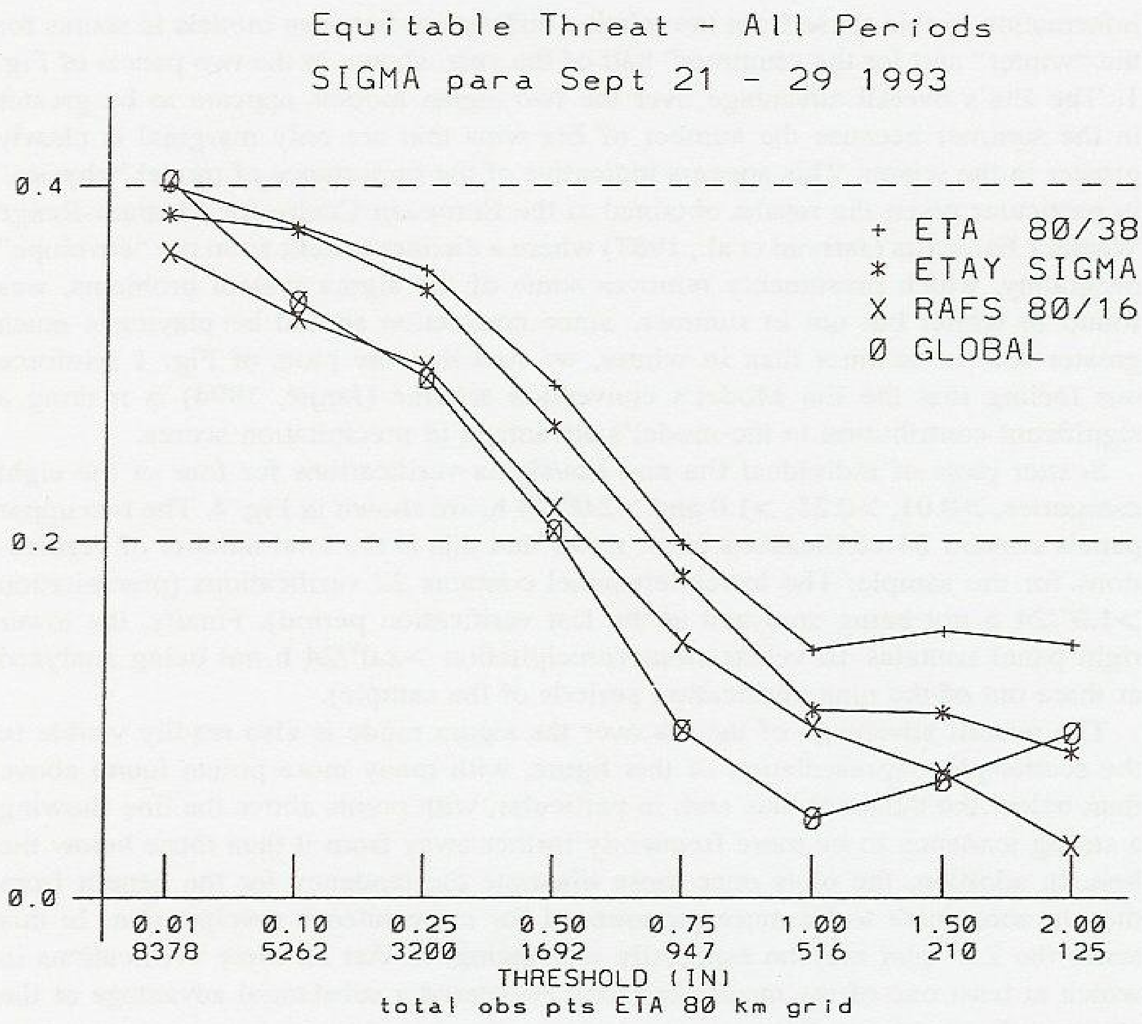


Fig. 3 Equitable precipitation threat scores for two versions of the Eta Model: Eta 80 km/38 layers ("ETA"), and the same version of the Eta Model but run using sigma coordinate ("ETAY"), and for the NGM (RAFS), and the Avn/MRF ("global") Model; for a sample of 16 forecasts verifying 1200 UTC 21 September through 1200 UTC 29 September 1993. Eight forecasts are each verified once, for 12–36 h, and the remaining eight each twice, for 00–24 and for the 24–48 h accumulated precipitation.

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"

Schär et al., *Mon. Wea. Rev.,* 2002;
Janjic, *Meteor. Atmos. Phys.,* 2003;
Steppeler et al., *Meteor. Atmos. Phys*., 2003;
Mass et al., *Bull. Amer. Meteor. Soc*., 2003;
Zängl, *Mon. Wea. Rev.,* 2003;
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

$$\phi = \phi_S - R_d \int_{p_S}^{p} T_v d \ln p \qquad (1)$$

Thus: PGF depends only on variables from the ground up to the considered p=const surface !

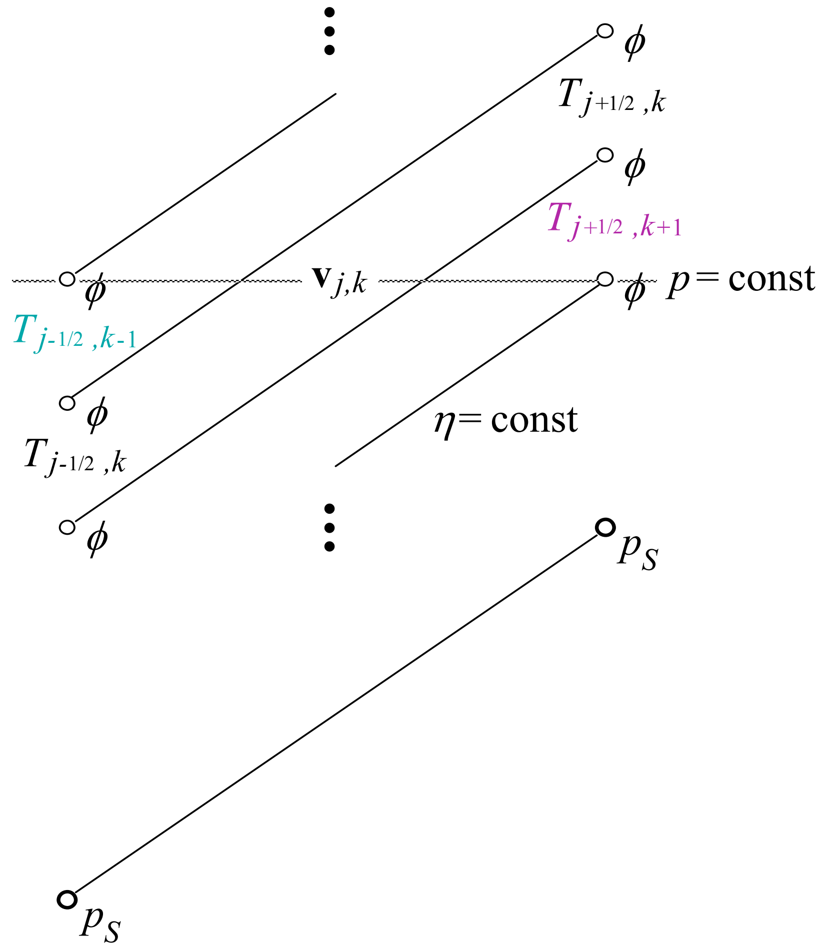
From this point of view, all PGF/ hydrostatic equation sigma system schemes, three groups:

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

b. "Level schemes": geopotentials used for PGF obtained by vertical integration of temperatures from the ground 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 (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=const surface



The best type of scheme:

will depend on $T_{j+1/2,k+1}$, which *it should not*;

will *not* depend on $T_{j-1/2,k-1}$, which *it should*.

The problem 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)

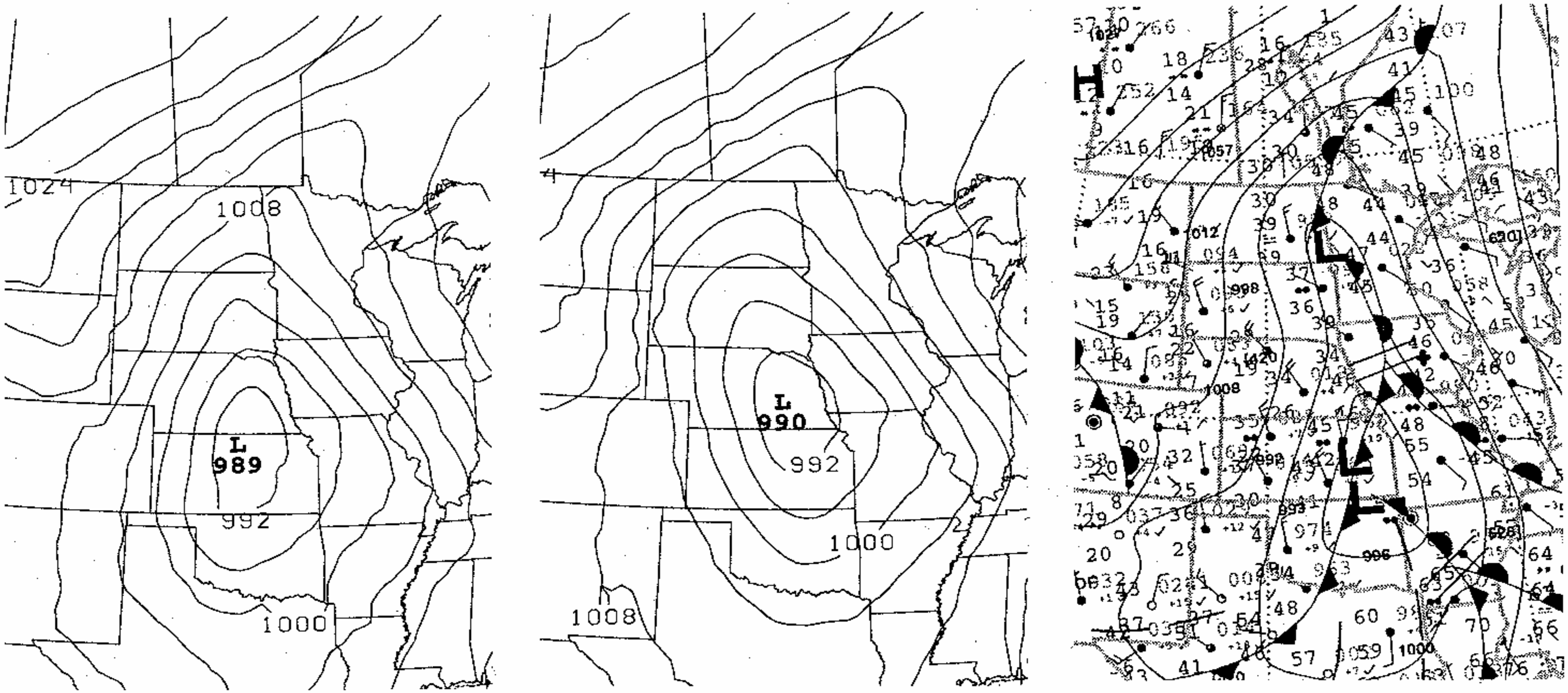
Not one of the "truncation error";

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

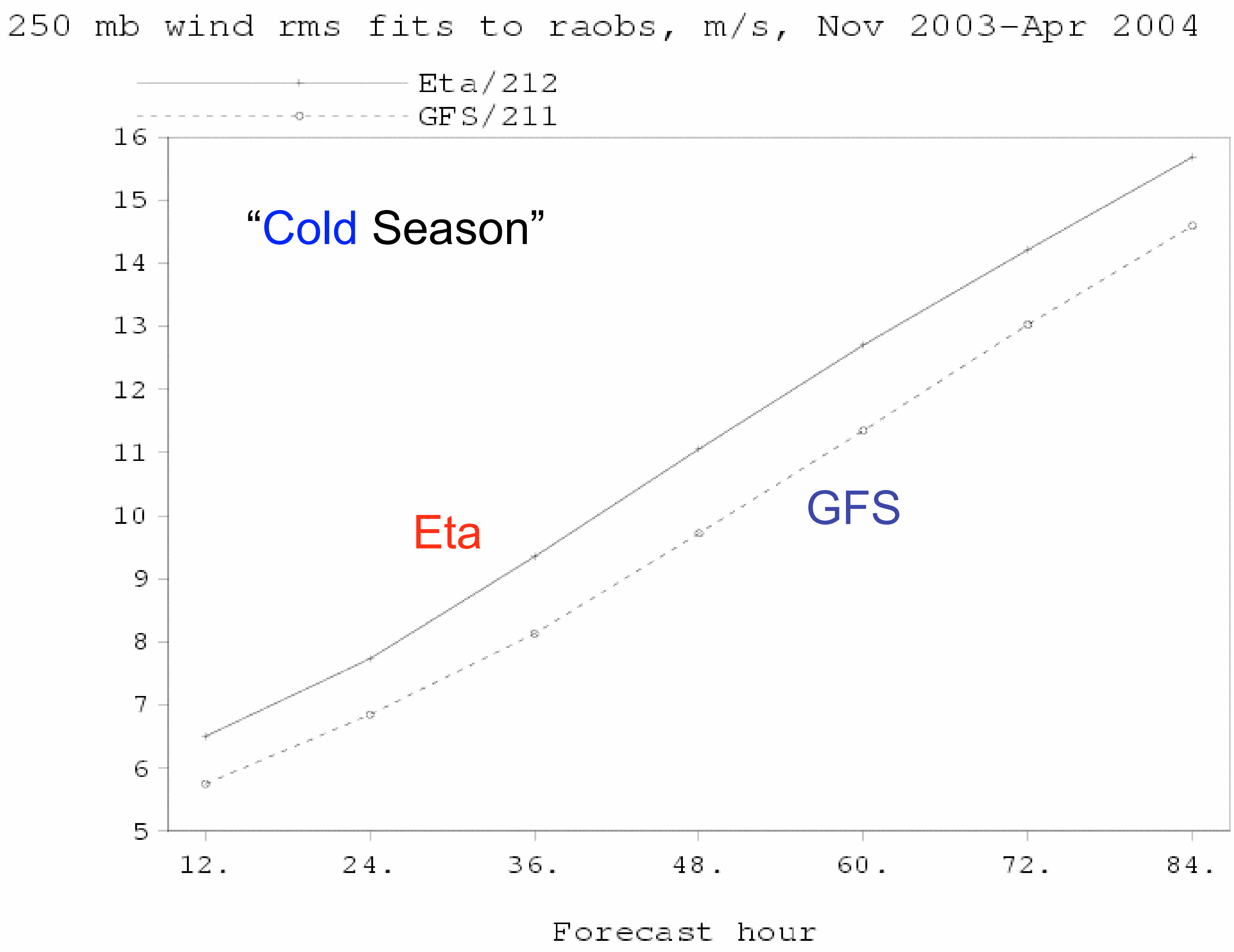


Recent performance results

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 sigma, driven by the Eta;
- GFS (Global Forecasting System) as of the end of Oct. 2002 T254 (55 km) resolution, sigma

6 h old GFS LBCs ?



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)

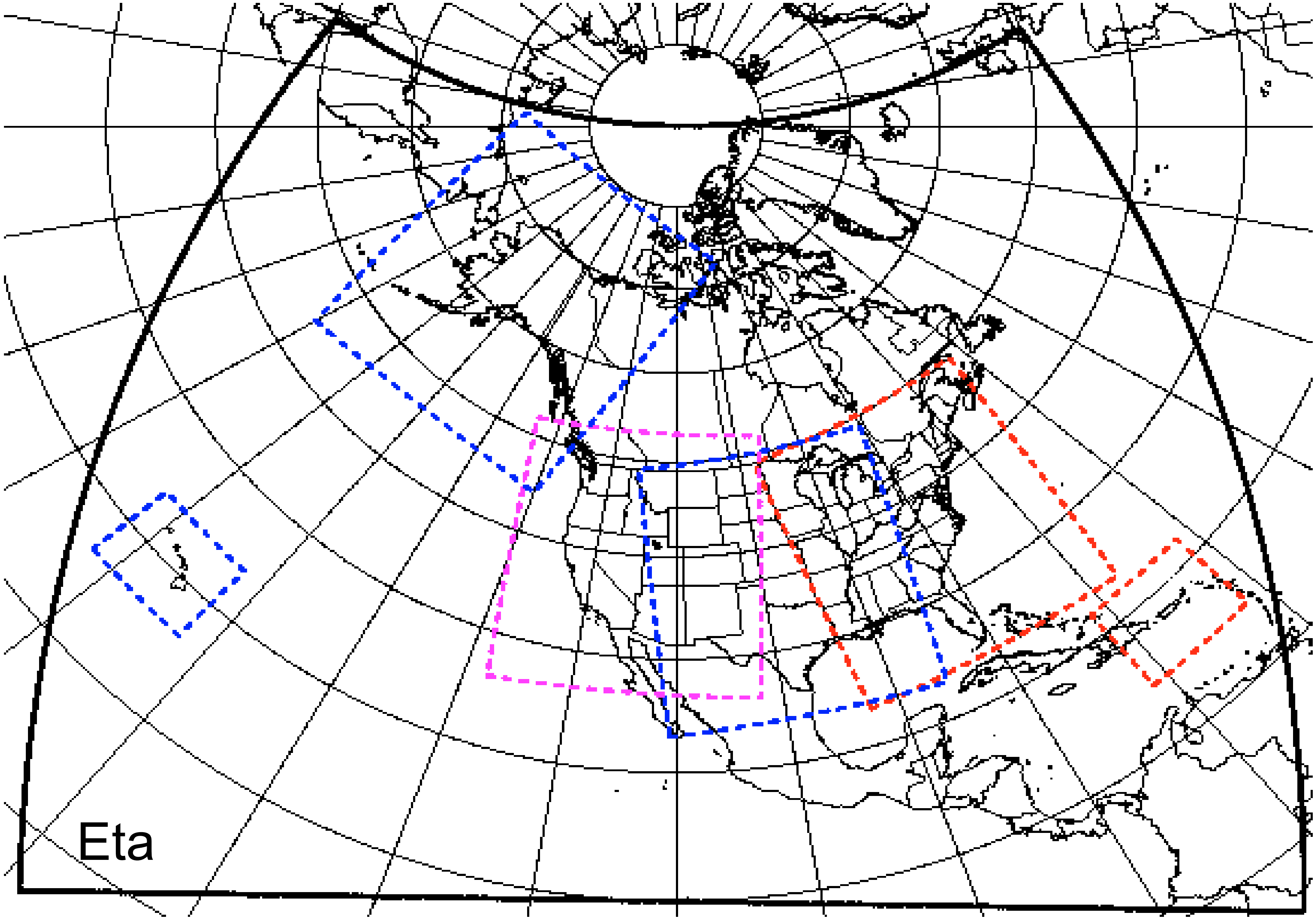
with the step-mountain coordinate

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 !

Baldwin and Kain (WF 2005, in preparation):

looked at 6 performance measures

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 :-(

J12.6
17th Prob. Stat. Atmos. Sci.; 20th WAF/16th NWP

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. 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: $$\frac{dH}{dF} = a(O - H), \quad a = const. \tag{1}$$

Solve (1) to get $$H(F) = be^{-aF} + O, \quad b = const. \tag{2}$$

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

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

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

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

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

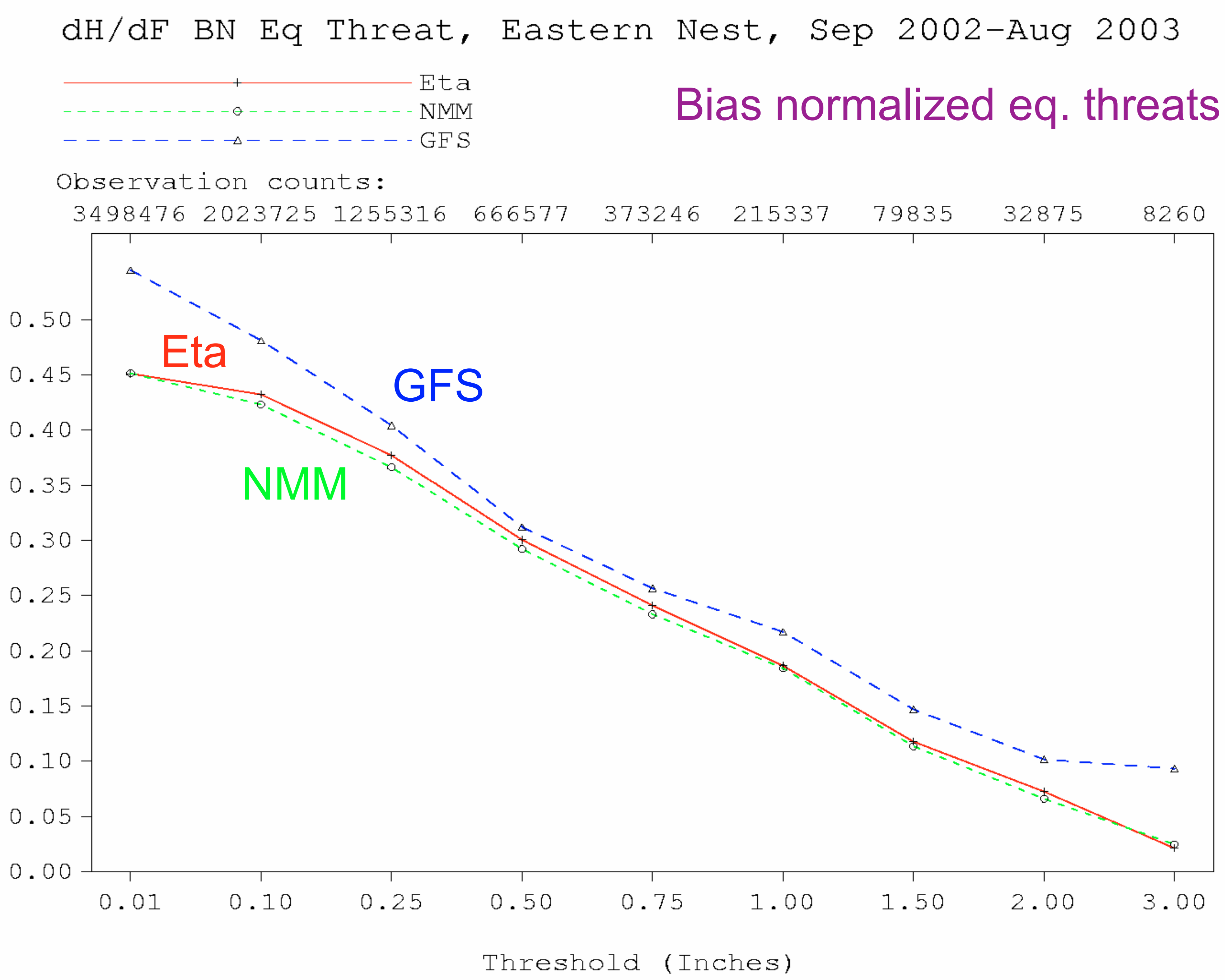
Note that the subscript b has been dropped from (7) as the distinction is no longer needed as it is in (6).

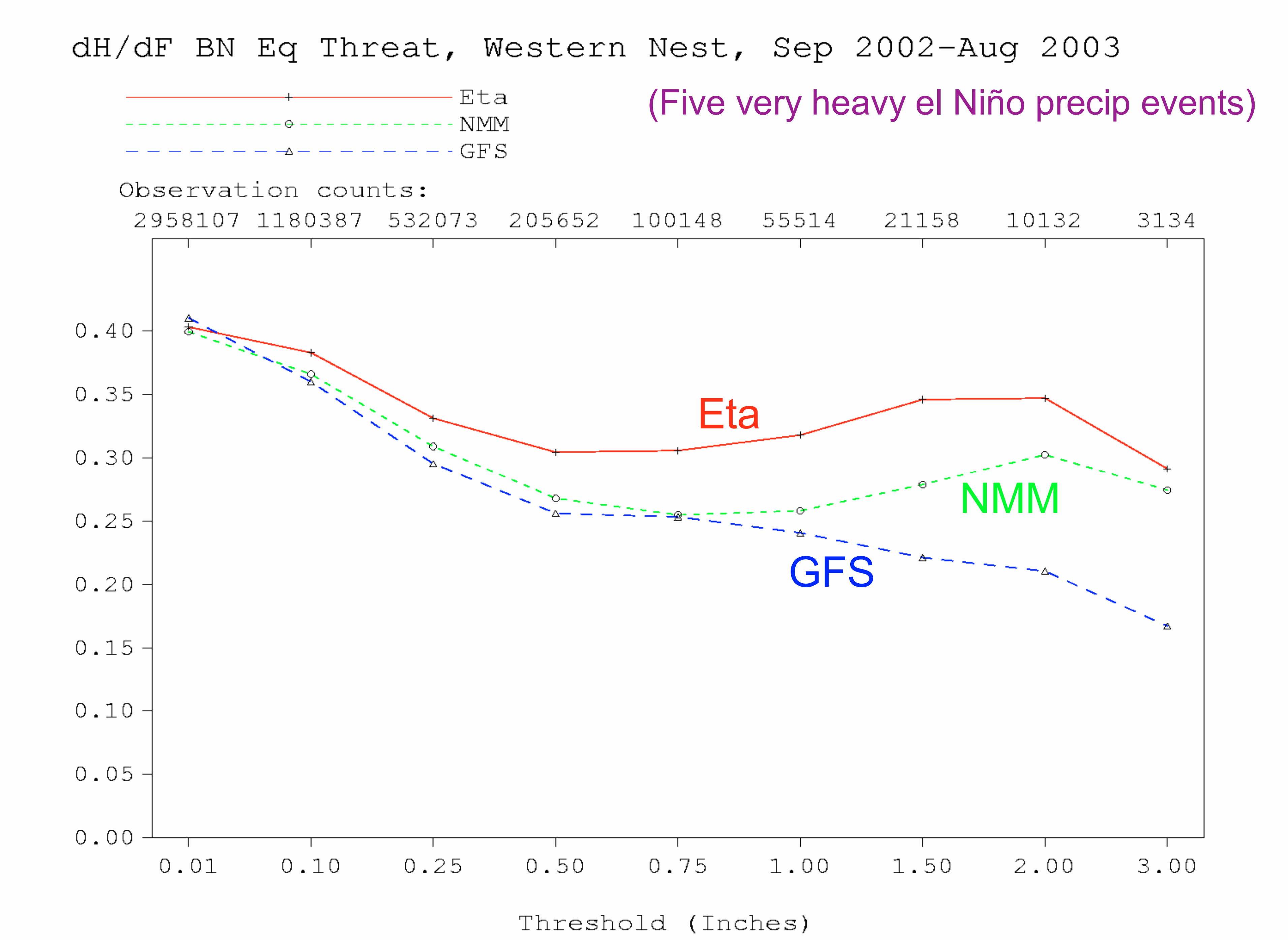
What has happened since ?

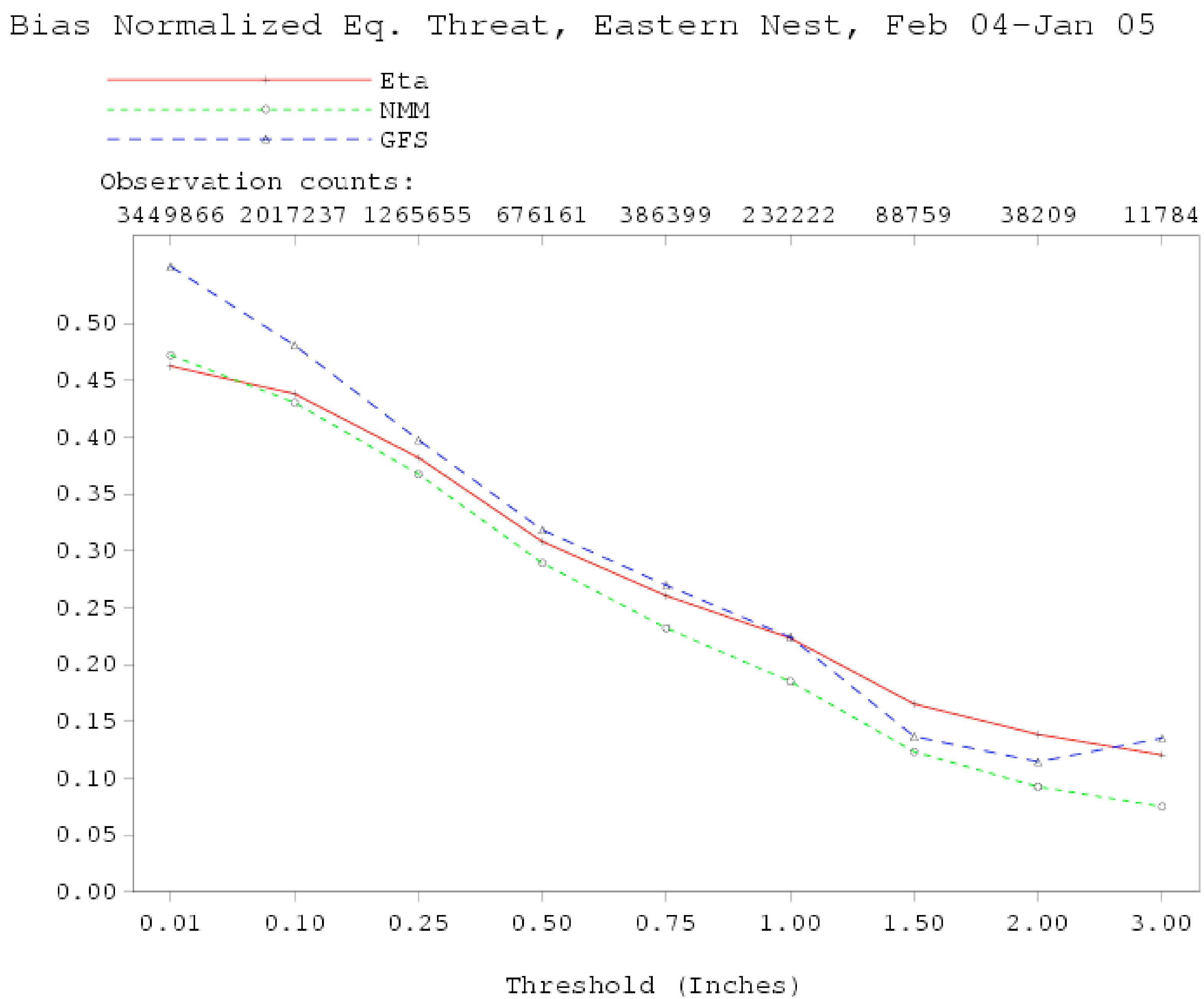
"Odds ratio method":

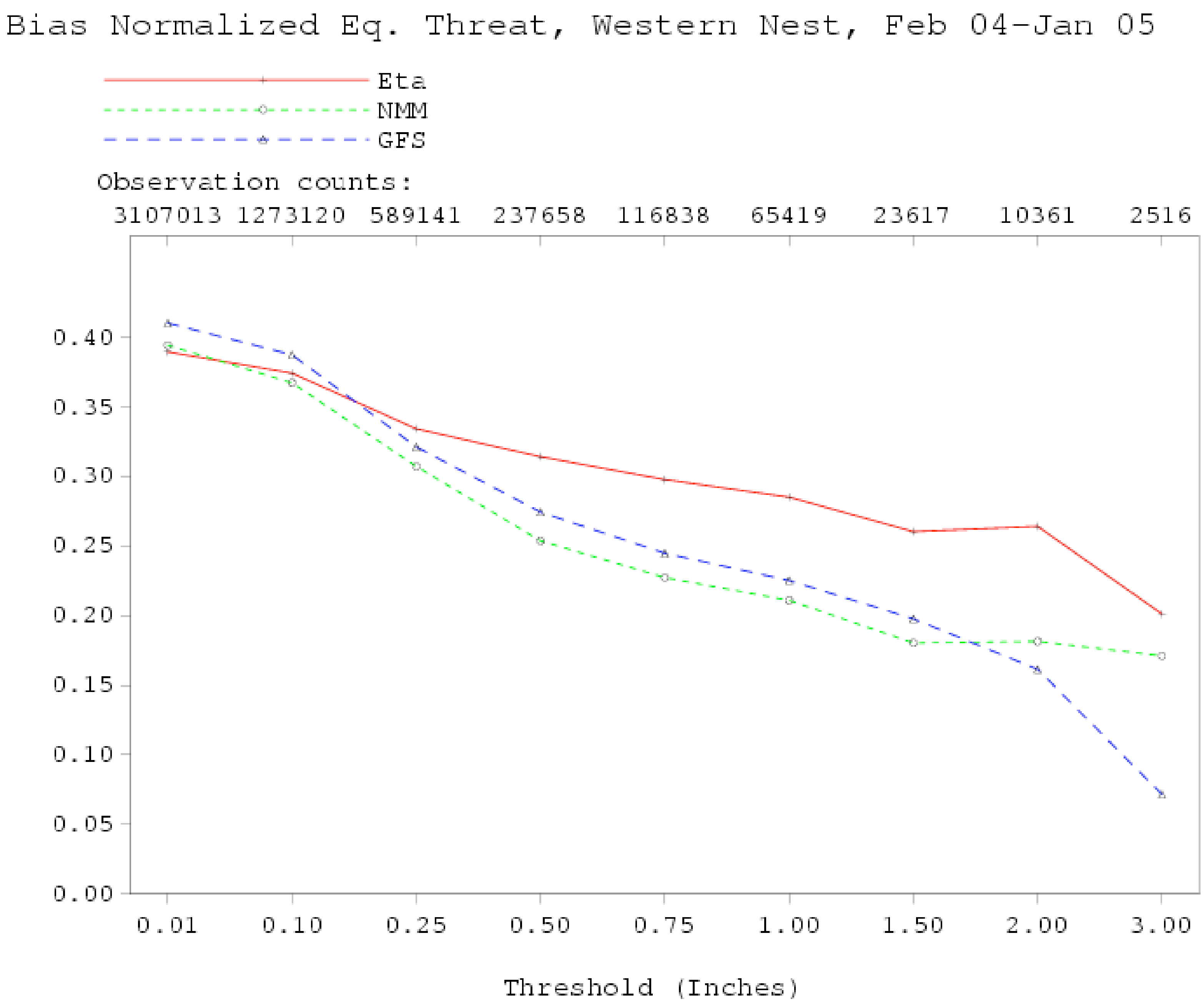
declared not to have a valid basis

(Manuscript on only one method about to be submitted/
in internal review)


dH/dF BN Eq Threat, Eastern Nest, Sep 2002-Aug 2003
Eta
NMM
GFS
Bias normalized eq. threats
Observation counts:
3498476 2023725 1255316 666577 373246 215337 79835 32875 8260
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
Eta
GFS
NMM
0.01
0.10
0.25
0.50
0.75
1.00
1.50
2.00
3.00
Threshold (Inches)


dH/dF BN Eq Threat, Western Nest, Sep 2002-Aug 2003
(Five very heavy el Niño precip events)
Eta
NMM
GFS
Observation counts:
2958107 1180387 532073 205652 100148 55514 21158 10132 3134
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0.01 0.10 0.25 0.50 0.75 1.00 1.50 2.00 3.00
Threshold (Inches)
Eta
NMM
GFS


Bias Normalized Eq. Threat, Eastern Nest, Feb 04-Jan 05
Eta
NMM
GFS
Observation counts:
3449866 2017237 1265655 676161 386399 232222 88759 38209 11784
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50
0.01
0.10
0.25
0.50
0.75
1.00
1.50
2.00
3.00
Threshold (Inches)


Bias Normalized Eq. Threat, Western Nest, Feb 04-Jan 05
Eta
NMM
GFS
Observation counts:
3107013 1273120 589141 237658 116838 65419 23617 10361 2516
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0.01 0.10 0.25 0.50 0.75 1.00 1.50 2.00 3.00
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) !

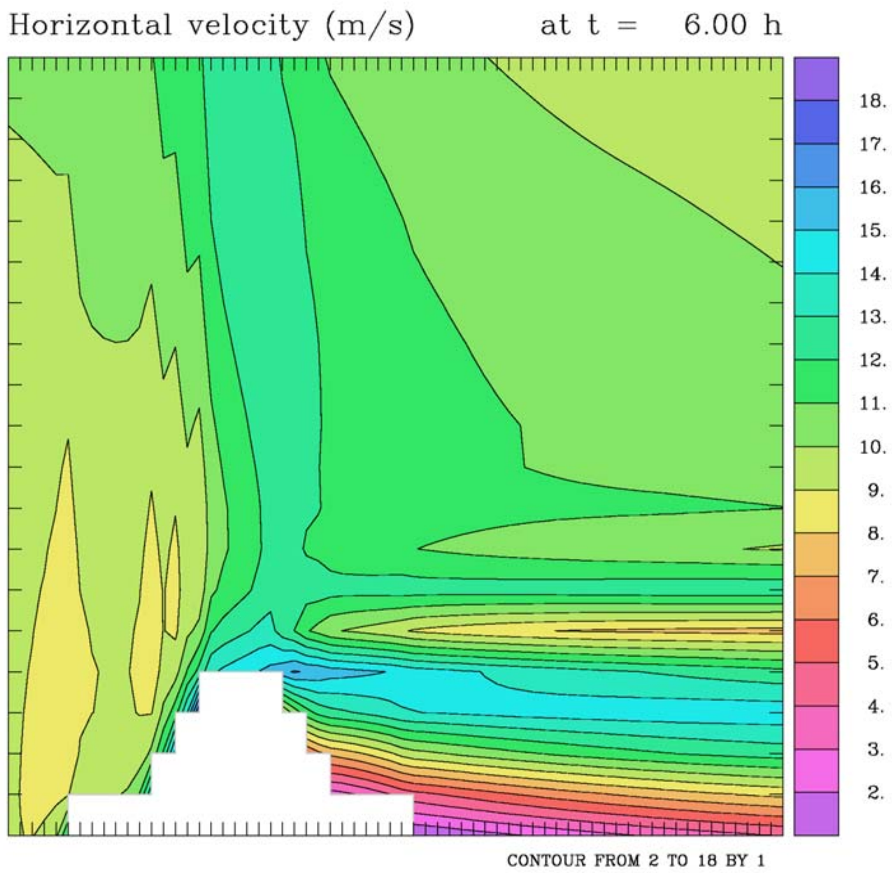
Thus, summary of performance results:

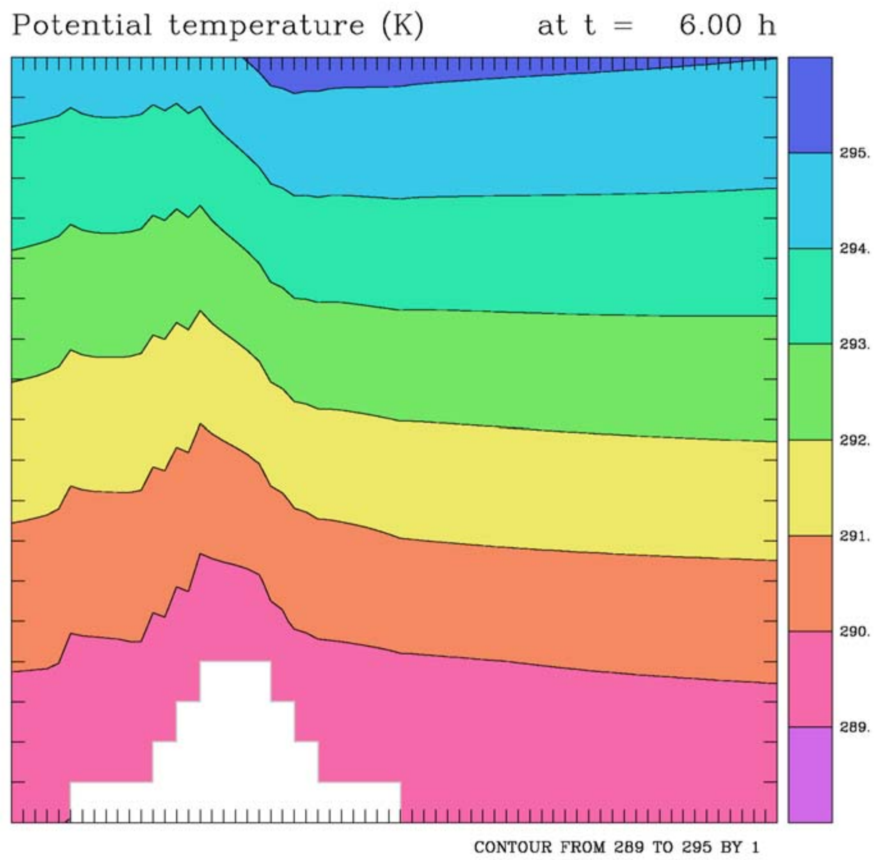
Very strong indication that the eta works extremely well !

But what about its downslope windstorm problem ?

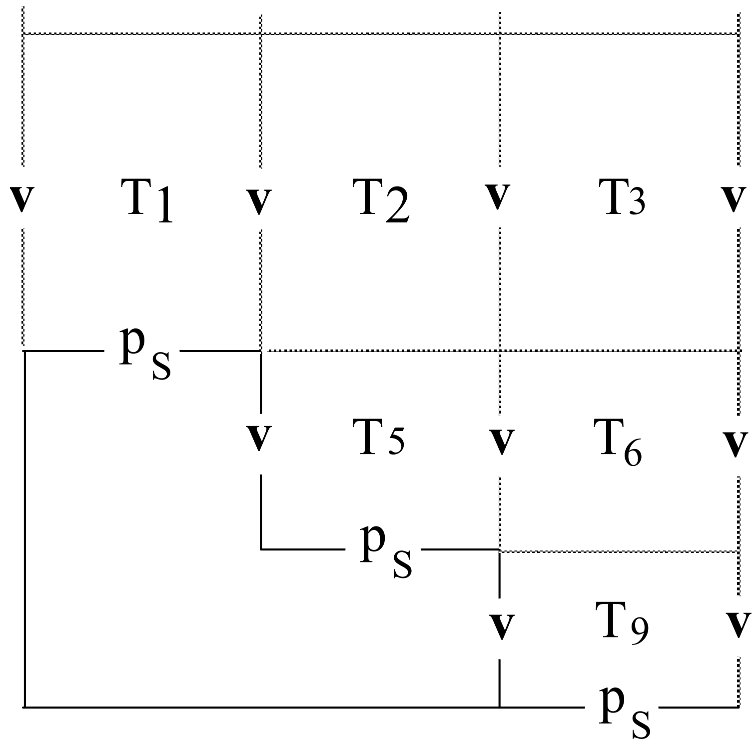
The Eta Problem:

Flow separation on the lee side (à la Gallus and Klemp 2000)





Suggested explanation



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 ($\dot{\eta}$ at p_S points not zero):

$$\frac{\partial p_S}{\partial t} = -\int_0^{\eta_S} \nabla \cdot \left(\mathbf{v} \frac{\partial p}{\partial \eta} \right) d\eta - \left(\dot{\eta} \frac{\partial p}{\partial \eta} \right)_S \qquad (3)$$

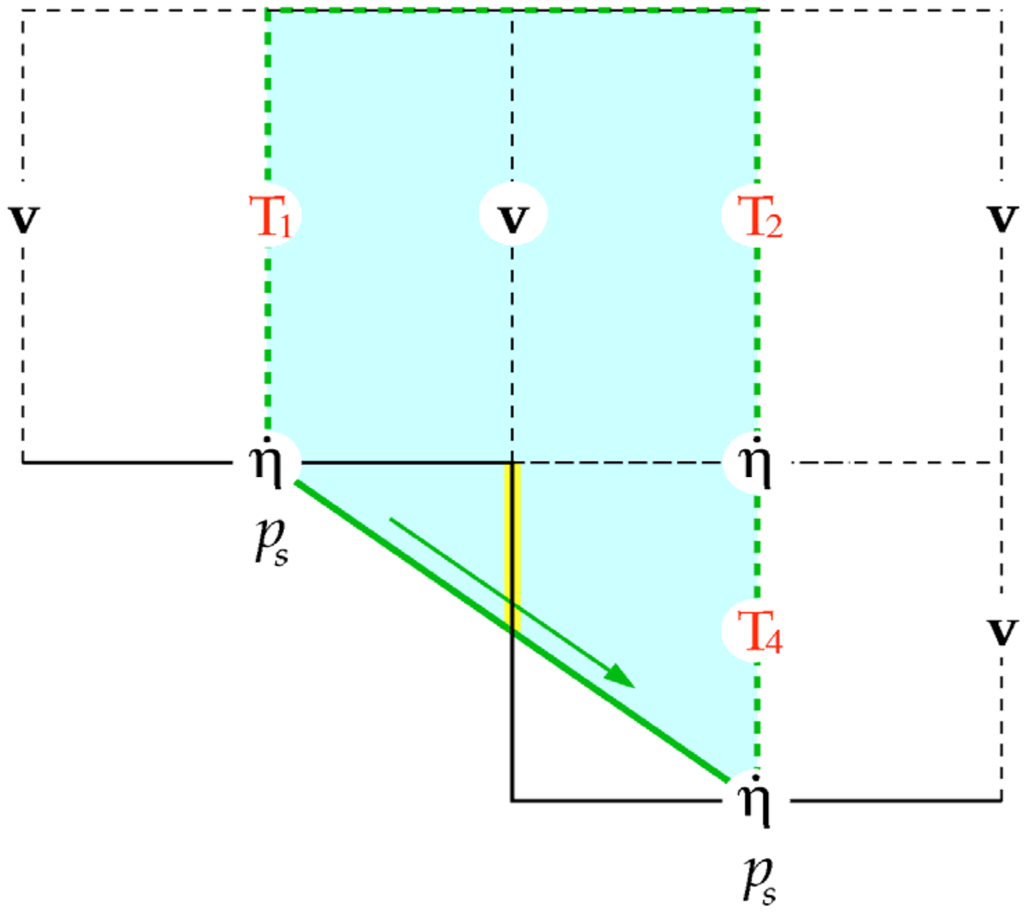
Approach:

Define slopes at **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

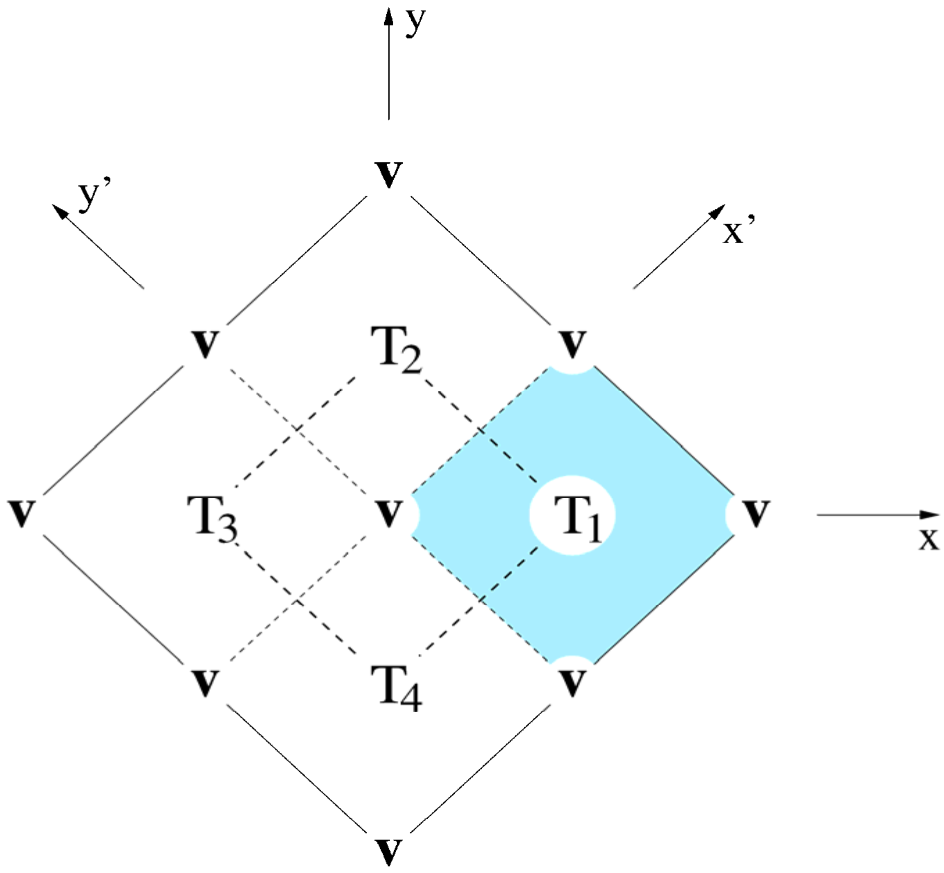
The central **v** box exchanges momentum, on its right side, with **v** boxes of two layers:



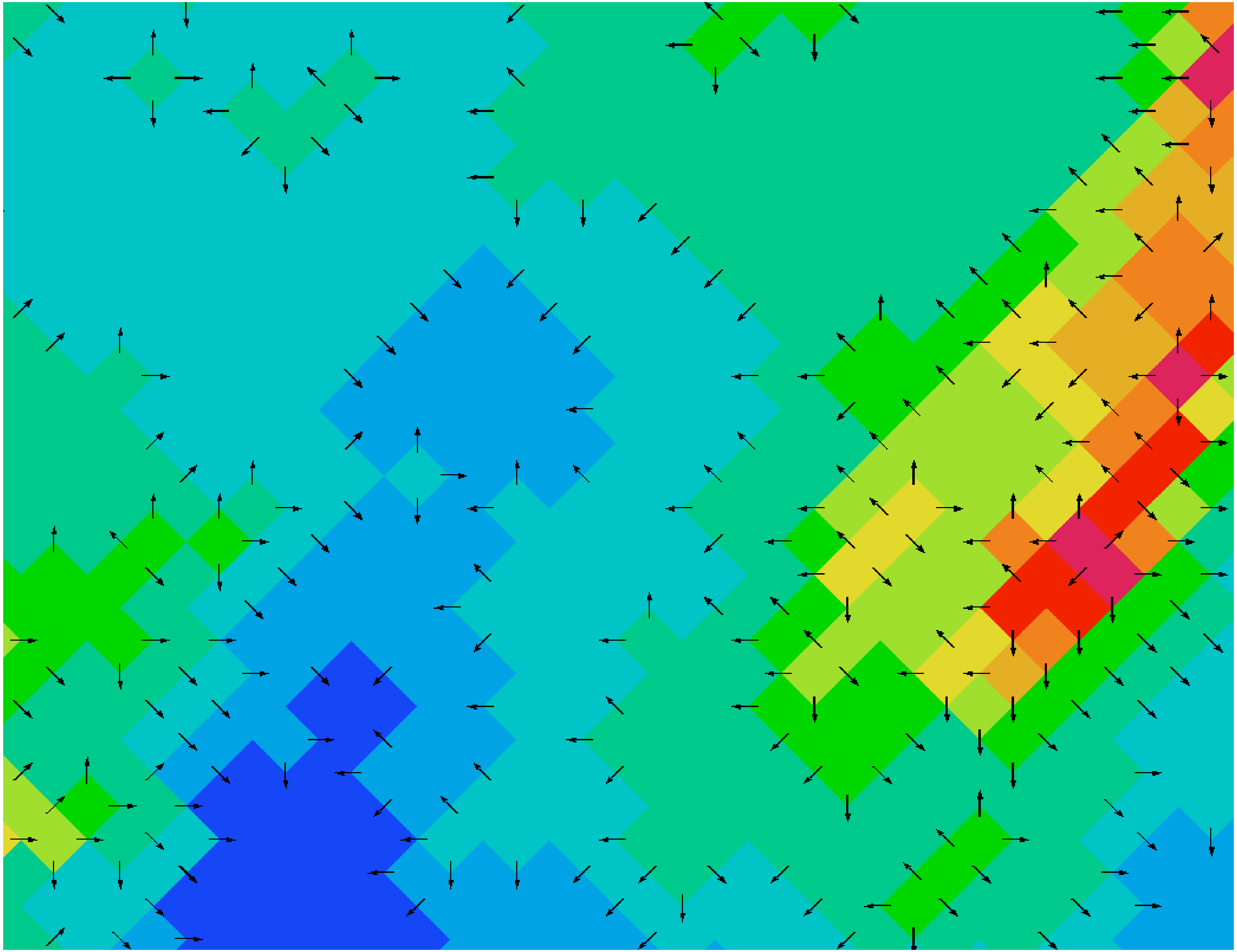
Horizontal treatment, 3D

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

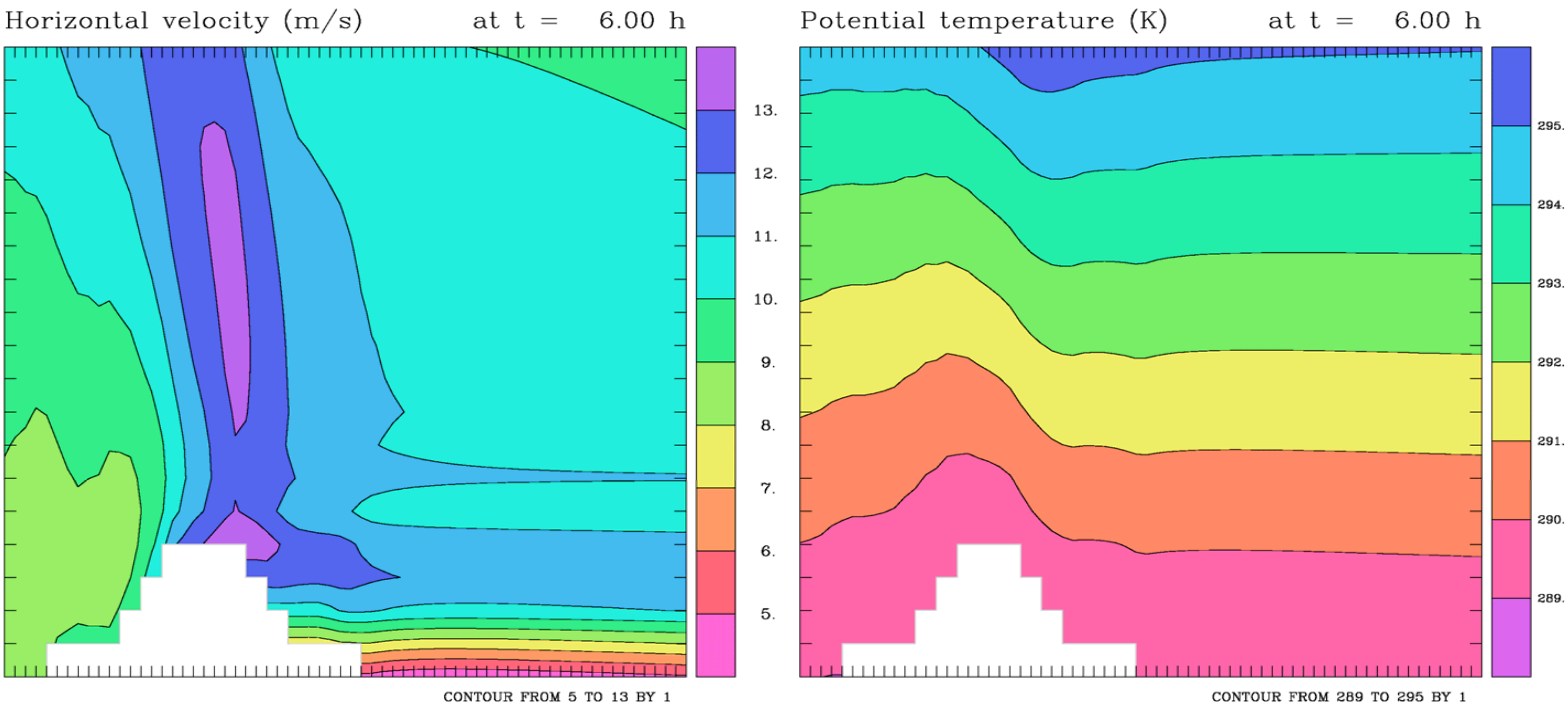
"Slope 1"



Inside the central **v** box, topography descends from the center of T1 box down by one layer thickness, linearly, to the centers of T2, T3 and T4



Slantwise advection of mass, momentum, and temperature, and "ωα":



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

Baldwin, M. E., and J. S. Kain, 2005: Sensitivity of several performance measures to displacement error, bias, and event frequency. *Wea. Forecasting* (in preparation).

Simmons, A. J., and D. M. Burridge, 1981: An energy and angular-momentum conserving vertical finite-difference scheme and hybrid vertical coordinates. *Mon. Wea. Rev*., **109**, 758-766.