The Eta Model Dynamics, Part II:

- Pressure-gradient force, eta coordinate;
- Finite volume vertical advection of **v**, T

1. Vertical coordinates with quasi-horizontal surfaces, e.g., eta:

Why?

The sigma system PGF problem

In hydrostatic systems:

$$-\nabla_p \phi \rightarrow -\nabla_\sigma \phi - RT\nabla \ln p_S$$

The way we calculate things, in models,

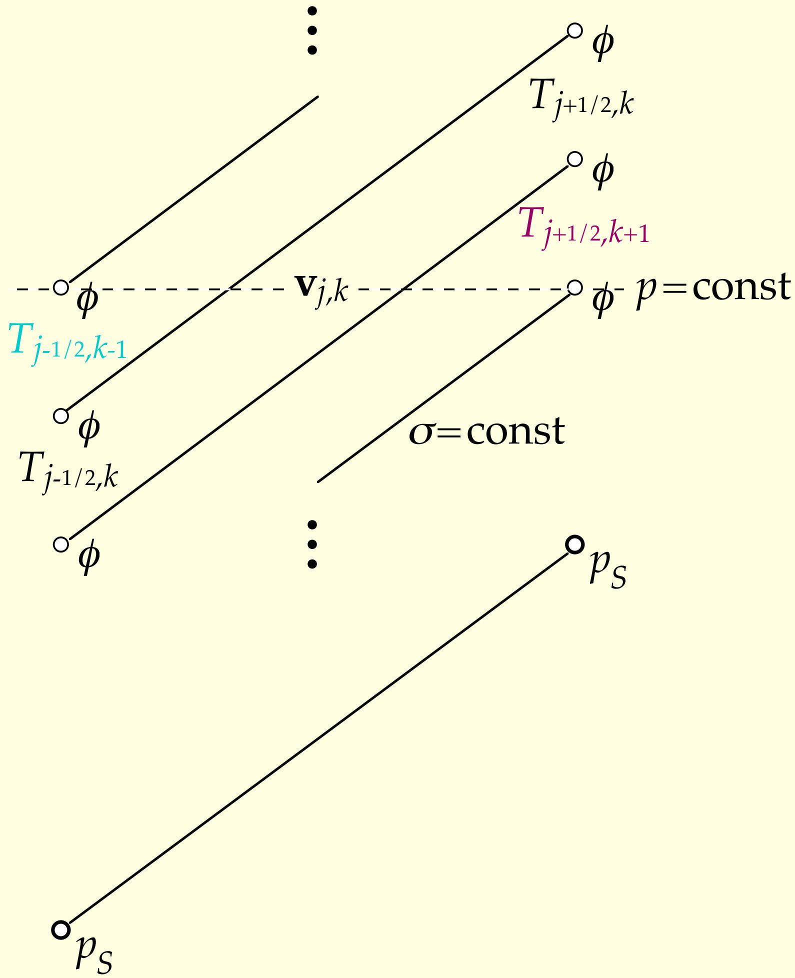
$$\phi = \phi_S - R_d \int_{p_S}^{p} T_v d \ln p$$

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

We could do the same integration from the top; but: we measure the surface pressure, thus, calculation "from the top" not an option !

In nonhydrostatic models: very nearly the same

Example, continuous case:
PGF should depend on,
and only on,
variables from the ground
up to the p=const surface:



The best type of sigma 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*.

Since the problem is one of missing information/ using information which should not be used: the error can be arbitrarily large !

- Can increased resolution help? If both vertical and horizontal increase at the same time, e.g., both doubled, no change. But if the steepness of the topography increases, which is a standard thing to do: it *gets worse* ! Thus: NO

- Can increased formal (Taylor series) accuracy help: NO

- Can reduction in the magnitude of the two PGF terms help? (Two "big" terms of opposite signs: subtract "reference atmosphere"): NO

Thus: vertical coordinate with quasi-horizontal surfaces!

Thus:

Norman Phillips (1957) "sigma":

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

(Arakawa ?)

Mesinger (1984) "eta":

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

“Step-topography” eta:

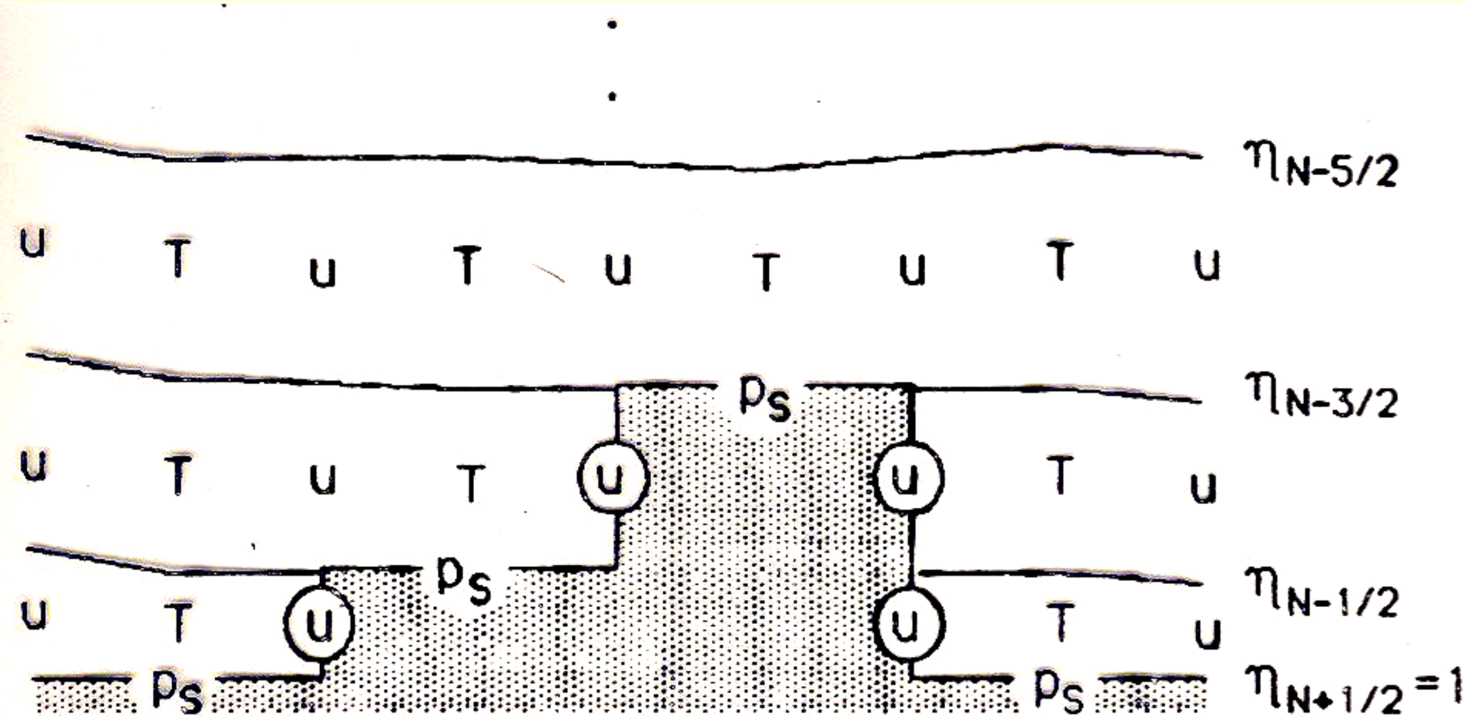


FIG. 1. Schematic representation of a vertical cross section in the eta coordinate using step-like representation of mountains. Symbols u, T and p_s represent the u component of velocity, temperature and surface pressure, respectively. N is the maximum number of the eta layers. The step-mountains are indicated by shading.

Downsides? #1:

Poor vertical resolution over higher topography? Well, OK, yes. But very high vertical resolution (sigma) not ideal either. Hybrid vertical coordinates (moving to pressure faster than with simple sigma): things are improved around the troposphere and higher up, but layers over high topography get thinner still.

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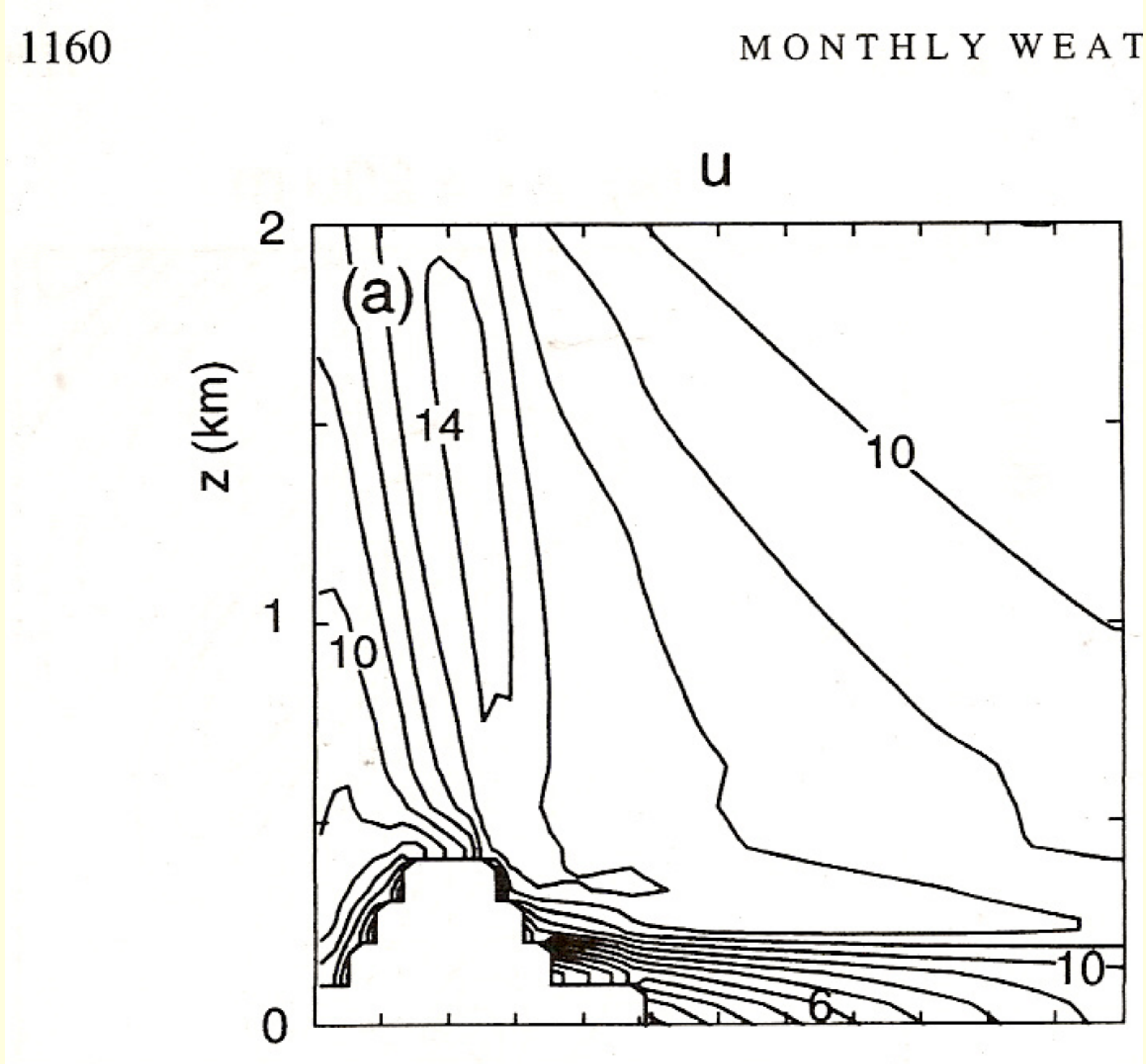
#2:

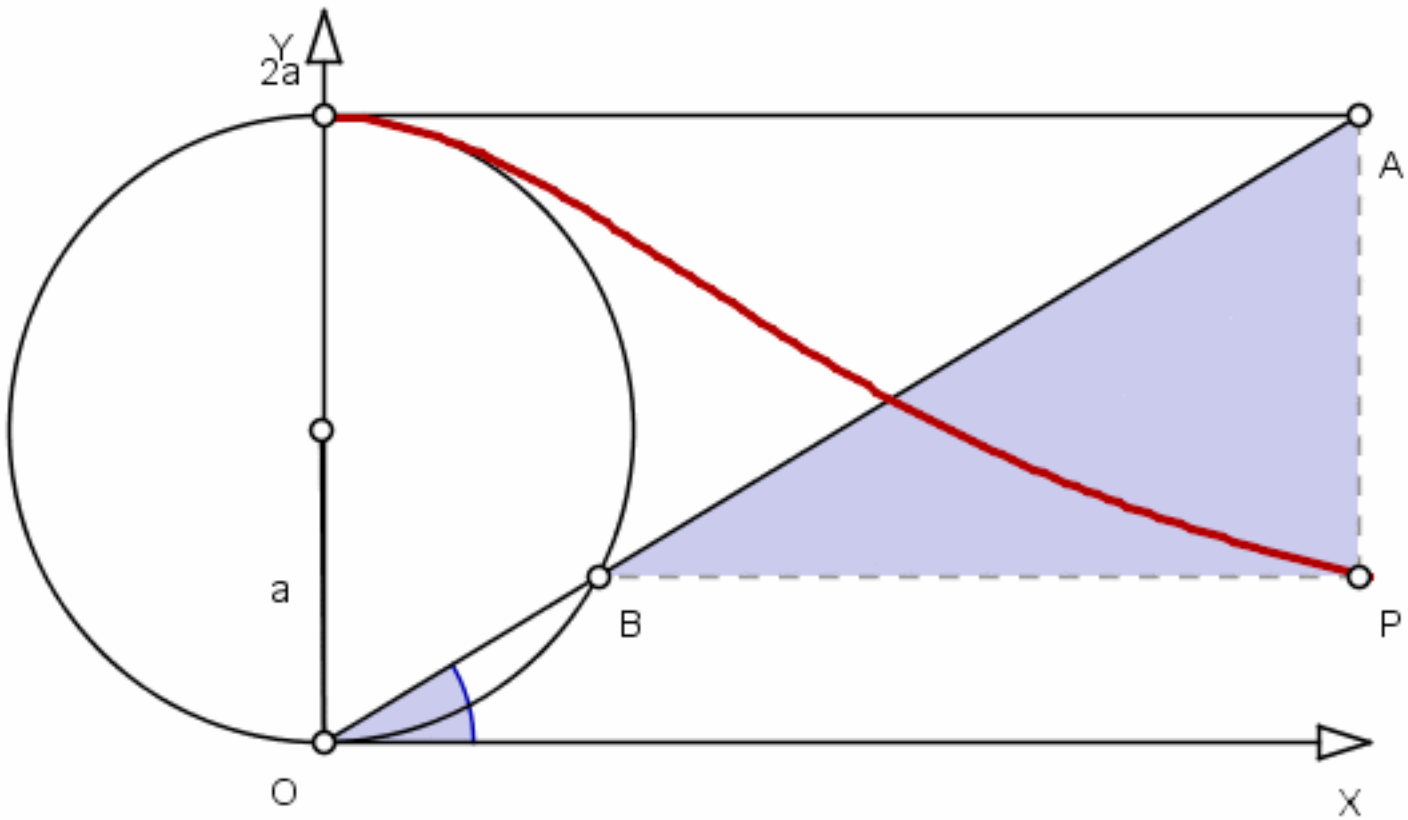
The flow down the slopes noticed to have been in some situations not realistic – tendency for flow separation. Wasatch downslope windstorm, Gallus, Klemp (MWR 2000), a case of Santa Ana wind. But a zonda case (Conf. Southern Hem. Meteor. Ocean. 1966, another later here) done adequately.



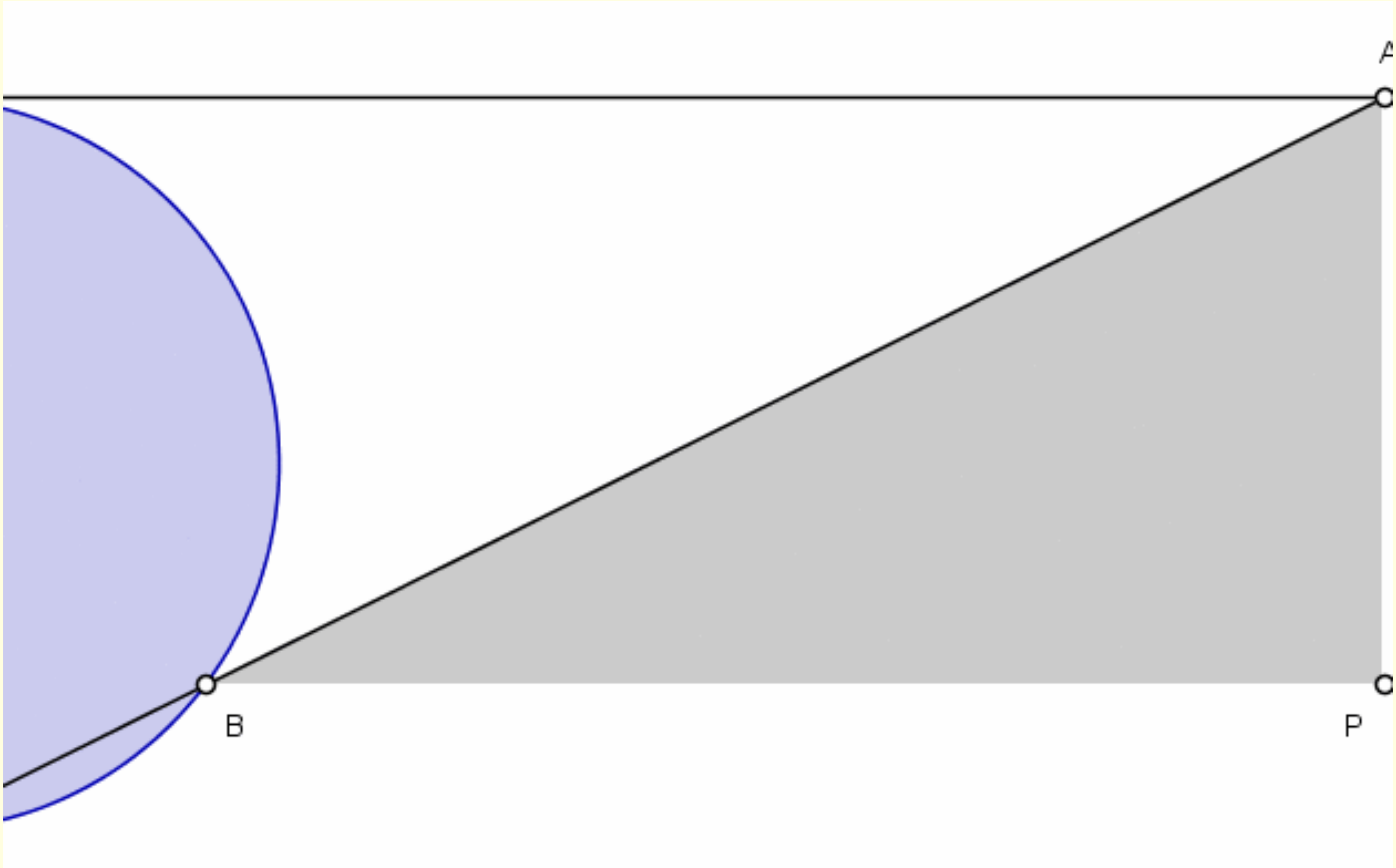
Gallus, Klemp, MWR 2000, Fig. 6 (a), horizontal velocity

("Witch of Agnesi" mountain)

"Witch of Agnesi":

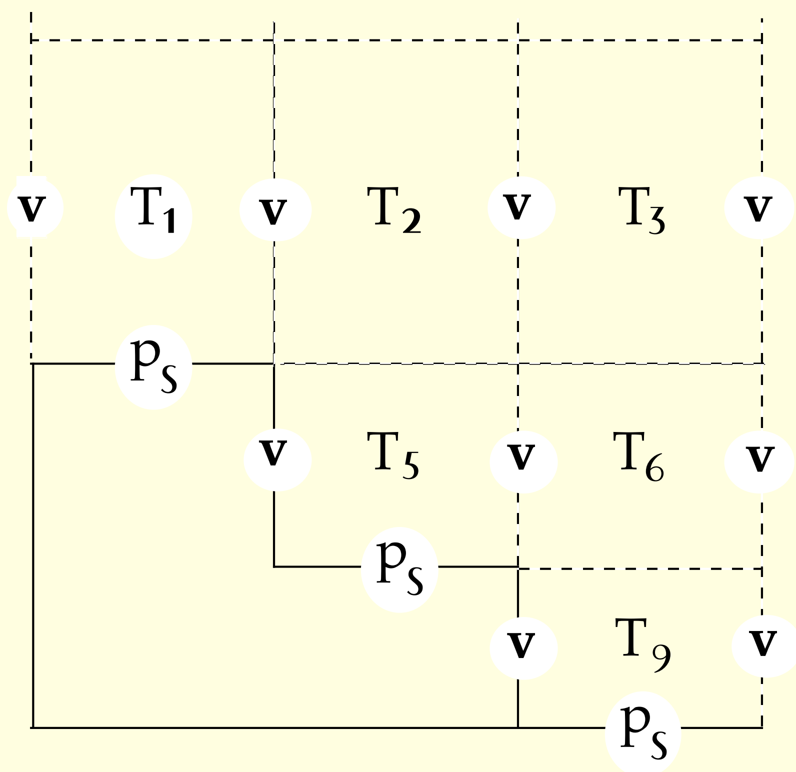


Acklowledgement: Wikipedia, Merrill



Studied by: Pierre de Fermat, 1630, Guido Grandi, 1703, Maria Agnesi, 1748
In Italian: la versiera di Agnesi ("the curve of Agnesi")
Cambridge professor John Colson: "l'avversiera di Agnesi" ("woman contrary to God"), identified as "witch", mistranslation stuck !

Suggested explanation



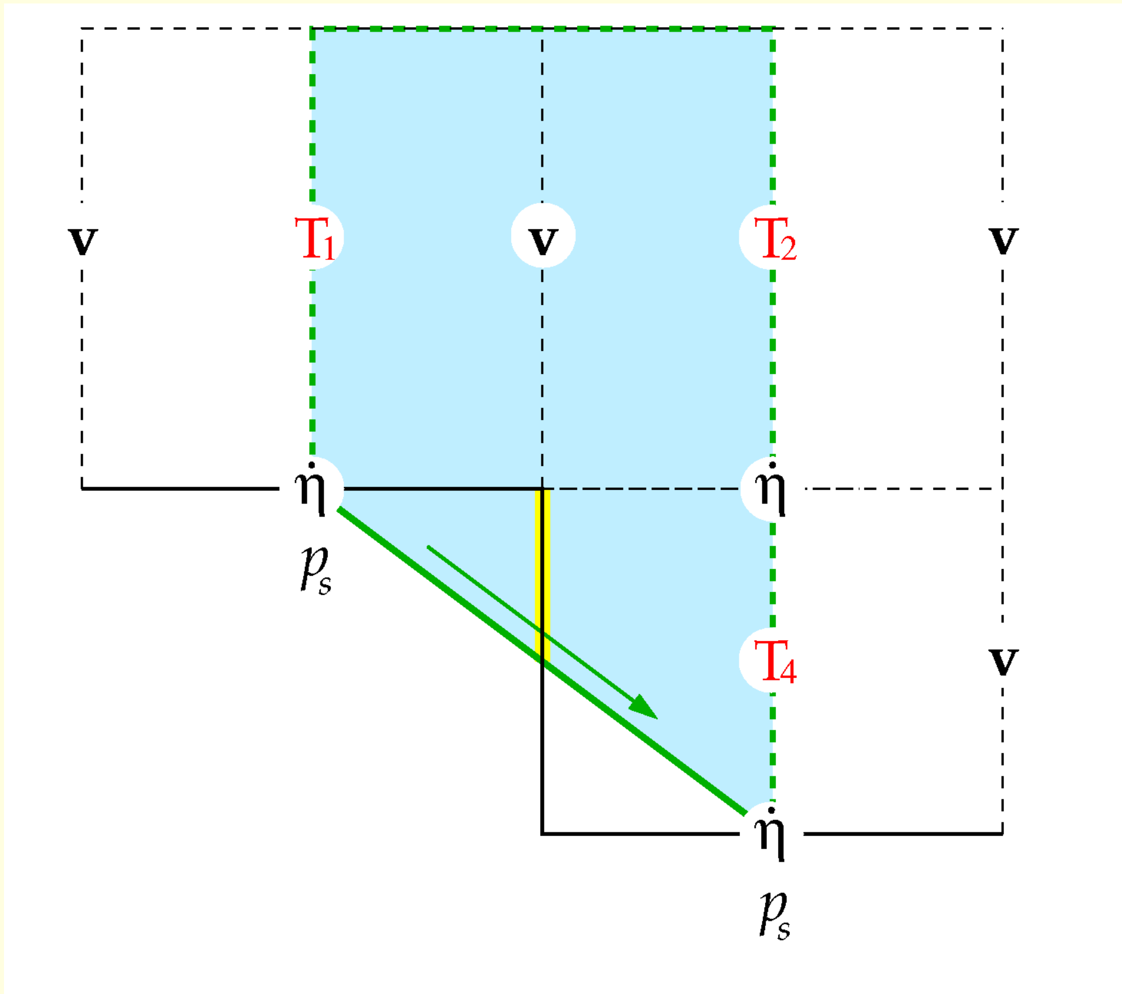
Flow attempting to move from box 1 to 5 is forced to enter box 2 first.

Missing: slantwise flow directly from box 1 into 5 !

As a result: some of the air which should have moved slantwise from box 1 directly into 5 gets deflected horizontally into box 3.

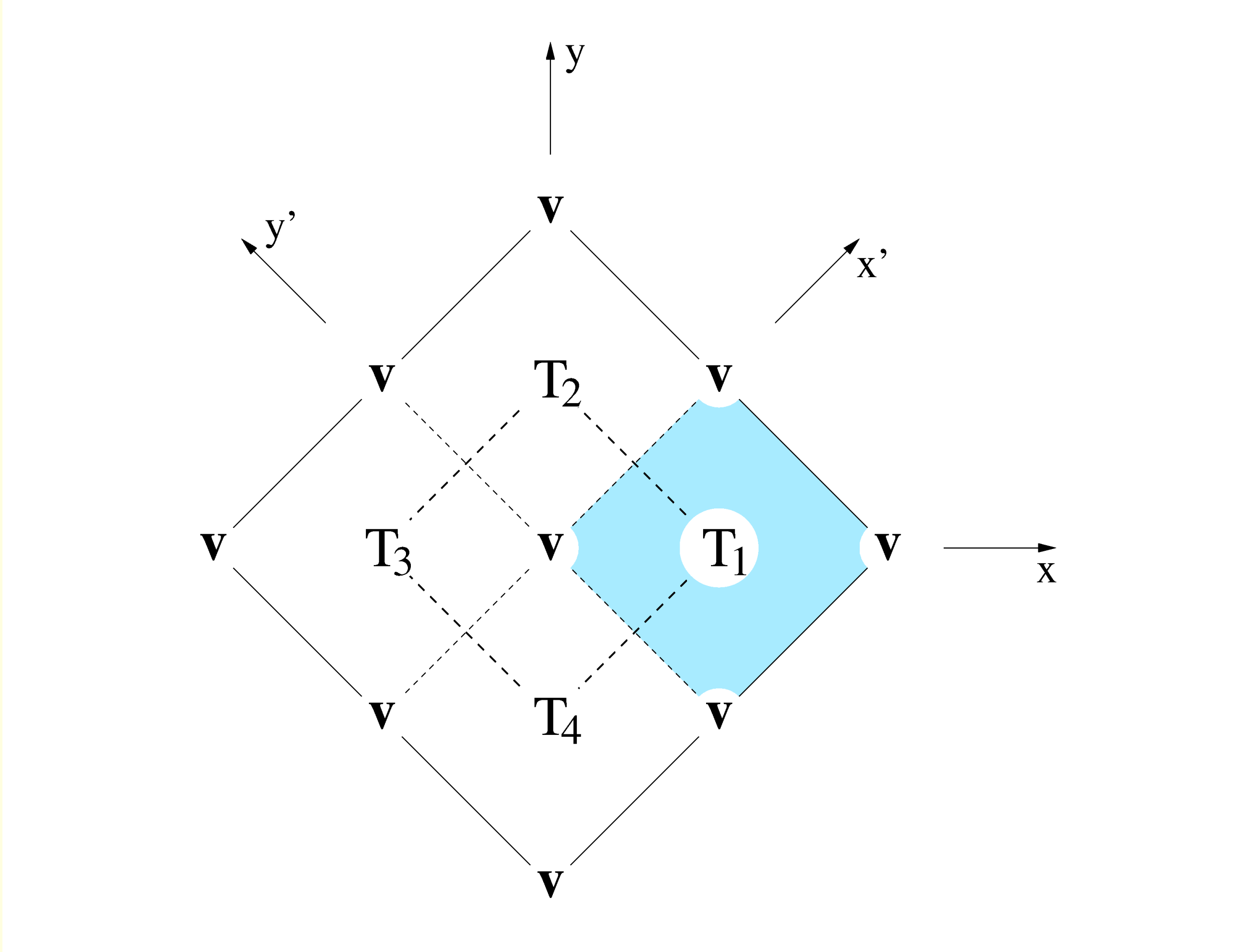
Remedy: The sloping steps, vertical grid

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



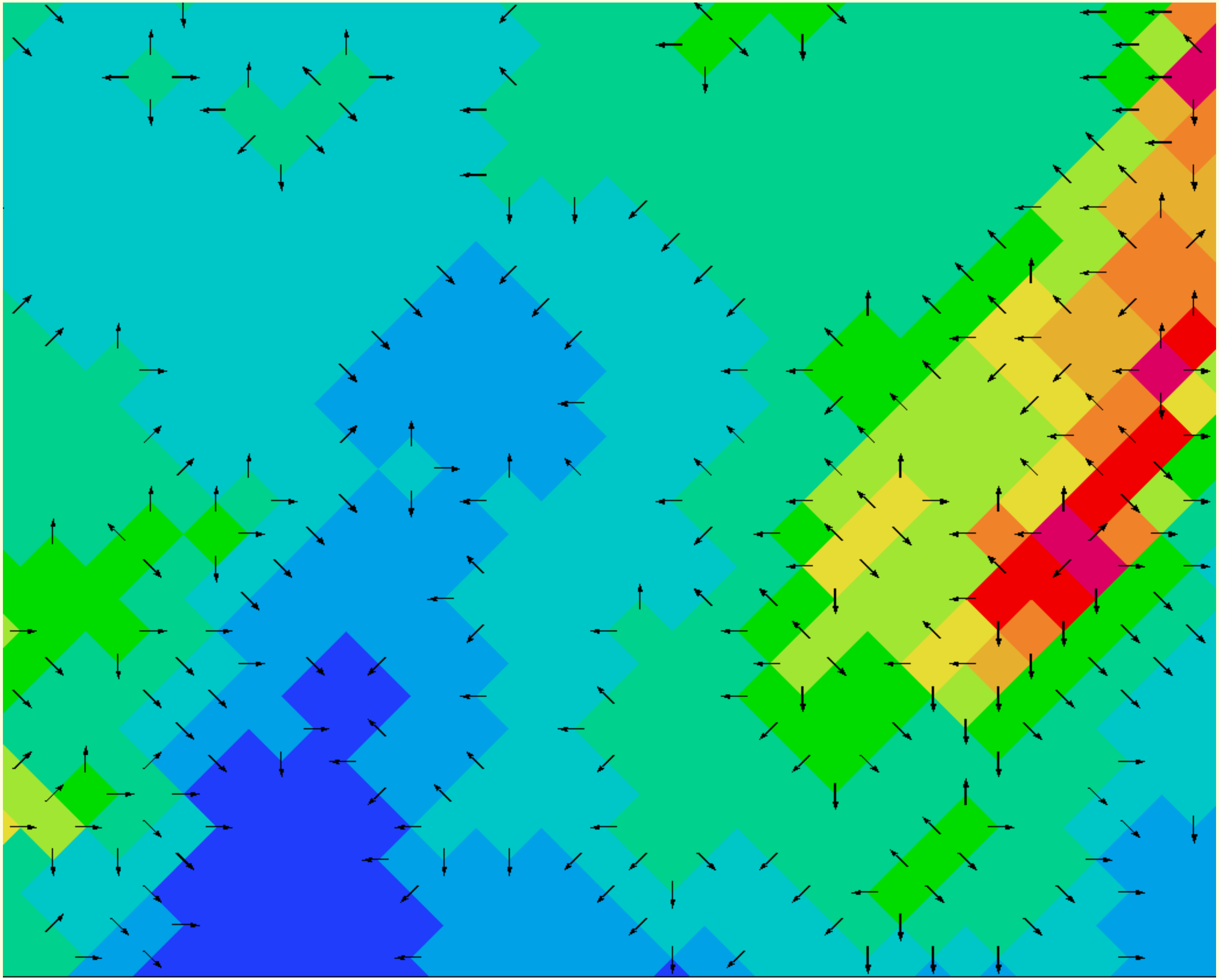
Horizontal treatment, 3D

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



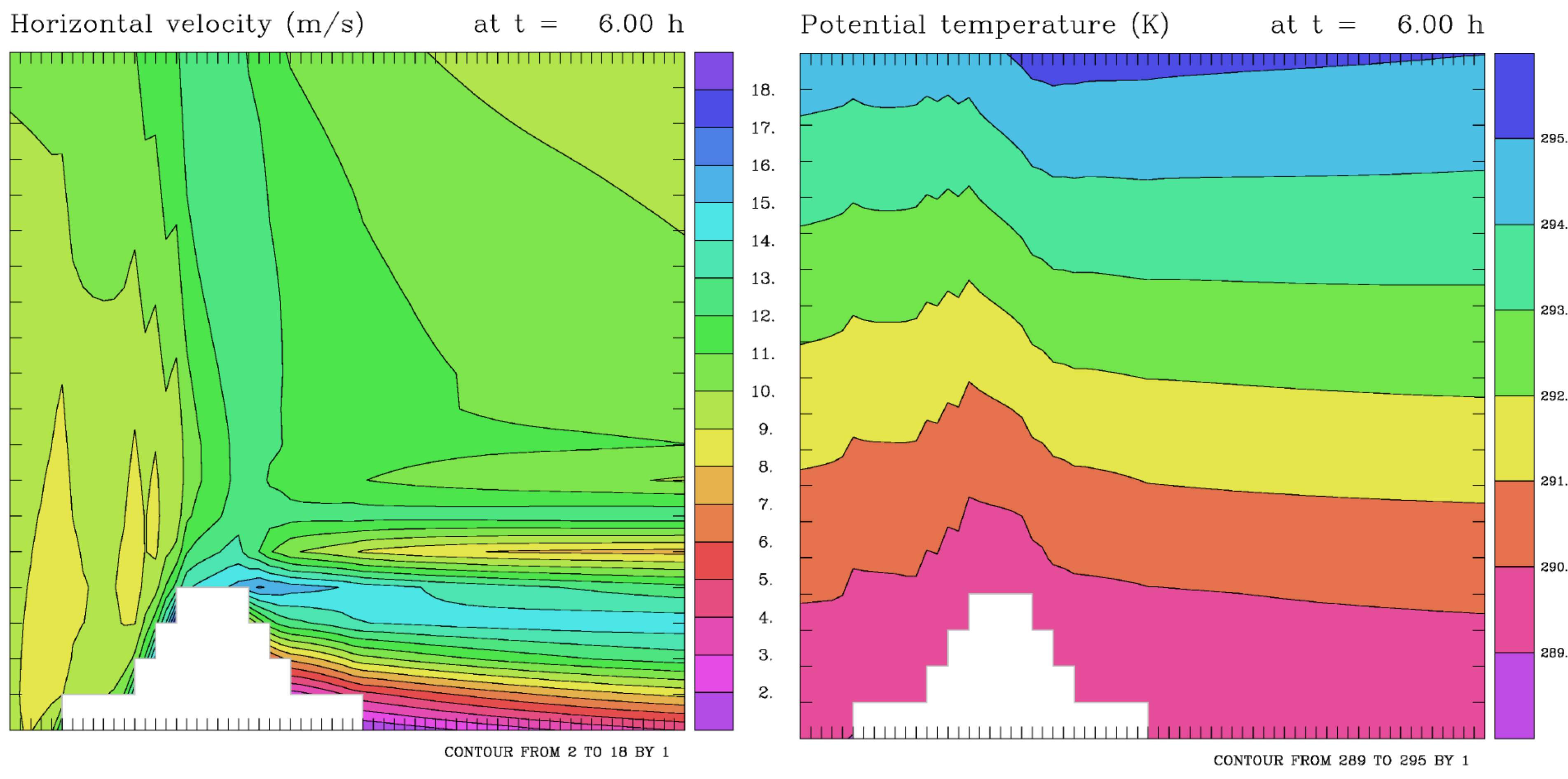
Inside the central **v** box, topography descends from the center of T1 box down by one layer thickness, linearly, to the centers of T2, T3 and T4

Example of slopes with an actual model topography:

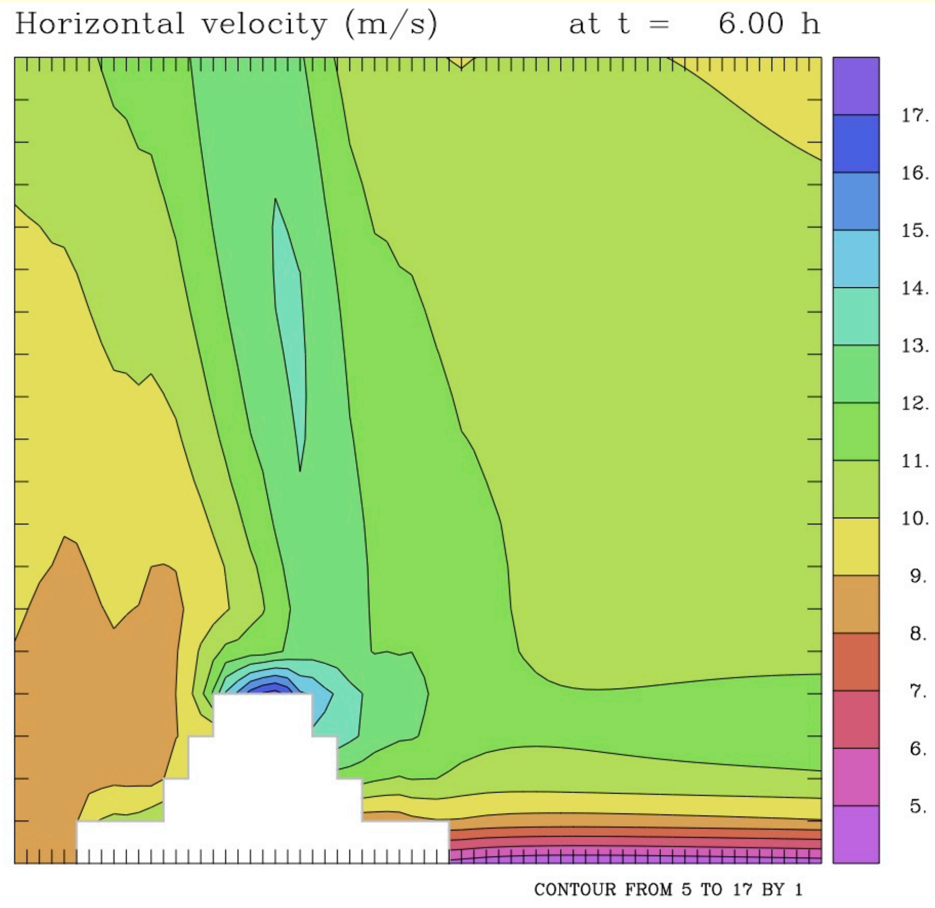


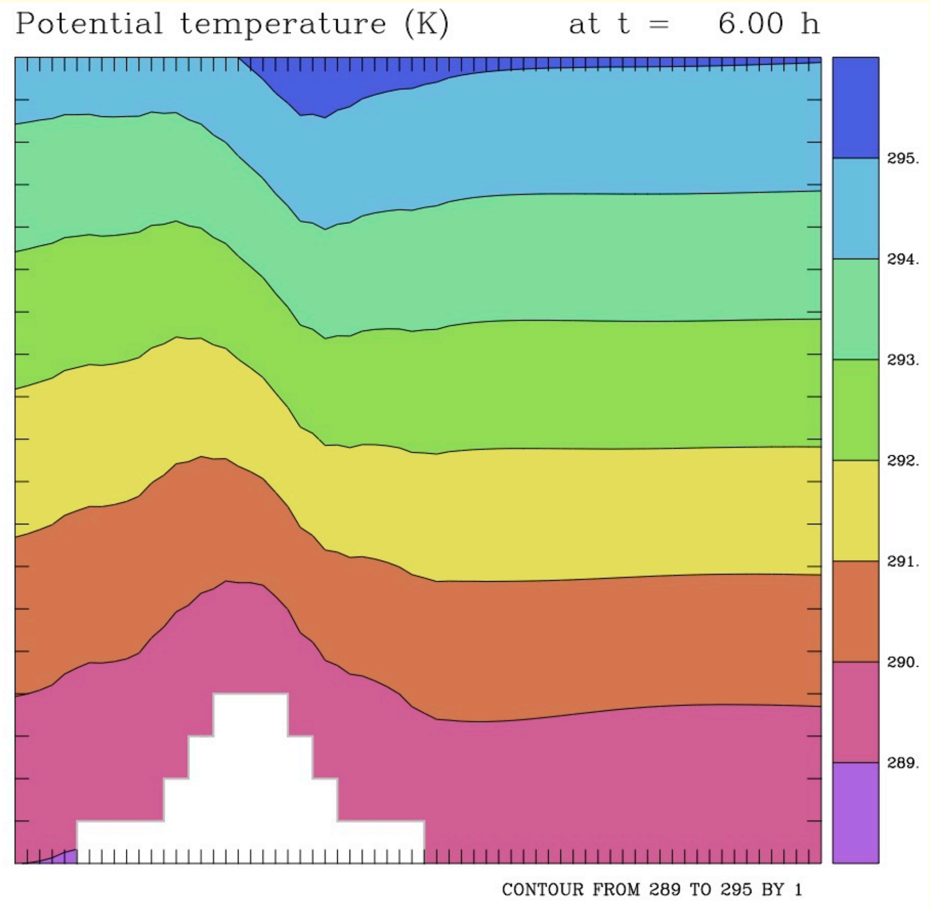
The Eta Problem: before

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



After: Emulation of the Gallus-Klemp experiment, Sloping steps code ("poor-man's shaved cells"), corrected:





Velocity at the ground immediately behind the mountain increased from between 1 and 2, to between 4 and 5 m/s. "lee-slope separation" much reduced. Zig-zag features in isentropes at the upslope side removed.

A real data experiment:

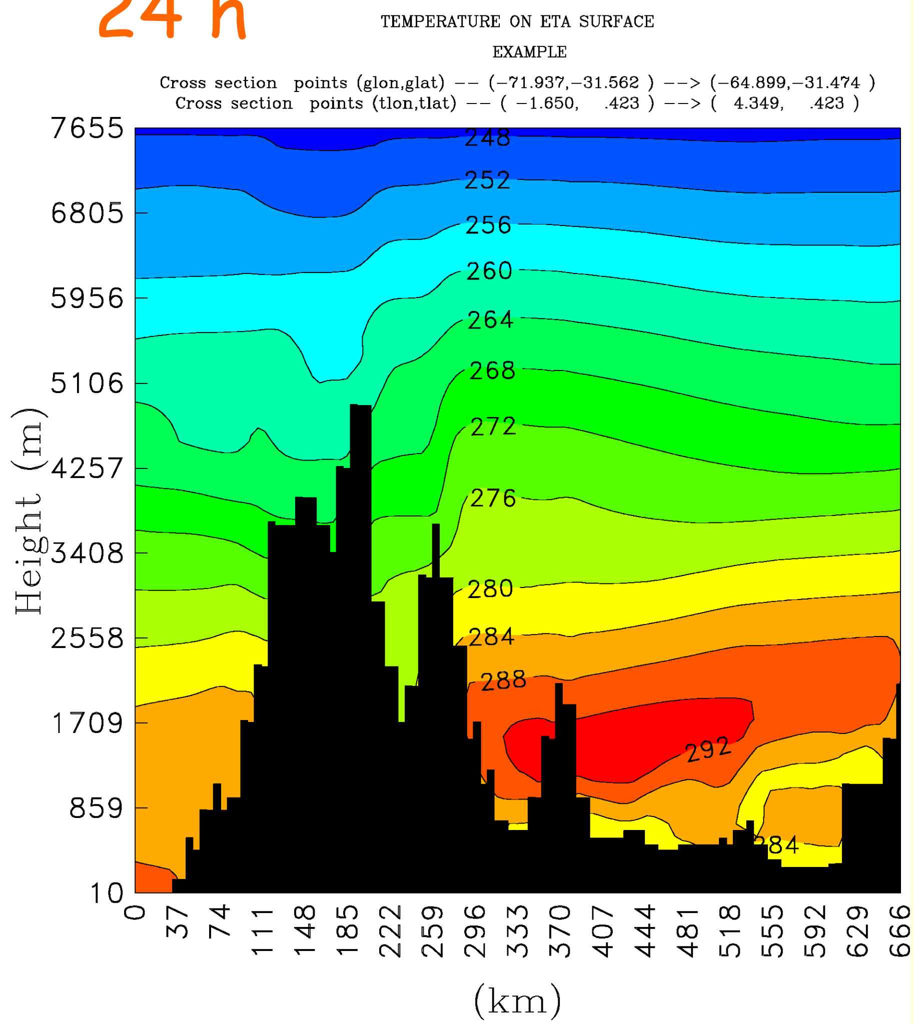
Zonda case of 11-12 July 2006

Acknowledgement:

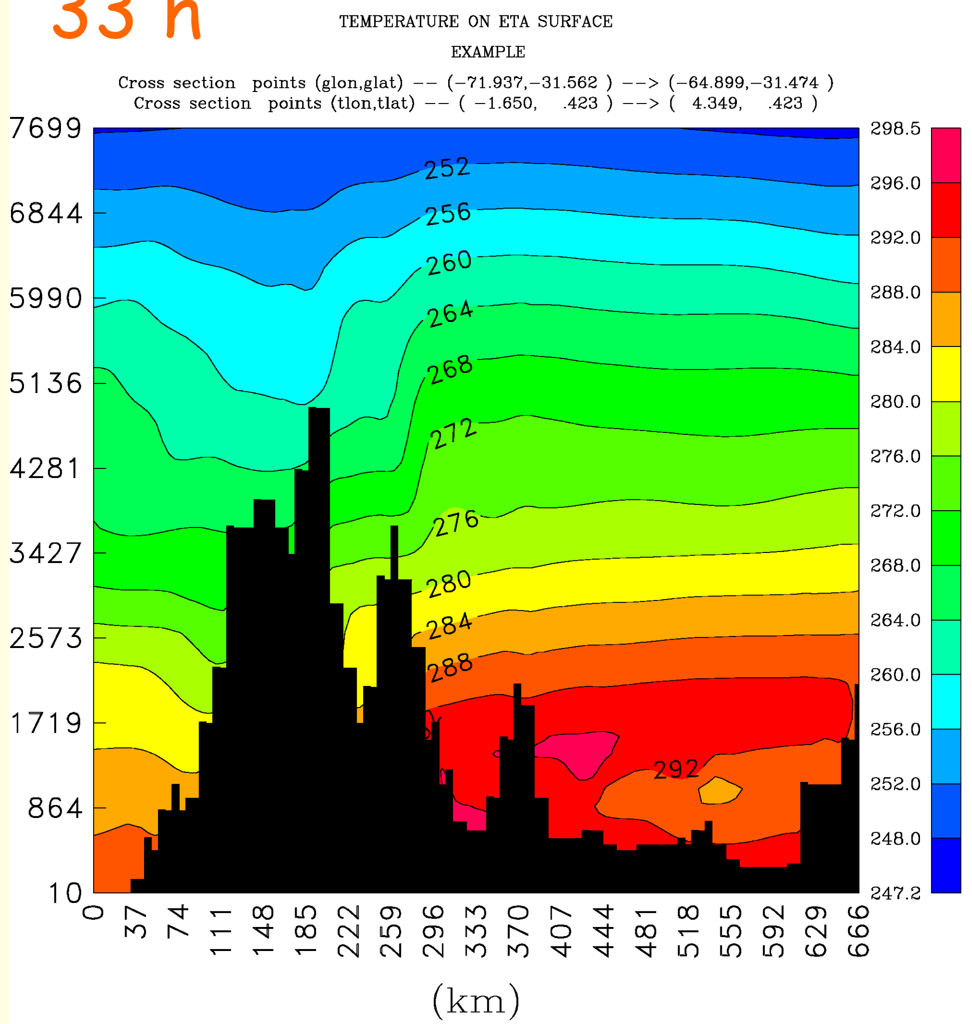
. . .

Initial condition: 1200 UTC 10 July 2006

24 h



33 h



T change in the San Juan area from < 284 K to > 296 K !

- Benefit from the quasi-horizontal, e.g., eta, vs sigma coordinate:

Quite a few (4-5?) tests using the switch eta/ sigma.

All very convincingly favoring the eta !

The very first:

Sigma Eta

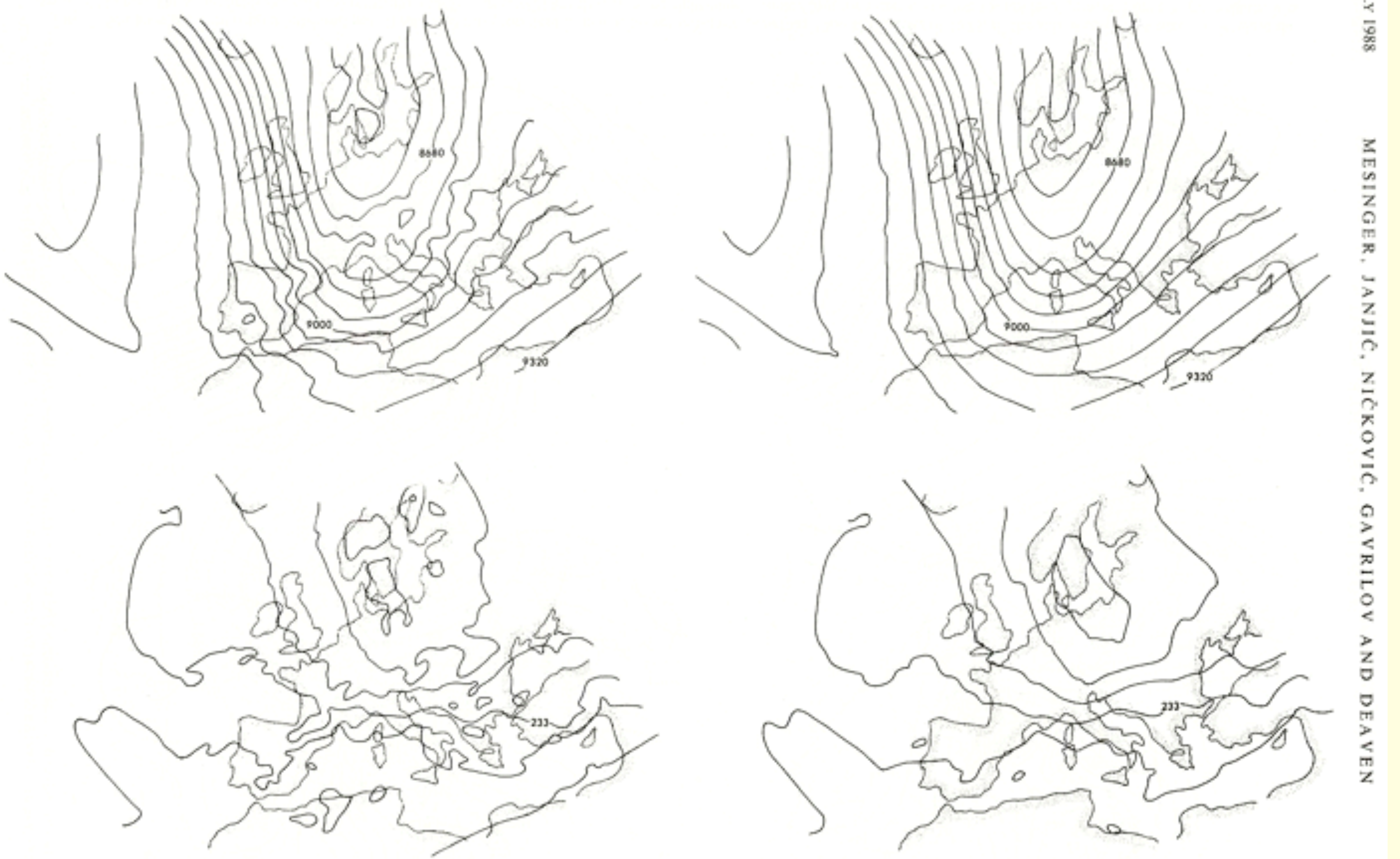


FIG. 6. 300 mb geopotential heights (upper panels) and temperatures (lower panels) obtained in 48 h simulations using the sigma system (left-hand panels) and the eta system (right-hand panels). Contour interval is 80 m for geopotential height and 2.5 K for temperature.

Some addressing precipitation scores, e.g.,

André Robert Memorial Volume:

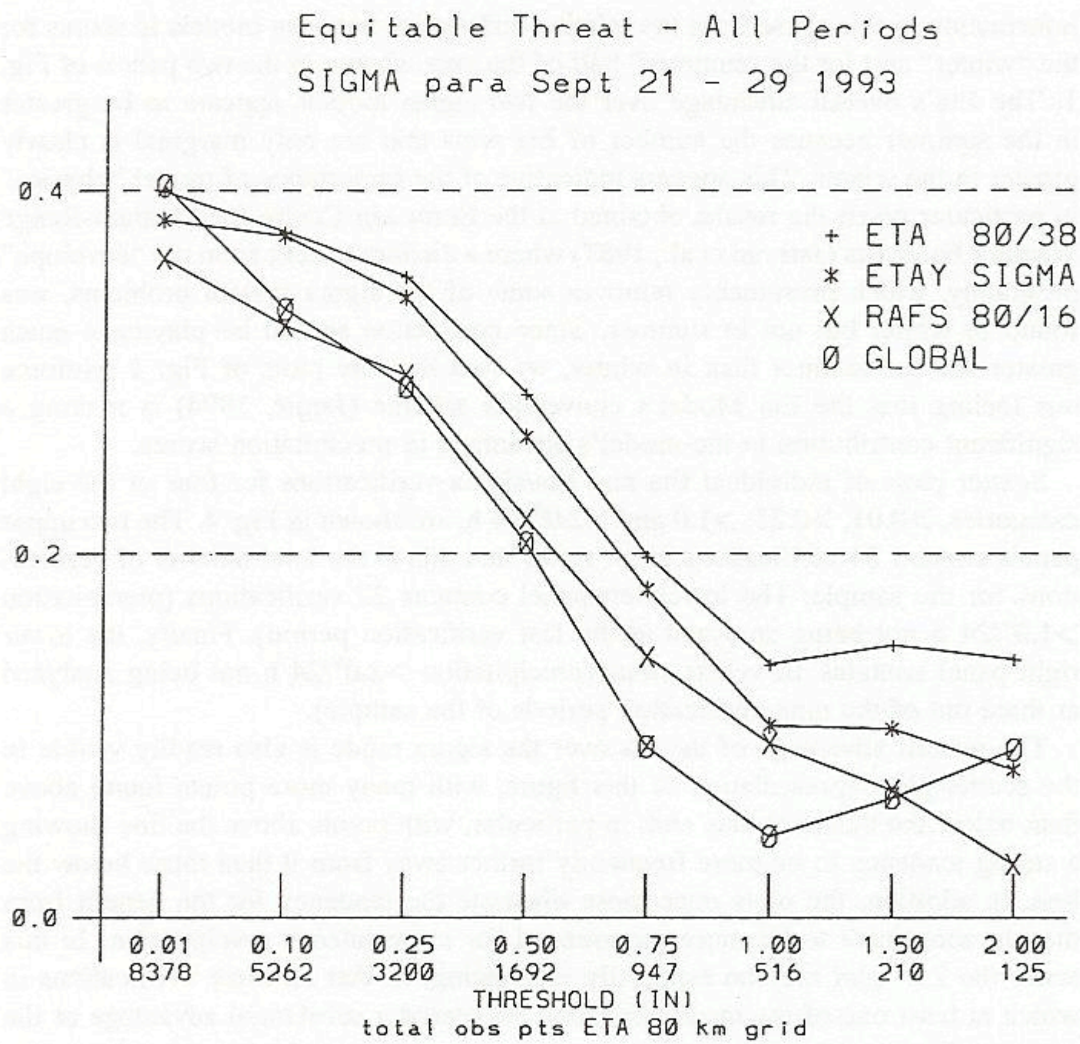


Fig. 3 Equitable precipitation threat scores for two versions of the Eta Model: Eta 80 km/38 layers ("ETA"), and the same version of the Eta Model but run using sigma coordinate ("ETAY"), and for the NGM (RAFS), and the Avn/MRF ("global") Model; for a sample of 16 forecasts verifying 1200 UTC 21 September 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.

Note also:

Russell, G. L., 2007: Step-mountain technique applied to an atmospheric C-grid model, or how to improve precipitation near mountains. *Mon. Wea. Rev.,* **135**, 4060–4076.

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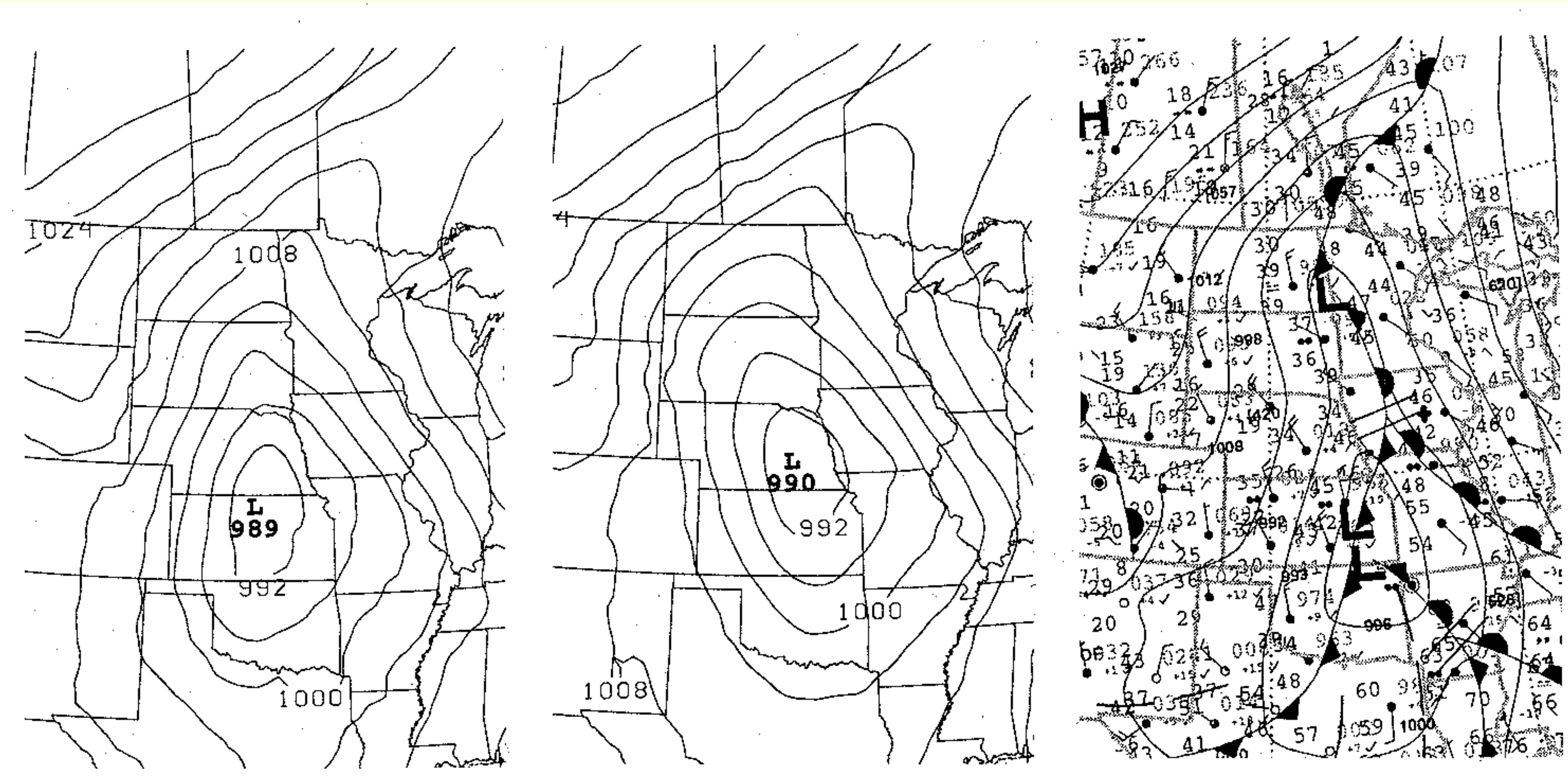
A number of tests on positions of low centers, such as in the lee of the Rockies… The most recent one:

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

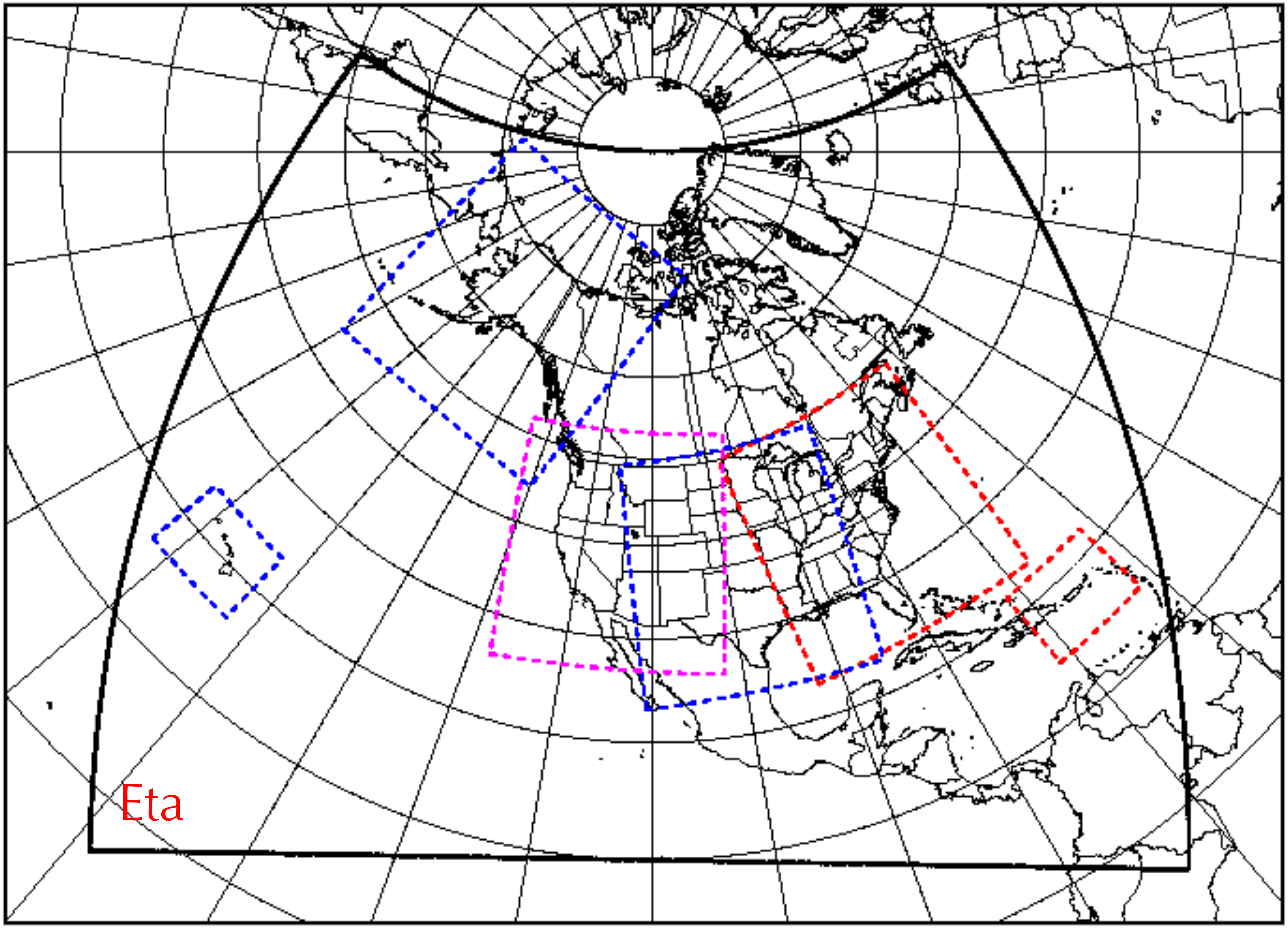


~ Just as in earlier experiments at lower resolution

Examples which are not clear tests of one or the other feature, but for which it can be hopefully **convincingly argued** that the main contribution to the success **does come from one (the quasi-horizontal coordinate) or both of the preceding features**:

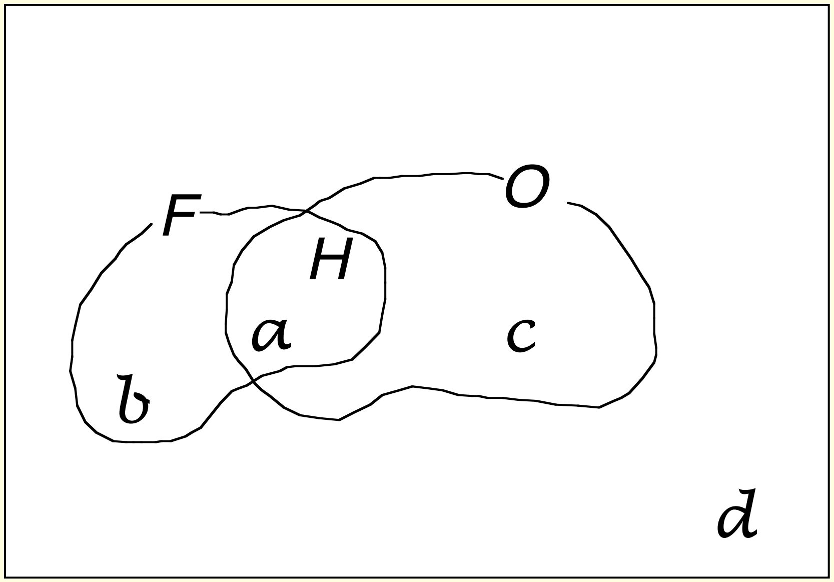
• Precipitation scores. Not a direct test, but in *many* comparisons over the years the Eta at NCEP was *each time* outperforming NCEP's sigma system models, over land. Examples: the last 12 months of three model scores: GFS, NMM, Eta (in Mesinger 2008), Parellel: Eta system/ NMM system;

• The three low centers case;



Nested Meso-08 Domains

Forecast, Hits, and Observed (*F*, *H*, *O*) area,
or number of model grid boxes:



Most popular "traditional statistics":
ETS (Equitable Threat Score), Bias:

$$ETS = \frac{H - FO/N}{F + O - H - FO/N}$$

$$Bias = F/O$$

Problem: what does the ETS tell us ?

"The higher the value, the better the model skill is for the particular threshold"

(a recent MWR paper)

? ?

An apparently popular view, but in fact wrong, since ETS can be increased by increasing the bias beyond unity

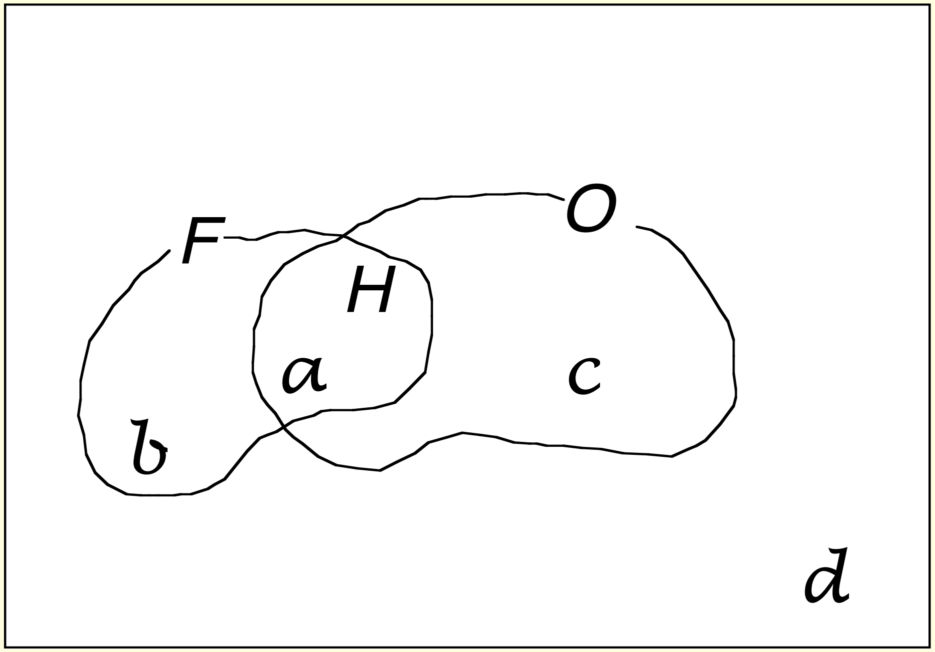
Methods to correct for bias:

Hamill, T. M.: 1999: Hypothesis tests for evaluating numerical precipitation forecasts. Wea. Forecasting, 14, 155–167;

Mesinger, F., 2008: Bias adjusted precipitation threat scores. *Adv. Geosciences*, **16**, 137-143. [Available online at http://www.adv-geosci.net/16/137/2008/adgeo-16-137-2008.pdf.]

"dHdA" method:

F : forecast,
H : correctly forecast: "hits"
O : observed



Assume as F is increased by dF, ratio of the infinitesimal increase in H, dH, and that in false alarms $dA=dF-dH$, is proportional to the yet unhit area:

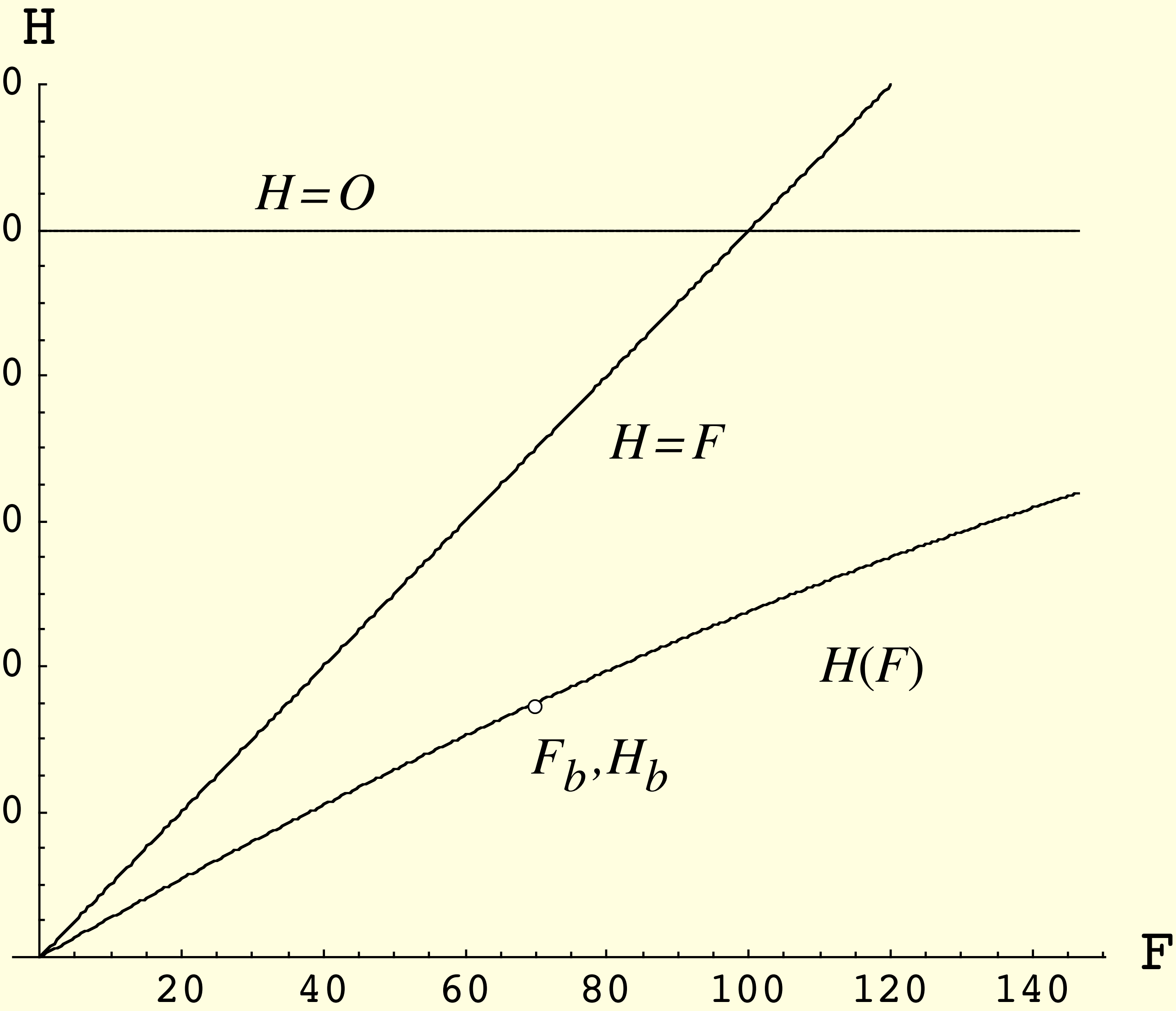
$$\frac{dH}{dA} = b(O - H) \qquad b = const$$

Differential equation, can be solved

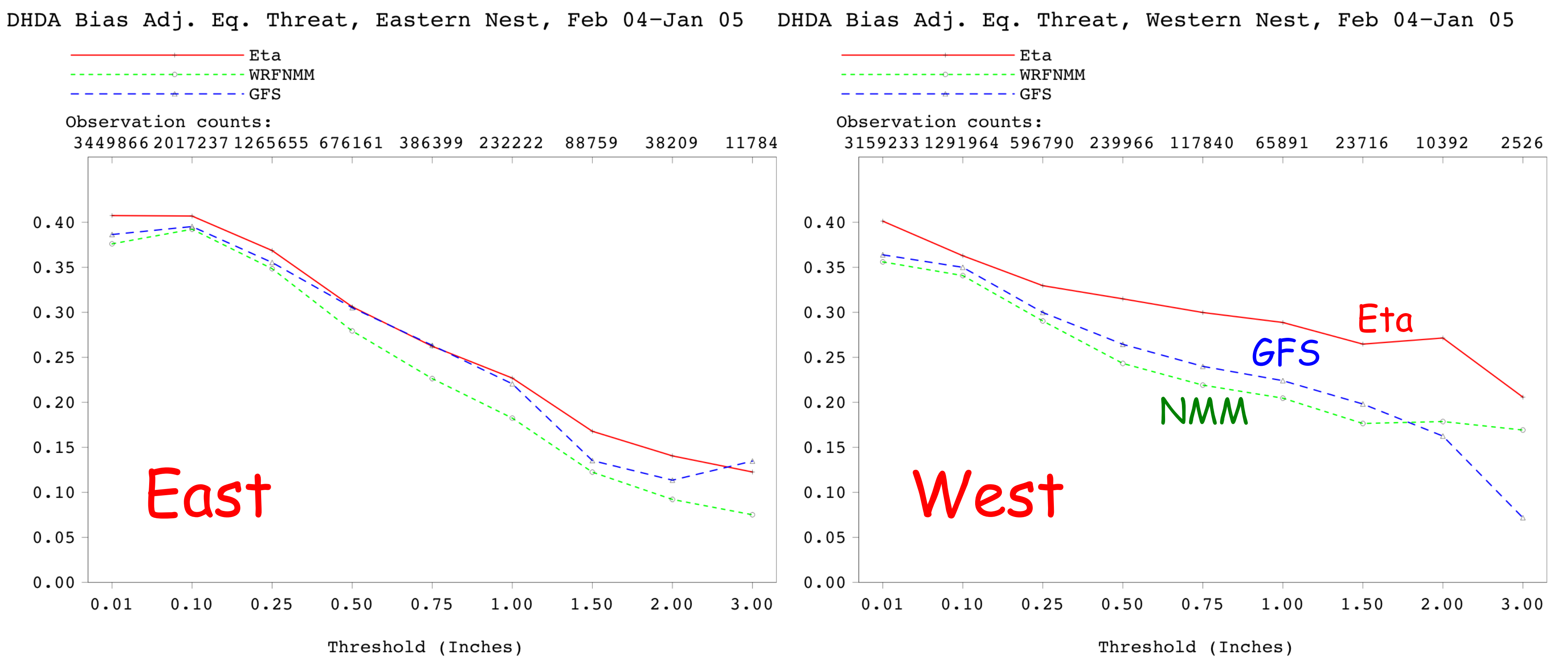
(Mathematica, or MATLAB)

$H(F)$ obtained that now satisfies an additional requirement of dH/dF never > 1

dHdA method



ETS corrected for bias



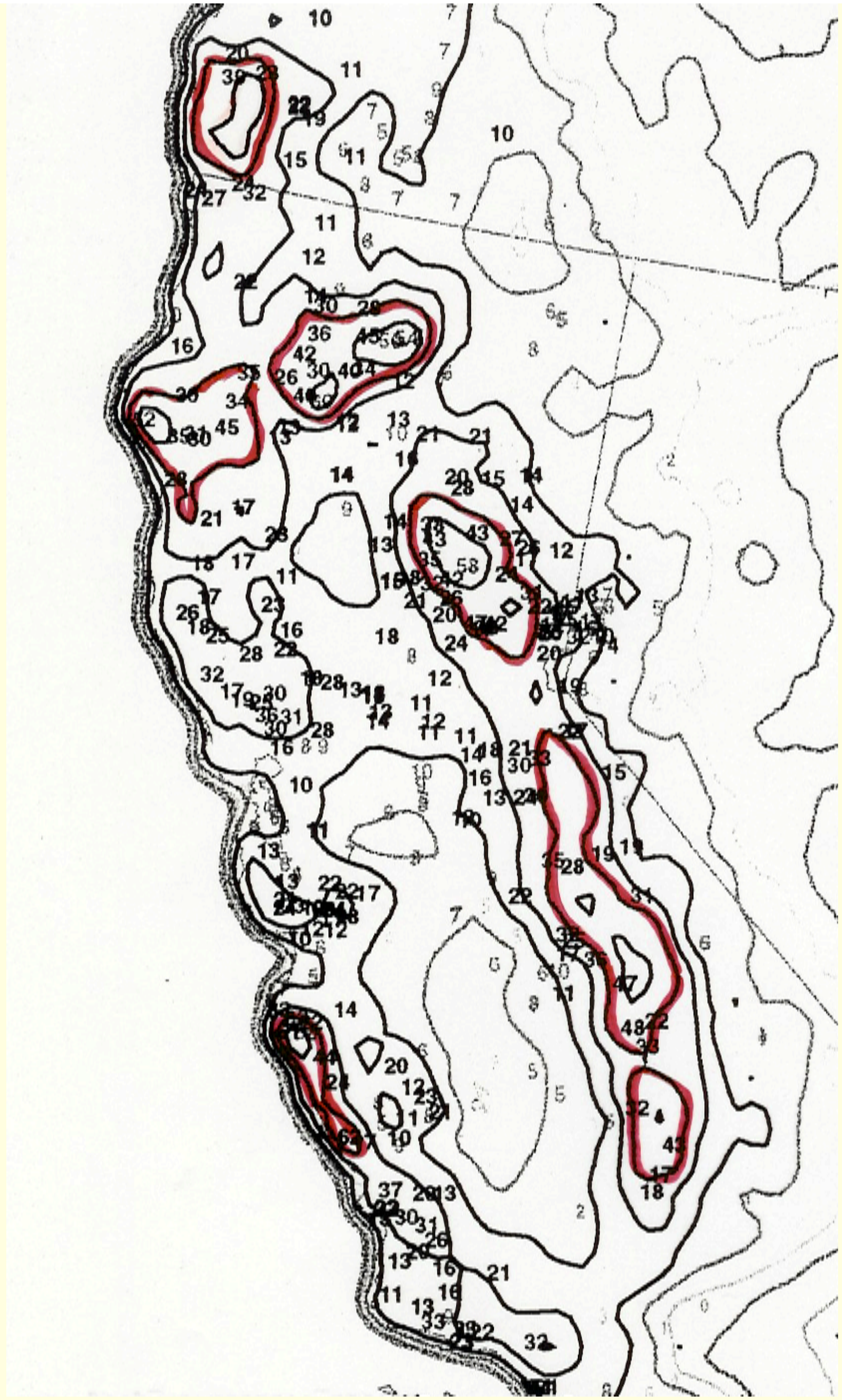
Correction for bias: Mesinger (Adv. Geosci. 2008): In order to obtain score that verifies placement of precipitation !

An example of precip at one of such events:

(8 Nov. 2002,

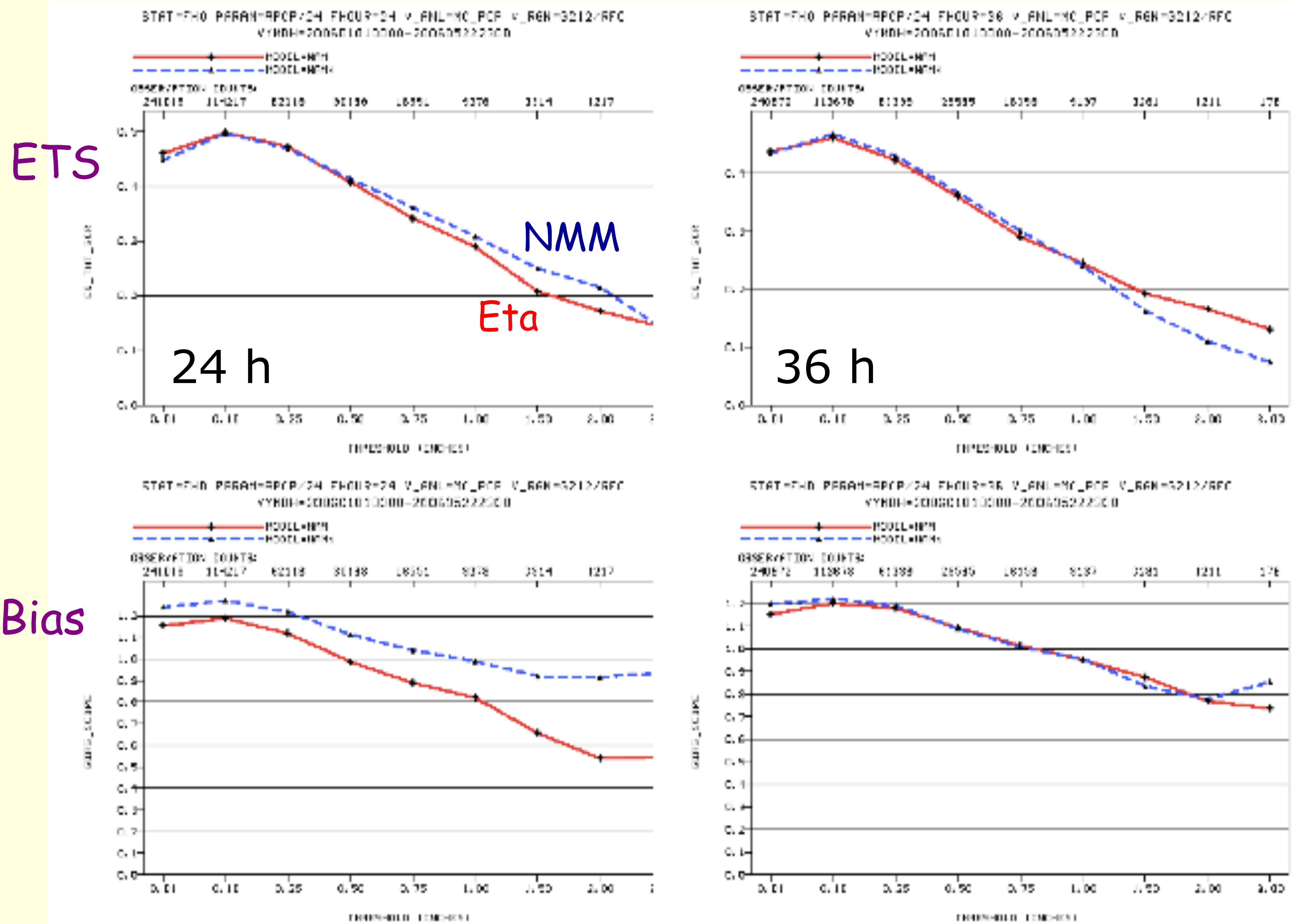
red contours: 3 in/24 h)

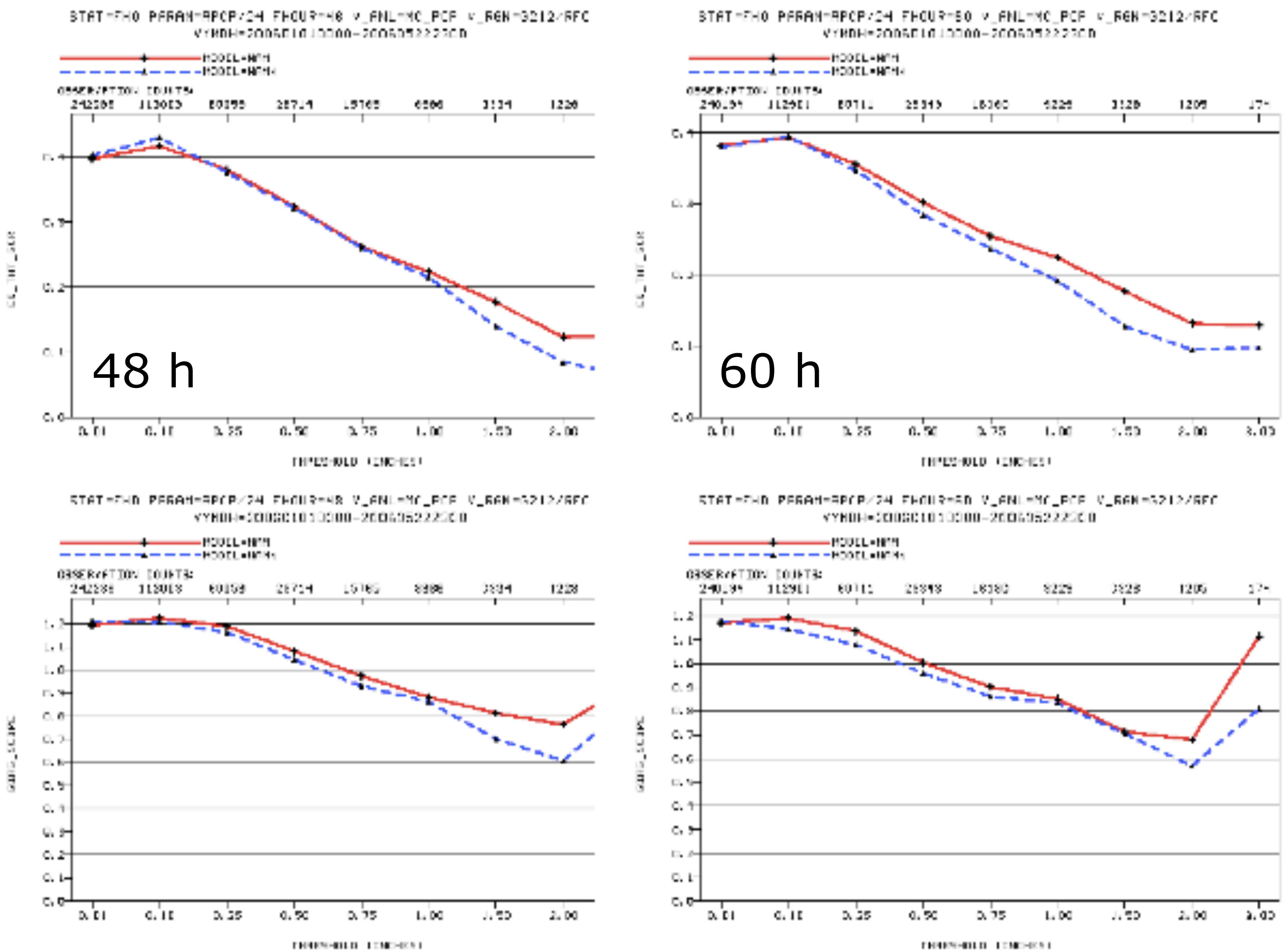
An extraordinary challenge to do well in QPF sense !

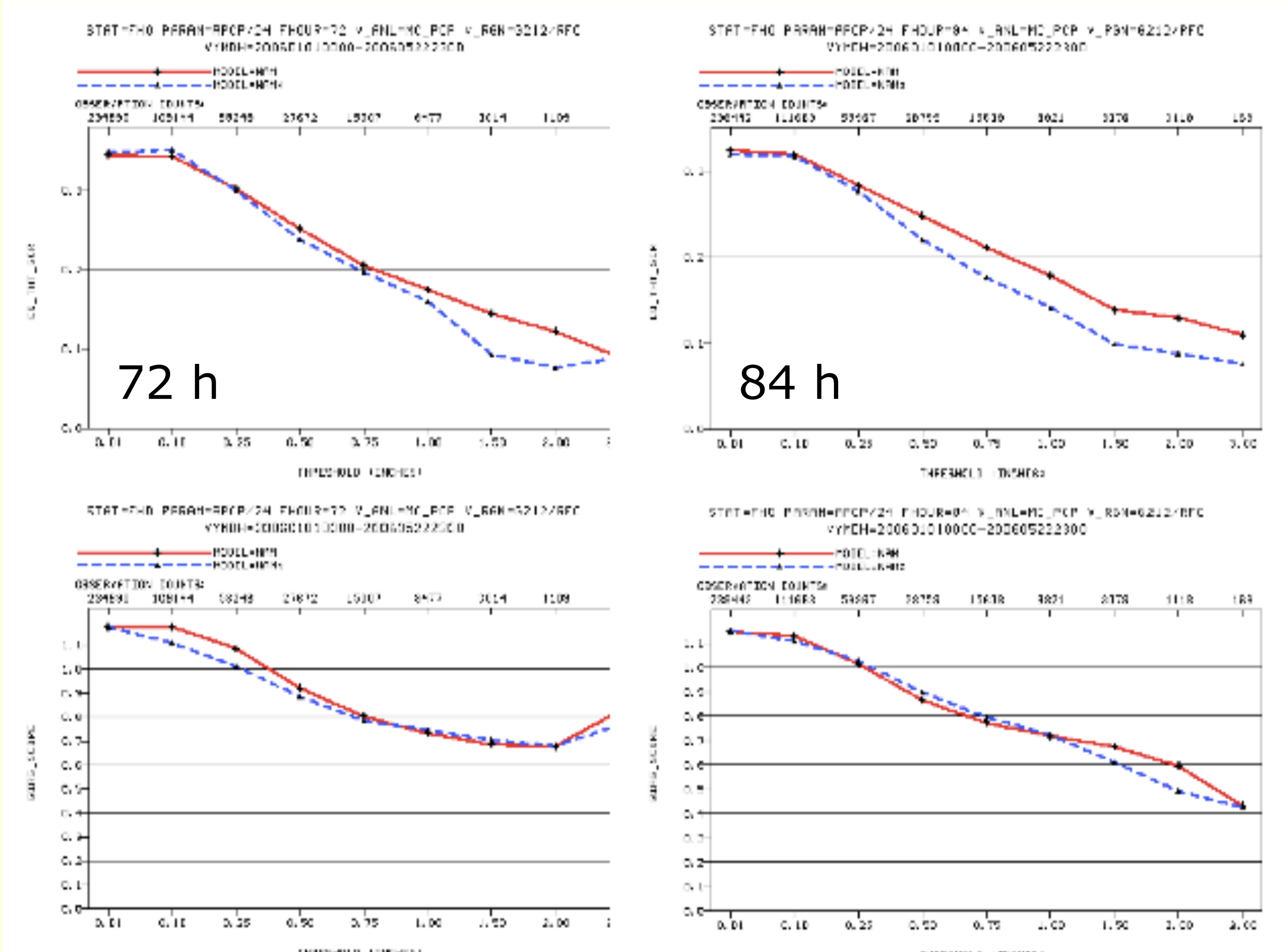


More recent results – comparison of Eta against the WRF-NMM, but with WRF-NMM using a new data assimilation system (from DiMego 2006)

Unfortunately, no correction for bias – not needed if biases are about the same


ETS
NMM
Eta
24 h
36 h
Bias


48 h
60 h



(From DiMego 2006)

The three low centers case

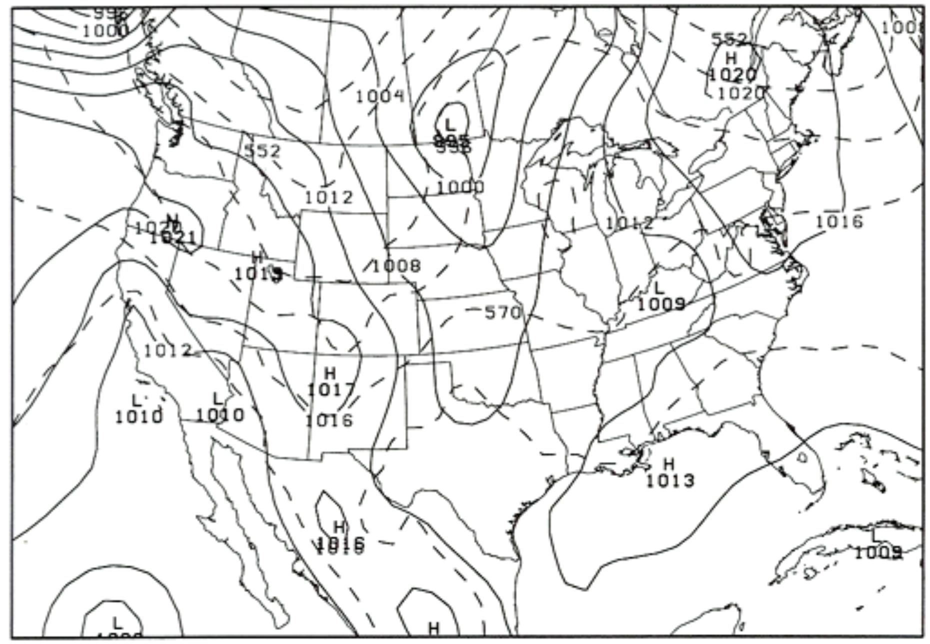
Valid at

12z 18 September 2002

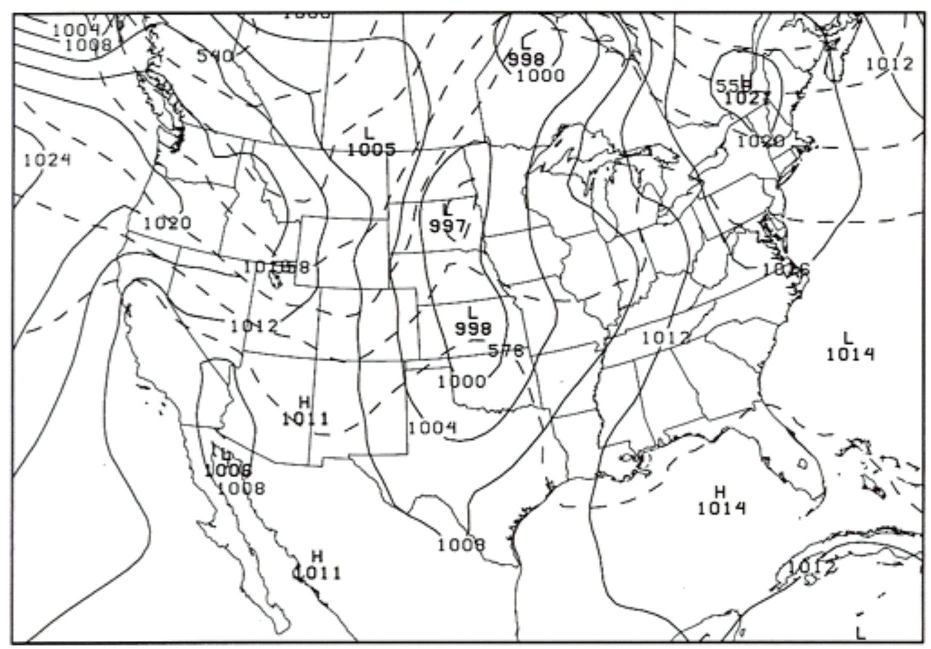
Avn

Eta

60 h fcsts

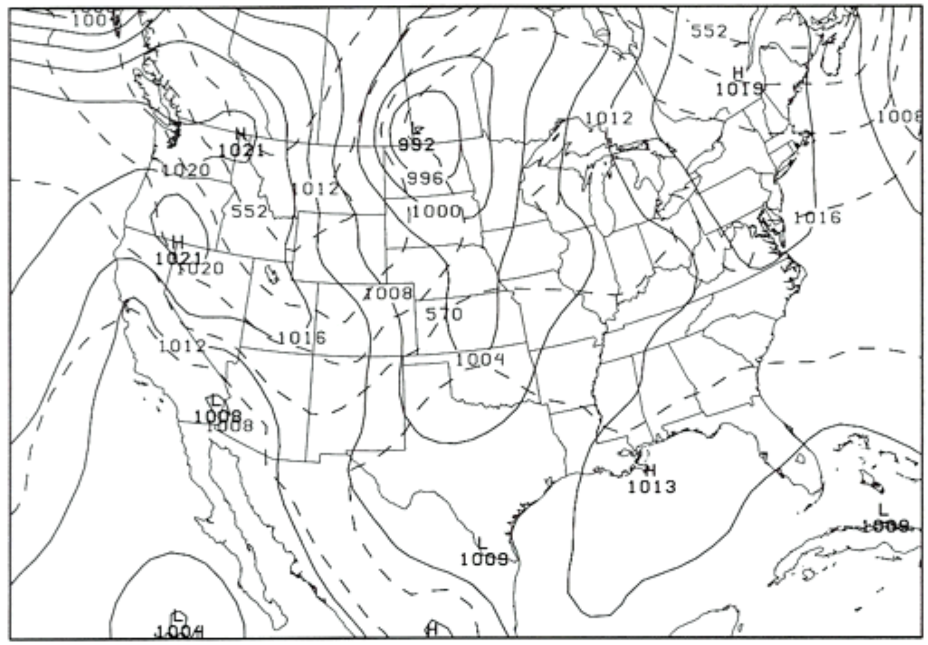


020918/1200V060 SFC MSLP & THCK -- AVN

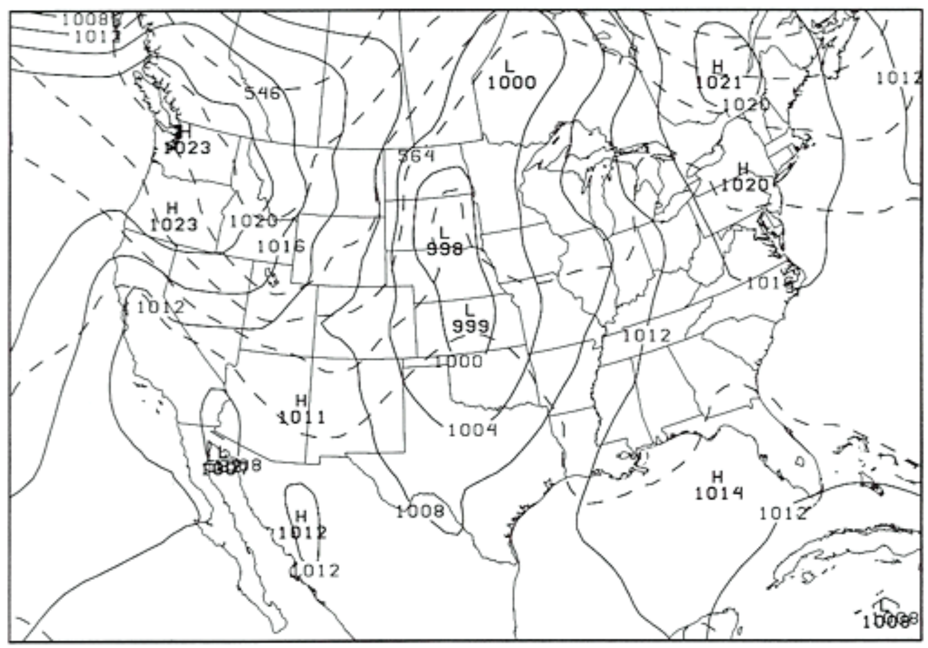


020918/1200V060 SFC MSLP & THCK -- ETA

Avn

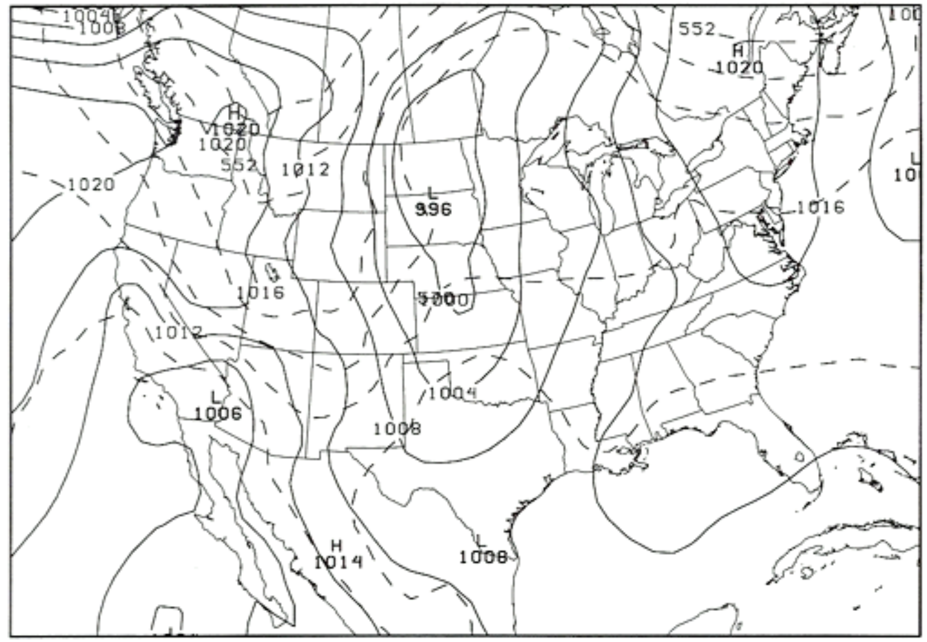


Eta



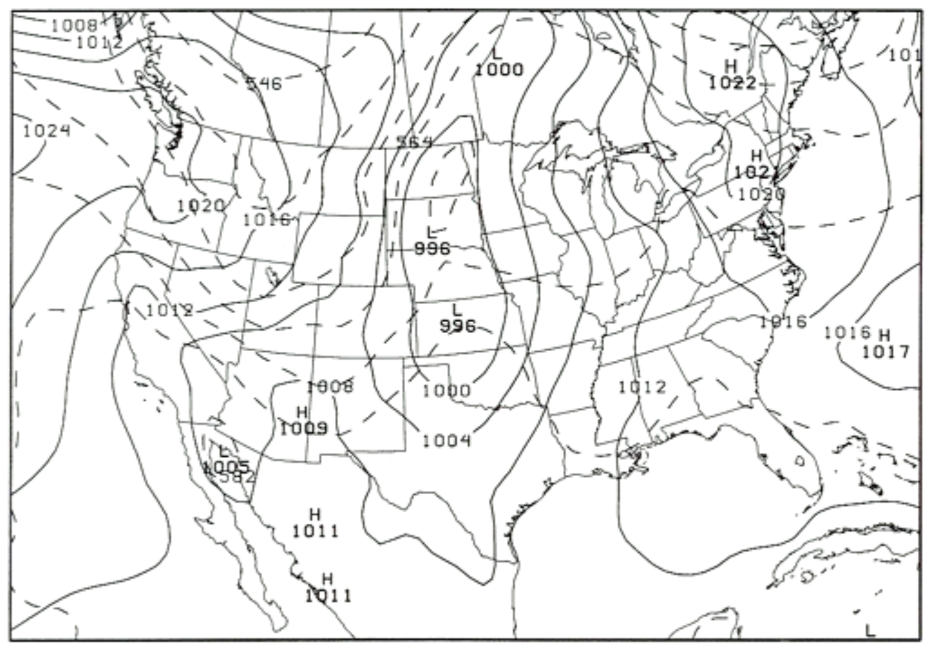
48 h fcsts

Avn



020918/1200V036 SFC MSLP & THCK -- AVN

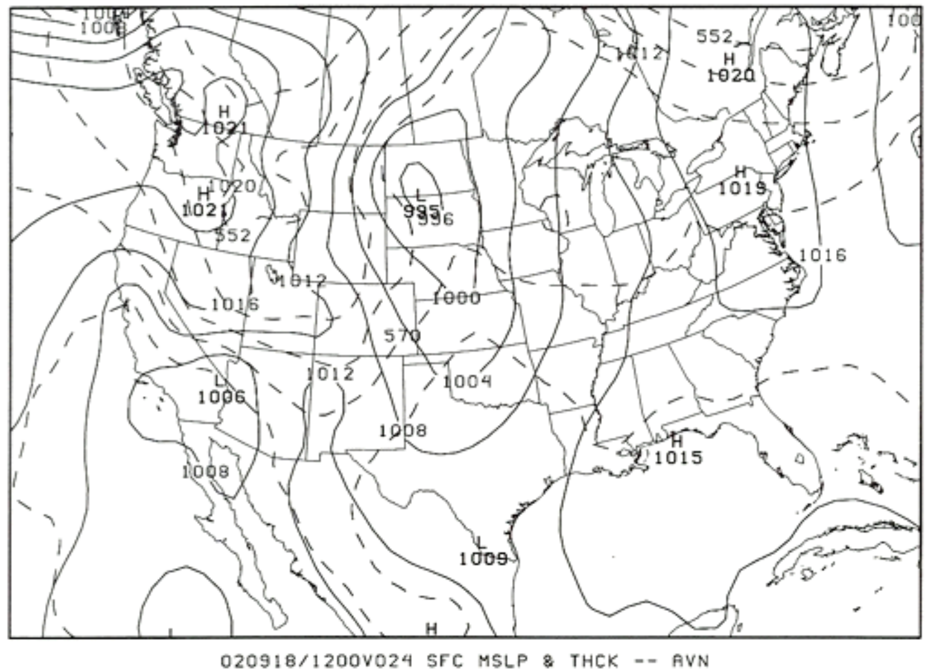
Eta



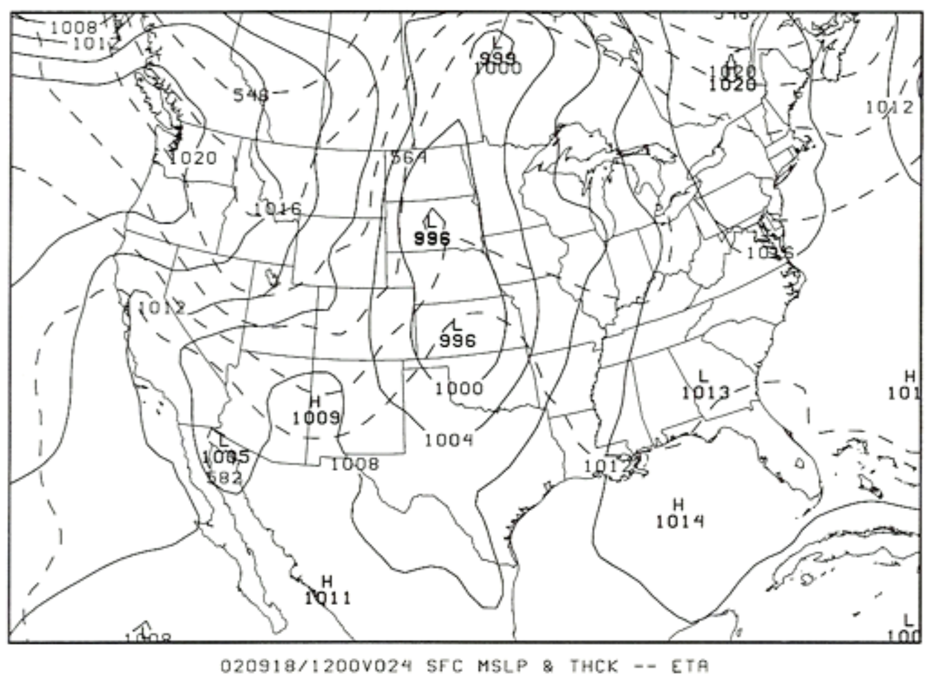
020918/1200V036 SFC MSLP & THCK -- ETA

36 h fcsts

Avn

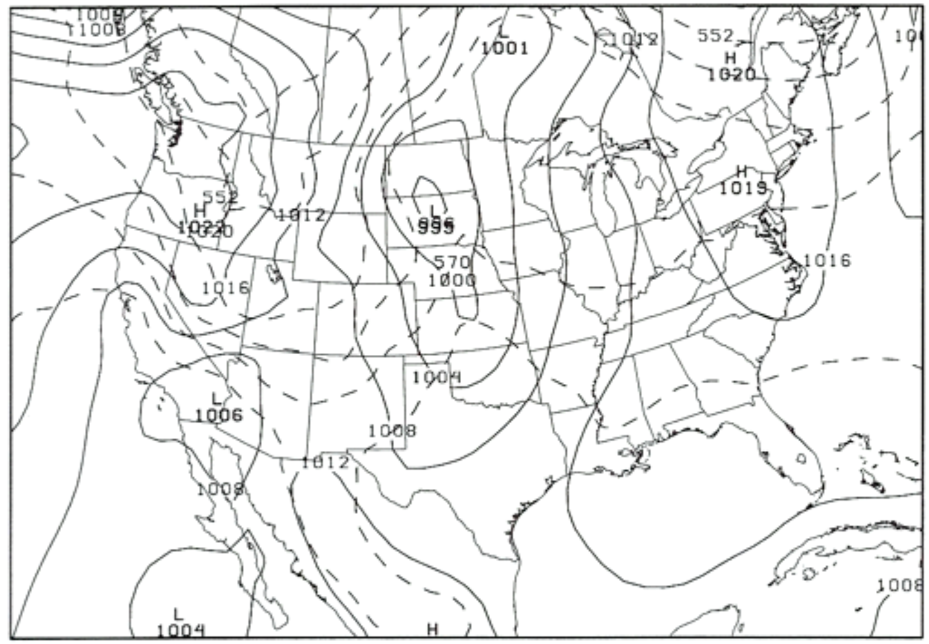


Eta



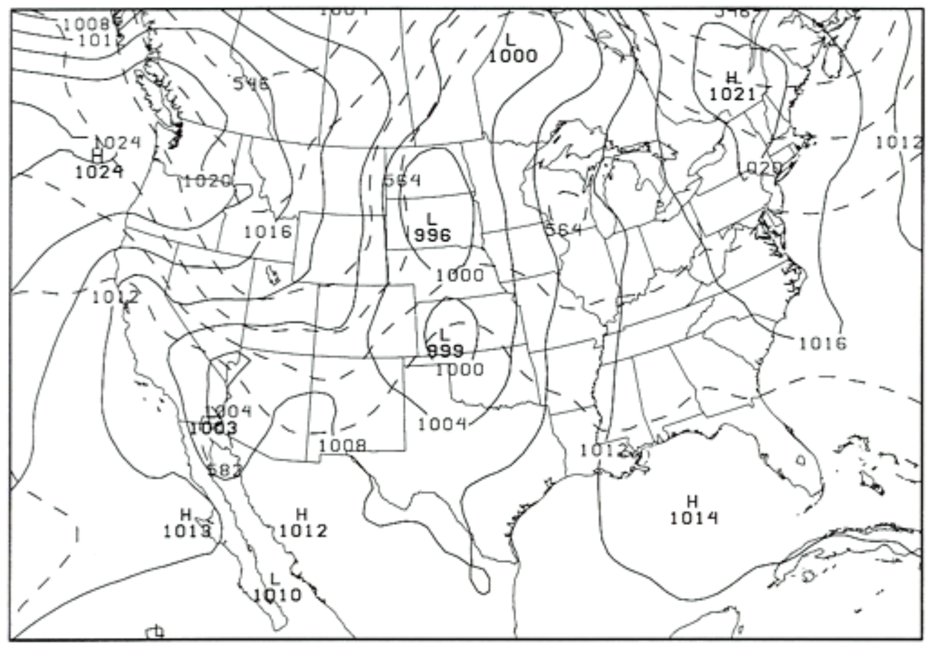
24 h fcsts

Avn



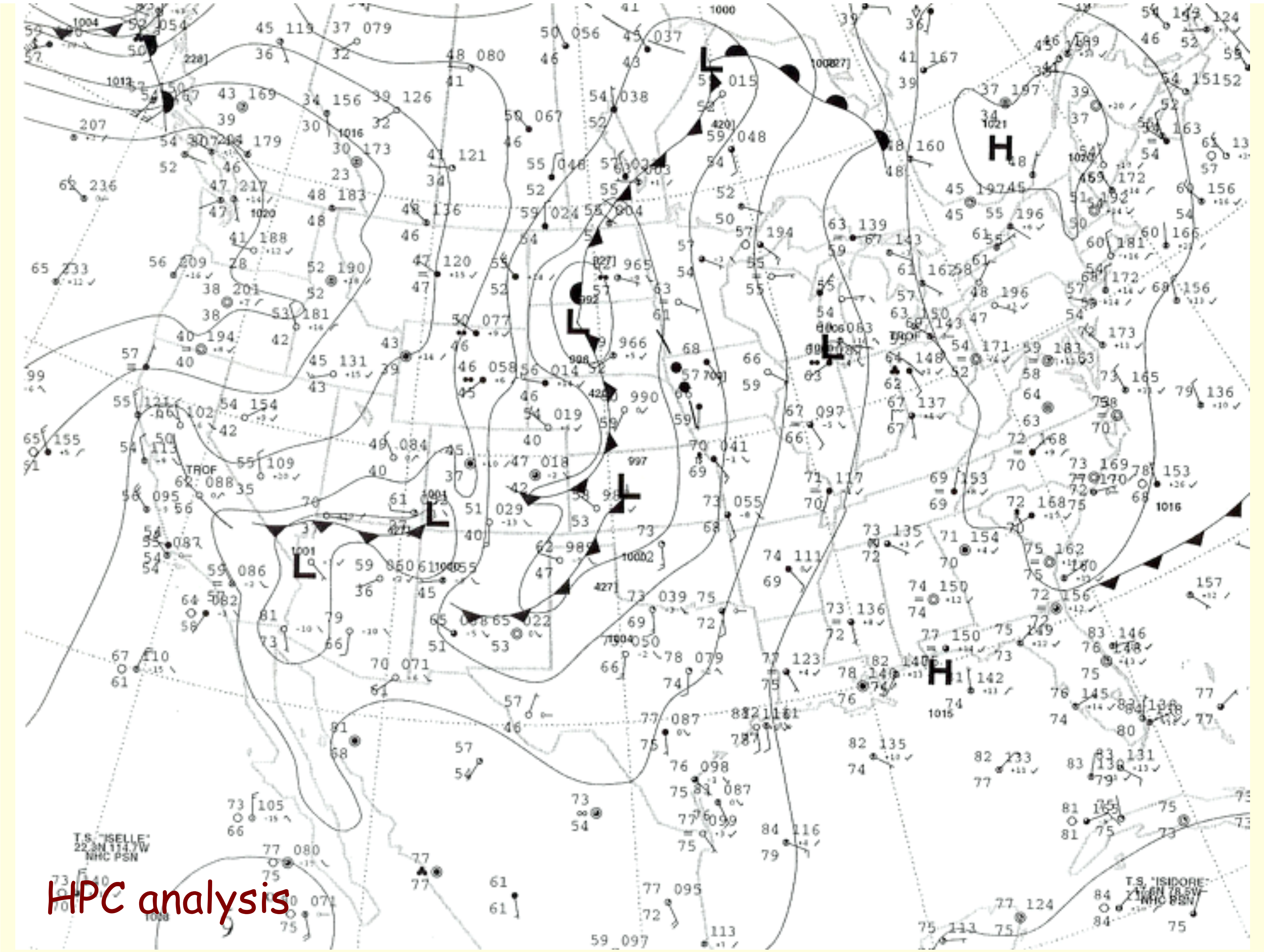
020918/1200V012 SFC MSLP & THCK -- AVN

Eta



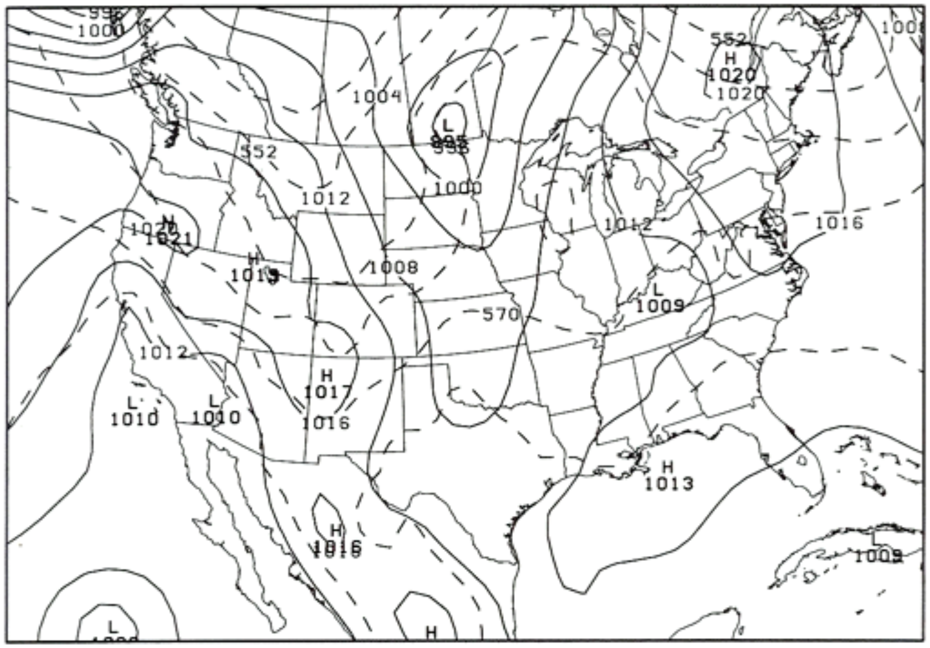
020918/1200V012 SFC MSLP & THCK -- ETA

12 h fcsts

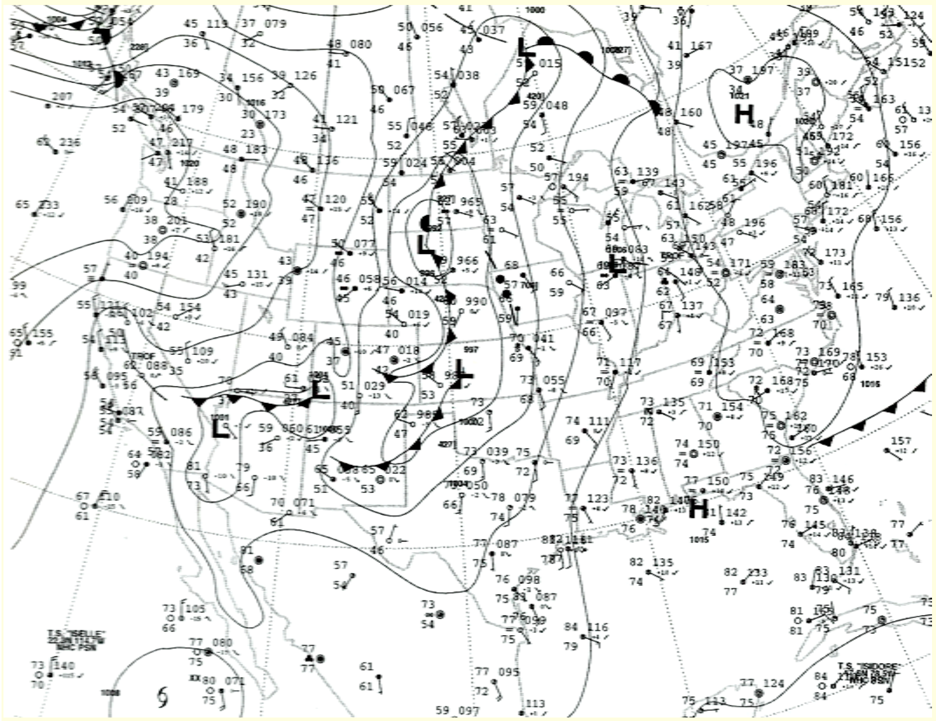


HPC analysis

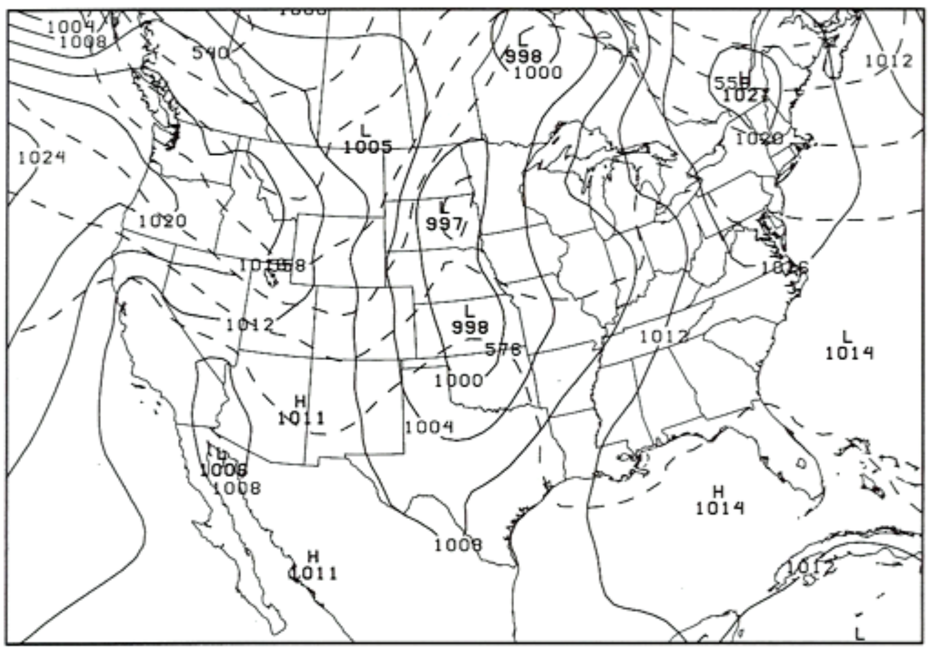
Avn, 60 h fcst



020918/1200V060 SFC MSLP & THCK -- AVN



HPC analysis



020918/1200V060 SFC MSLP & THCK -- ETA

Eta, 60 h fcst

Other model "families":

RAMS, MM5, NCAR WRF, . . .

Among models using or having an option to use

quasi-horizontal (eta or eta-like) coordinates :

- Univ. of Wisconsin (G. Tripoli);
- RAMS/OLAM (C. Tremback; R. Walko);
- DWD Lokal Modell (LM: Steppeler et al. 2006);
- MIT, Marshall et al. (MWR 2004);
- NASA GISS (NY), G. Russell, (MWR 2007)

Apparently increasing as time goes on ?

Vertical advection of **v**, T:

"Standard" Eta: centered Lorenz-Arakawa, e.g.,

$$\frac{\partial T}{\partial t} = \ldots - \overline{\dot{\eta}\frac{\partial T}{\partial \eta}}^{\eta}$$

E.g., Arakawa and Lamb (1977, "the green book", p. 222). Conserves first and second moments (e.g., for u,v: momentum, kin. energy).

There is a problem however: false advection occurs from below ground. Replaced with a piecewise linear scheme of Mesinger and Jovic (2002)

From Mesinger and Jovic :

Dashed: original distribution

Solid: after 1st iteration

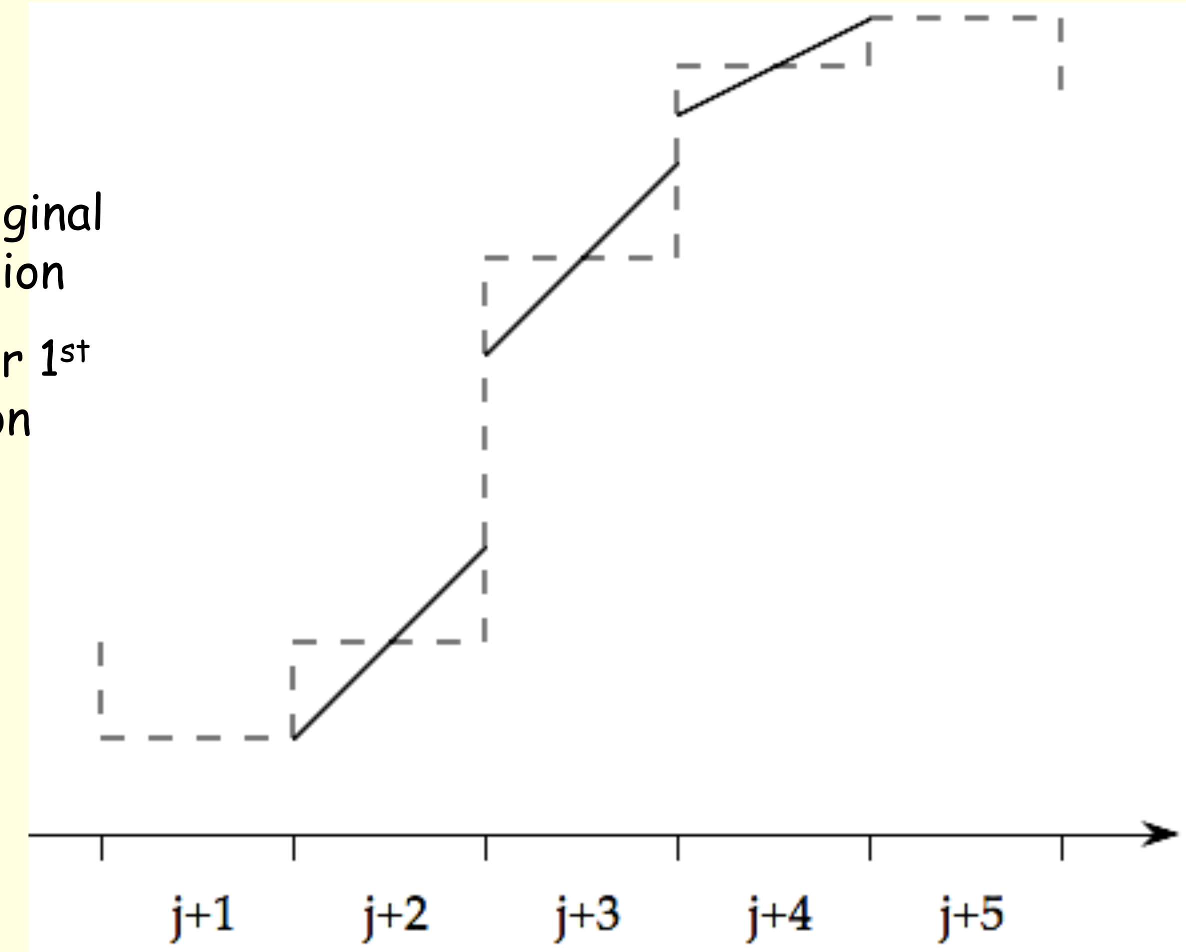


Figure 1. An example of the Eta iterative slope adjustment algorithm. The initial distribution is illustrated by the dashed line, with slopes in all five zones shown equal to zero. Slopes resulting from the first iteration are shown by the solid lines. See text for additional detail.

Mesinger, F., and D. Jovic, 2002: The Eta slope adjustment: Contender for an optimal steepening in a piecewise-linear advection scheme? Comparison tests. NCEP Office Note 439, 29 pp (available online at http://www.emc.ncep.noaa.gov/officenotes).

A comprehensive study of the Eta piecewise linear scheme including comparison against five other schemes (three Van Leer's, Janjic 1997, and Takacs 1985):

Most accurate; only one of van Leer's schemes comes close!

E.g., the comparison against Takacs (1985) third-order scheme:

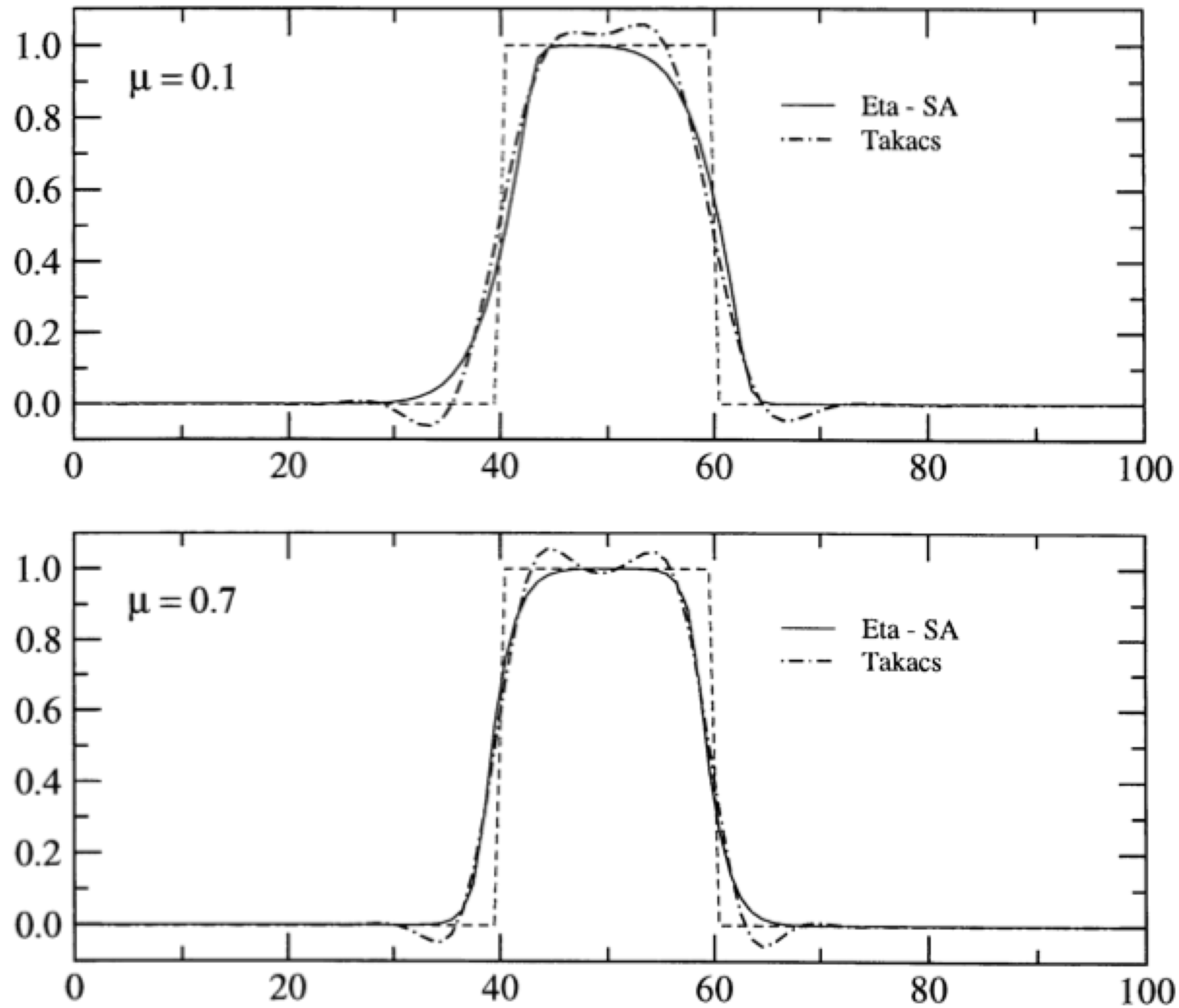


Figure 9. Same as Fig. 2, except for the Eta slope-adjustment scheme results (SA, solid line) compared against those using the Takacs (1985) third-order "minimized dissipation and dispersion errors" scheme (dot-dashed line). See text for definitions of schemes.

The nonlinear case

$$-\dot{\eta}\frac{\partial T}{\partial \eta} = T\frac{\partial \dot{\eta}}{\partial \eta} - \frac{\partial(\dot{\eta}T)}{\partial \eta}$$

Concluding remark: since piecewise-linear advection of dynamic variables replaces the only remaining purely finite-difference scheme, and since with the eta coordinate horizontal sides of neighboring grid cells are very nearly of the same area, this makes the Eta very nearly a finite-volume model. Recall though that many Eta dynamical core features are not achieved in standard finite-volume models.

Some of the references used in Part II:

Colle, B. A., K. J. Westrick, and C. F. Mass, 1999: Evaluation of MM5 and Eta-10 precipitation forecasts over the Pacific Northwest during the cool season. *Wea. Forecasting*, **14**, 137-154.

DiMego, G., 2006: WRF-NMM & GSI Analysis to replace Eta Model & 3DVar in NAM Decision Brief. 115 pp. Available online at http://www.emc.ncep.noaa.gov/WRFinNAM/ .

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