The Eta model dynamical core, and an ECMWF driven 32-day Eta ensemble:

Can a nested model improve forecasts on large scale ?

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Part I:

- Approach;

Time and horizontal differencing:

- Gravity-wave coupling/ time differencing;
- Horizontal advection:
- Energy transformations;
- Nonhydrostatic effects

“Philosophy” of the Eta numerical design:
“Arakawa approach”

Attention focused
on the physical properties
of the finite difference analog
of the continuous equations

- Formal, Taylor series type accuracy:
  not emphasized;
- Help not expected from merely increase
  in resolution

"Physical properties . . ." ?

Properties (e.g., kinetic energy, enstrophy) defined using grid point values as model grid box averages /

as opposed to their being values of continuous and differentiable functions at grid points

(Note "physics": done on grid boxes ! !)

Arakawa, at early times:

- Conservation of energy and enstrophy;
- Avoidance of computational modes;
- Dispersion and phase speed;
- . . .

Akio Arakawa:

Design schemes so as to emulate as much as possible physically important features of the continuous system !

Understand/ solve issues by looking at schemes for the minimal set of terms that describe the problem

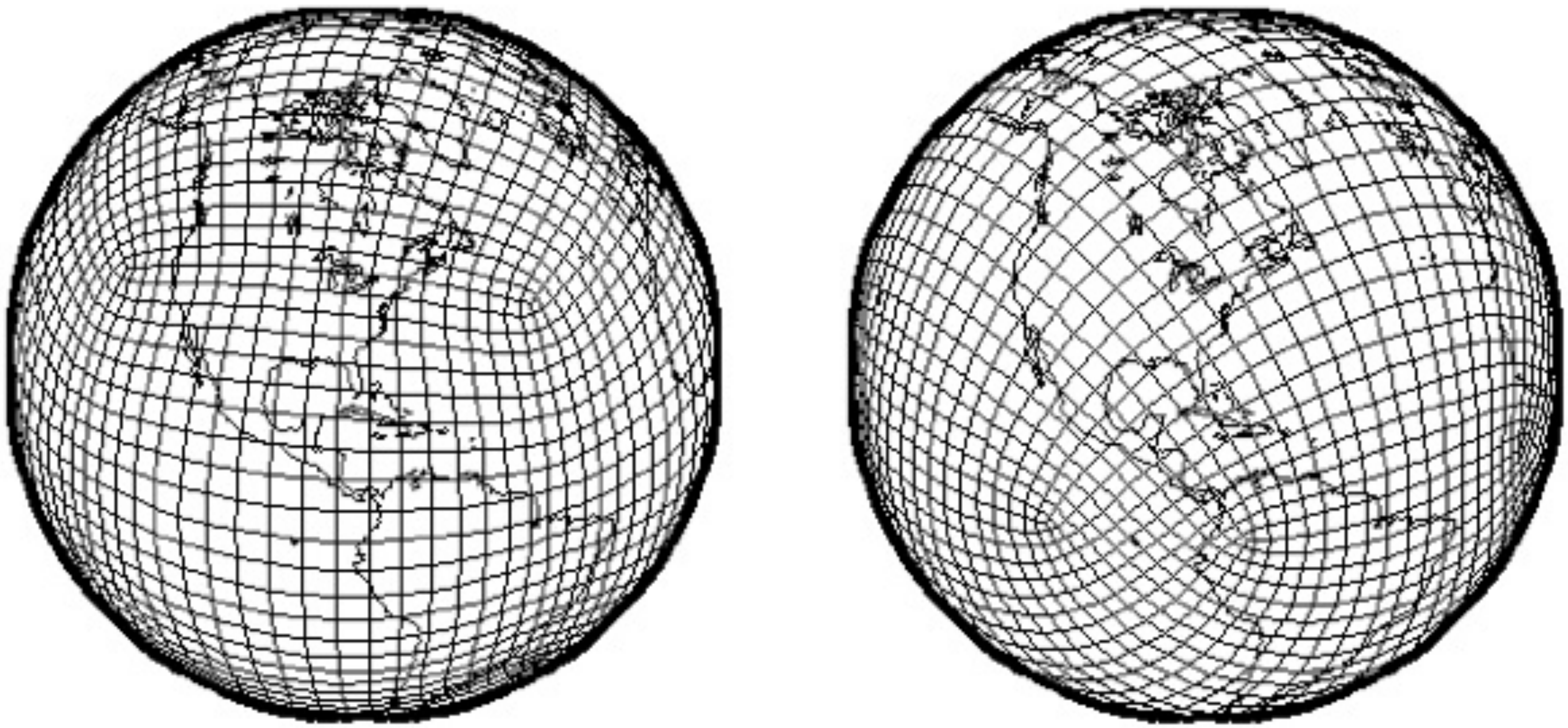
Akio Arakawa:

The Eta (as mostly used up to now) is a regional model:

Lateral boundary conditions (LBCs) are needed

There is now also a global Eta Model (runs at CPTEC, Brazil):

Zhang, H., and M. Rancic: 2007: A global Eta model on quasi-uniform grids. *Quart. J. Roy. Meteor. Soc.*, **133**, 517-528.



Eta dynamics: What is being done ?

- Gravity wave terms, on the B/E grid: forward-backward scheme that

(1) avoids the time computational mode of the leapfrog scheme, and is neutral with time steps twice leapfrog;

(2) modified to enable propagation of a height point perturbation to its nearest-neighbor height points/ suppress space computational mode;

- Split-explicit time differencing (very efficient);
- Horizontal advection scheme that conserves energy and C-grid enstrophy, on the B/E grid, in space differencing (Janjić 1984);
- Conservation of energy in transformations between the kinetic and potential energy, in space differencing;
- Nonhydrostatic option;
- The eta vertical coordinate, ensuring hydrostatically consistent calculation of the pressure gradient ("second") term of the pressure-gradient force (PGF);
- Finite-volume vertical advection of dynamic variables (**v**, T)

Lateral boundary conditions:

Defined along a single outermost row of grid points;
prescribed or, at outflow points, tangential velocity extrapolated from inside (Mesinger 1977);

"Fairly well-posed" according to McDonald (1997);

No Davies' (1976) "boundary relaxation"

- Gravity wave (gravity-inertia wave) scheme

Linearized shallow-water equations:

The forward-backward scheme:

(Richtmyer ?)

$$u^{n+1} = u^n - g\Delta t\, \delta_x h^{n+1},$$

$$v^{n+1} = v^n - g\Delta t\, \delta_y h^{n+1},$$

$$h^{n+1} = h^n - H\Delta t\, (\delta_x u + \delta_y v)^n.$$

A. Gadd (May 1973): ref. to Ames

Stable, and neutral, for time steps twice those of the leapfrog scheme;

No computational mode

Coriolis terms: trapezoidal scheme

$$u^{n+1} = \dots \quad + \tfrac{1}{2} f \Delta t\, (v^n + v^{n+1})$$

$$v^{n+1} = \dots \quad - \tfrac{1}{2} f \Delta t\, (u^n + u^{n+1})$$

Unconditionally neutral

(Fischer, MWR, 1965)

Elimination of u,v from pure gravity-wave system leads to the wave equation; in 1D, for simplicity, (5.6):

(From Mesinger, Arakawa, 1976)

$$\frac{\partial^2 h}{\partial t^2} - gH\frac{\partial^2 h}{\partial x^2} = 0. \qquad (5.6)$$

We can perform the same elimination for each of the finite difference schemes.

The forward-backward and space-centered approximation to (5.5) is

$$\frac{u_j^{n+1} - u_j^n}{\Delta t} + g\frac{h_{j+1}^n - h_{j-1}^n}{2\Delta x} = 0,$$
$$\frac{h_j^{n+1} - h_j^n}{\Delta t} + H\frac{u_{j+1}^{n+1} - u_{j-1}^{n+1}}{2\Delta x} = 0, \qquad (5.7)$$

We now substract from the second of these equations an analogous equation for time level $n-1$ instead of n, divide the resulting equation by Δt, and, finally, eliminate all u values from it using the first of Eqs. (5.7), written for space points $j+1$ and $j-1$ instead of j. We obtain

Forward-backward:

$$\frac{h_j^{n+1} - 2h_j^n + h_j^{n-1}}{(\Delta t)^2} - gH\frac{h_{j+2}^n - 2h_j^n + h_{j-2}^n}{(2\Delta x)^2} = 0. \qquad (5.8)$$

This is a finite difference analogue of the wave equation (5.6). Note that although each of the two equations (5.7) is only of the first order of accuracy in time, the wave equation analogue equivalent to (5.7) is seen to be of the second order of accuracy.

Leapfrog:

If we use a leapfrog and space-centered approximation to (5.5), and follow an elimination procedure like that used in deriving (5.8), we obtain

$$\frac{h_j^{n+1} - 2h_j^{n-1} + h_j^{n-3}}{(2\Delta t)^2} - gH\frac{h_{j+2}^{n-1} - 2h_j^{n-1} + h_{j-2}^{n-1}}{(2\Delta x)^2} = 0. \qquad (5.9)$$

This also is an analogue to the wave equation (5.6) of second-order accuracy. However, in (5.8) the second time derivative was approximated using values at three consecutive time levels; in (5.9) it is approximated by values at every second time level only, that is, at time intervals $2\Delta t$. Thus, with the leapfrog scheme, as far as the pure gravity wave terms are concerned, we are carrying out two independent integrations at the same time – no wonder it takes twice the computer time to do this !!!

Moving back to 2D: a choice of space grid is needed

Arakawa 1997:

Reviews of various discretization methods applied to atmospheric models include Mesinger and Arakawa (1976), GARP (1979), ECMWF (1984), WMO (1984), Arakawa (1988) and Bourke (1988) for finite-difference, finite-element and spectral methods and Staniforth and Côté (1991) for the semi-Lagrangian method.

7.2 Horizontal computational mode and distortion of dispersion relations

Among problems in discretizing the basic governing equations, computational modes and computational distortion of the dispersion relations in a discrete system require special attention in data assimilation. Here a computational mode refers to a mode in the solution of discrete equations that has no counterpart in the solution of the original continuous equations. The concept of the order of accuracy, therefore, which is based on the Taylor expansion of the residual when the solution of the continuous system is substituted into the discrete system, is not relevant for the existence or non-existence of a computational mode.

geostrophic ajustm.:

"the green book"

Arakawa, dynamics:

- geostrophic adjustment
- simulation of slow, quasi-geostrophic motions

$$\frac{\partial u}{\partial t} = -g\frac{\partial h}{\partial x} + fv,$$

$$\frac{\partial v}{\partial t} = -g\frac{\partial h}{\partial y} - fu,$$

$$\frac{\partial h}{\partial t} = -H\,\nabla\cdot\mathbf{v}$$

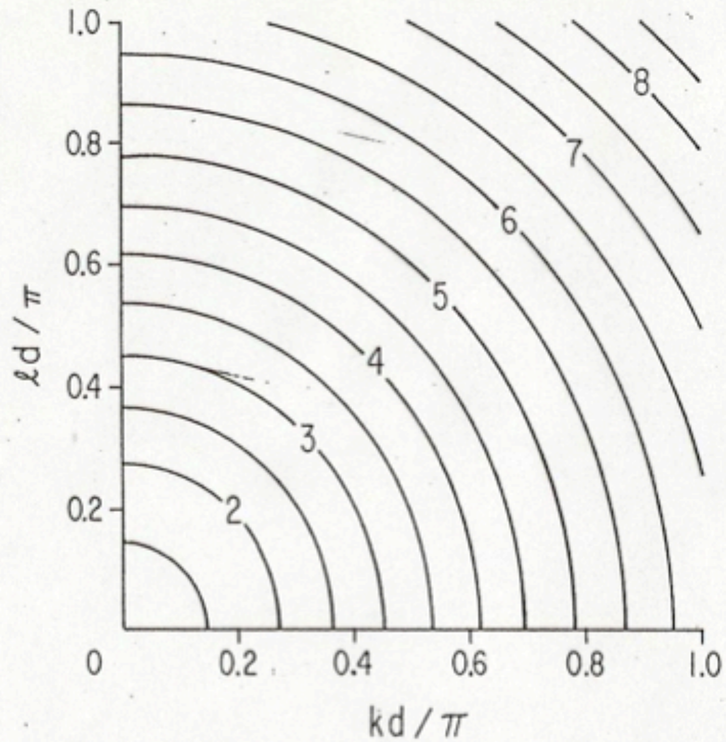


FIG. 9. Contours of the (nondimensional) frequency as a function of the (nondimensional) horizontal wave numbers for the differential shallow water equation for $\lambda/d = 2$, presented for comparison with Fig. 8.

$$\lambda \equiv \sqrt{gH}/f$$

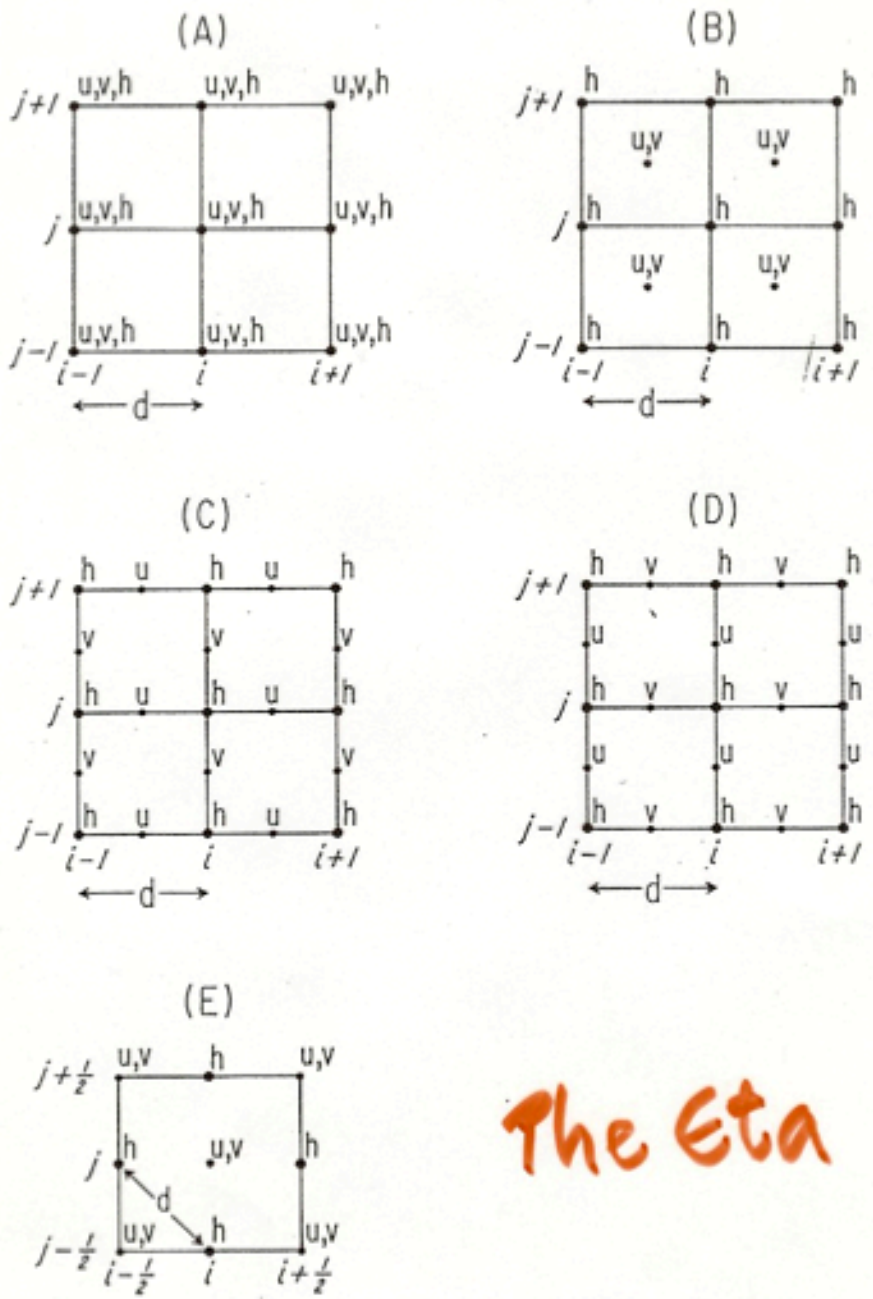
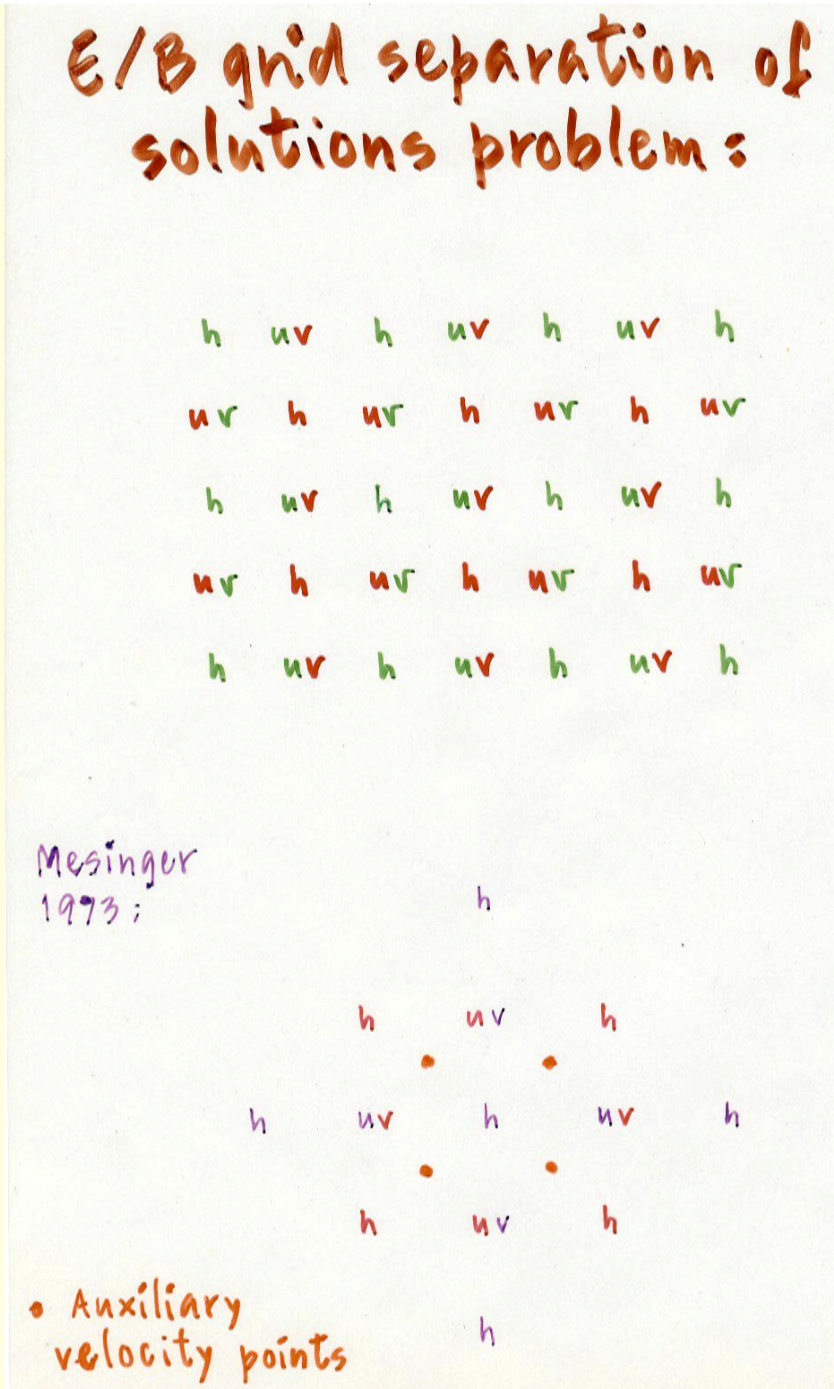


FIG. 3. Spatial distributions of the dependent variables on a square grid.

Note:

E grid is same as B, but rotated 45°. Thus, often: E/B, or B/E



(Two C-subgrids)

"The modification"

Pointed out (1973) that divergence equation can be used just as well; result is the same as when using the auxiliary velocity points

The method, 1973, applied to a number of time differencing schemes;

In Mesinger 1974:

applied to the "forward-backward" scheme

Back to "modification", gravity wave terms only:

on the lattice separation problem. If, for example, the forward–backward time scheme is used, with the momentum equation integrated forward,

$$u^{n+1} = u^n - g\Delta t \delta_x h^n, \qquad v^{n+1} = v^n - g\Delta t \delta_y h^n, \tag{2}$$

instead of

$$h^{n+1} = h^n - H\Delta t\left[(\delta_x u + \delta_y v) - g\Delta t \nabla_+^2 h\right]^n, \tag{3}$$

the method results in the continuity equation (Mesinger, 1974):

$$h^{n+1} = h^n - H\Delta t\left[(\delta_x u + \delta_y v) - g\Delta t\left(\frac{3}{4}\nabla_+^2 h + \frac{1}{4}\nabla_\times^2 h\right)\right]^n. \tag{4}$$

Single-point perturbation spreads to both *h* and *h* points !

Extension to 3D: Janjić, Contrib. Atmos. Phys., 1979

Eq. (4) (momentum eq. forward):

Following a pulse perturbation (height increase) at the initial time, at time level 1 increase in height occurs at four nearest points equal to 2/3 of the increase which occurs in four second nearest points.

This is not ideal, but is a considerable improvement over the situation with no change at the four nearest height points !

In the code: continuity eq. is integrated forward.

"Historic reasons". With this order, at time level 1 at the four second nearest points a decrease occurs, in the amount of 1/2 of the increase at the four nearest points !

Might well be worse? However:

Experiments made, doing 48 h forecasts,
with full physics, at two places, comparing

continuity eq. forward, vs momentum eq. forward

No visible difference ! (Why?)

Just published

Mesinger, F., and J. Popovic, 2010: Forward–backward scheme on the B/E grid modified to suppress lattice separation: the two versions, and any impact of the choice made? *Meteor. Atmos. Phys.*, **108**, 1-8, DOI 10.1007/s00703-010-0080-1.

Impact of "modification":

upper panel, used
lower panel, not used

- **Figure 8** Sea level pressure, 00 GMT 24 August 1975, 24 hr forecast with variable boundary conditions. Above: with w = .25; below: with w = 0.

Time differencing sequence ("splitting" is used):

Adjustment stage: cont. eq. forward, momentum backward

(the other way around in the Global Eta)

Vertical advection over 2 adj. time steps

Horizontal diffusion;

Repeat (except no vertical advection now, since it is done for two time steps)

Horizontal advection over 2 adjustment time steps

(first forward then off-centered scheme, approx. neutral);

Some physics calls;

Repeat all of the above;

More physics calls;

. . . . .

Time differencing: split explicit

A variety of time steps:

time →

Cont. eq.

1 3 6

2 4 . . . .

"forward-backward" sch.

Mom. eq. (adj. terms, incl. Cor. f. implicit)

5

. . .

Horiz. adv. (~ Heun)

. . .

Some physics
(incl. convection)

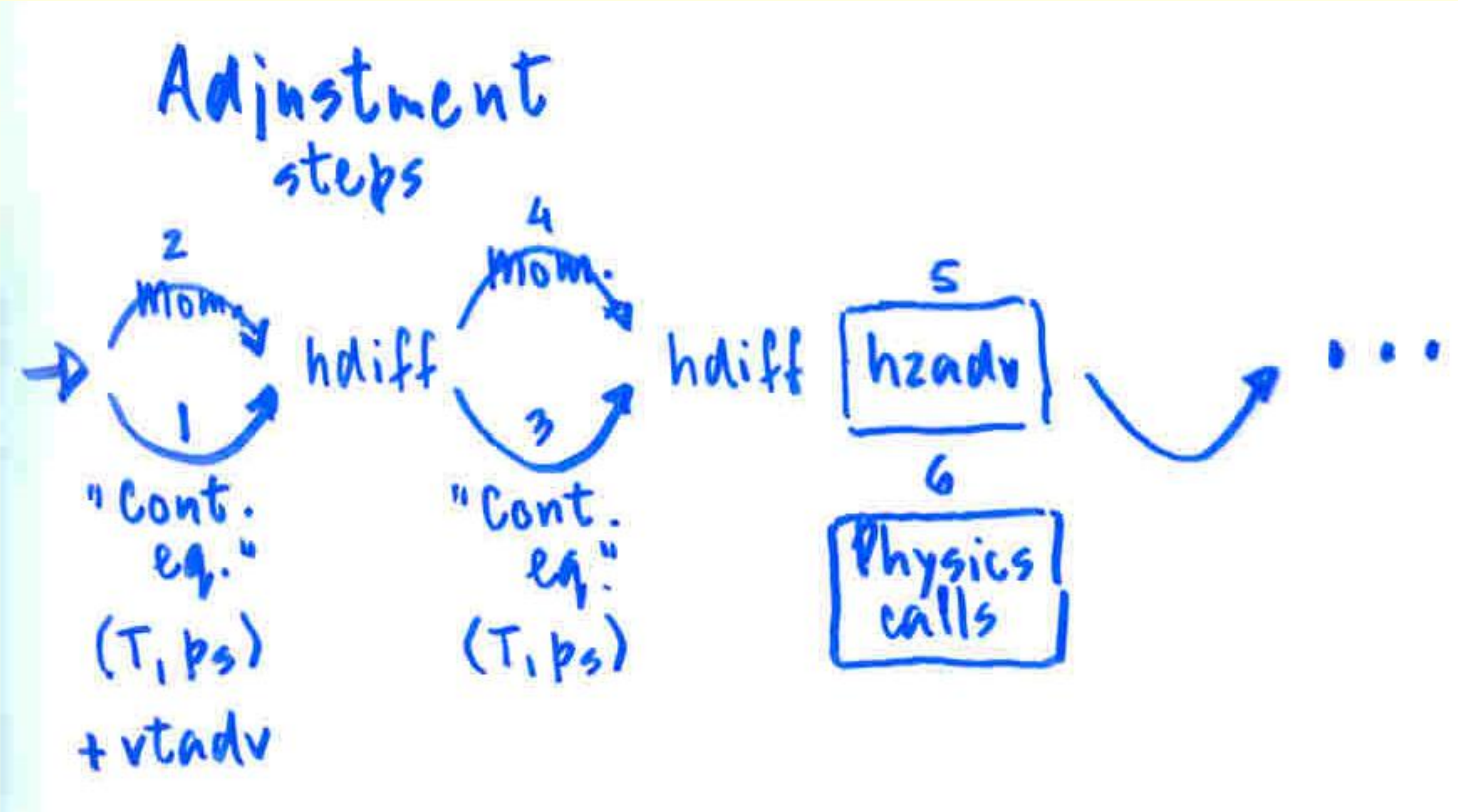
More physics

:

F. Mesinger

However:

"horizontal diffusion" following each forward-backward step:



Adj. step splitting used:

$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v}\cdot\nabla)\mathbf{v} = -f\,\mathbf{k}\times\mathbf{v} - g\nabla h,$$
$$\frac{\partial h}{\partial t} + \nabla\cdot(h\mathbf{v}) = 0. \qquad (1)$$

is replaced by

$$\frac{\partial \mathbf{v}}{\partial t} = -f\,\mathbf{k}\times\mathbf{v} - g\nabla h,$$
$$\frac{\partial h}{\partial t} + \nabla\cdot(h\mathbf{v}) = 0. \qquad (2)$$

as the "adjustment step",

and

$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v}\cdot\nabla)\mathbf{v} = 0, \qquad (3)$$

as the "advection step"

Note that height advection $\mathbf{v}\cdot\nabla h$ (corresponding to pressure in 3D case) is carried in the adjustment step (or, stage), even though it represents advection!

This is a necessary, but not sufficient, condition for energy conservation in time differencing in the energy transformation ("ωα") term (transformation between potential and kinetic energy). Splitting however, as above, makes exact conservation of energy in time differencing not possible (amendment to Janjic et al. 1995). Energy conservation in the Eta, in transformation between potential and kinetic energy is achieved in space differencing.

- Horizontal advection

The famous Arakawa horizontal advection scheme:

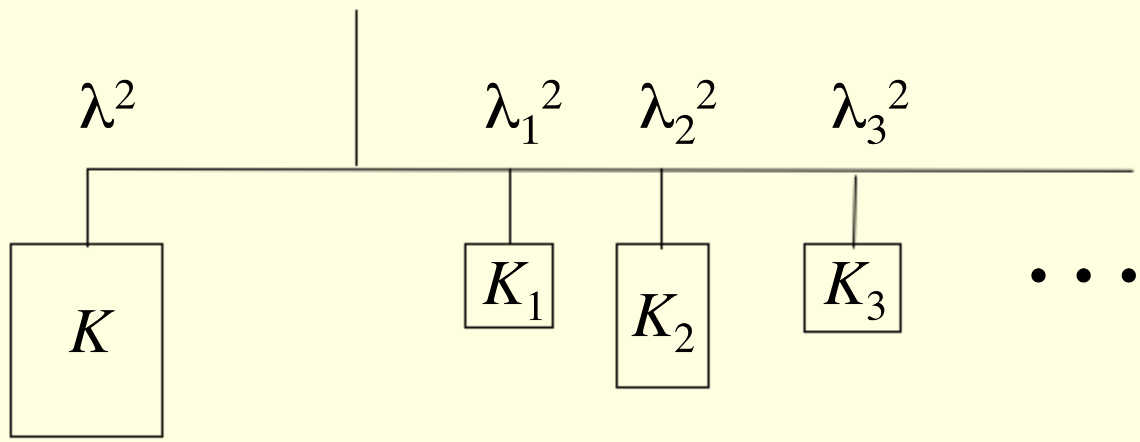
For two-dimensional and nondivergent flow:

One obtains*, average "enstrophy"=

$$\frac{1}{2}\overline{\zeta^2} = \sum_n \lambda_n{}^2 K_n = \text{const}$$

Define average wavenumber as $$\lambda = \sqrt{\sum_n \lambda_n{}^2 K_n / \sum_n K_n}$$

Thus:



(* Fjørtoft 1953, in Mesinger, Arakawa 1976; Charney 1966)

From the preceding slide: $$\lambda^2 \sum_n K_n = \sum_n \lambda_n{}^2 K_n$$

Thus, if one conserves analogs of average enstrophy*

$$\frac{1}{2}\overline{\zeta^2} = \sum_n \lambda_n{}^2 K_n$$

and of total kinetic energy $$\sum_n K_n$$

analog of the average wavenumber will also be conserved !!!

* "enstrophy": Cecil Leith

Arakawa 1966:
Discovered a way to reproduce this feature for the vorticity equation

Primitive equations ?

Arakawa, Lamb (1977): grid C

Janjic (1984): grid B/E

Note:

E grid is same as B, but rotated 45°. Thus, often: E/B, or B/E

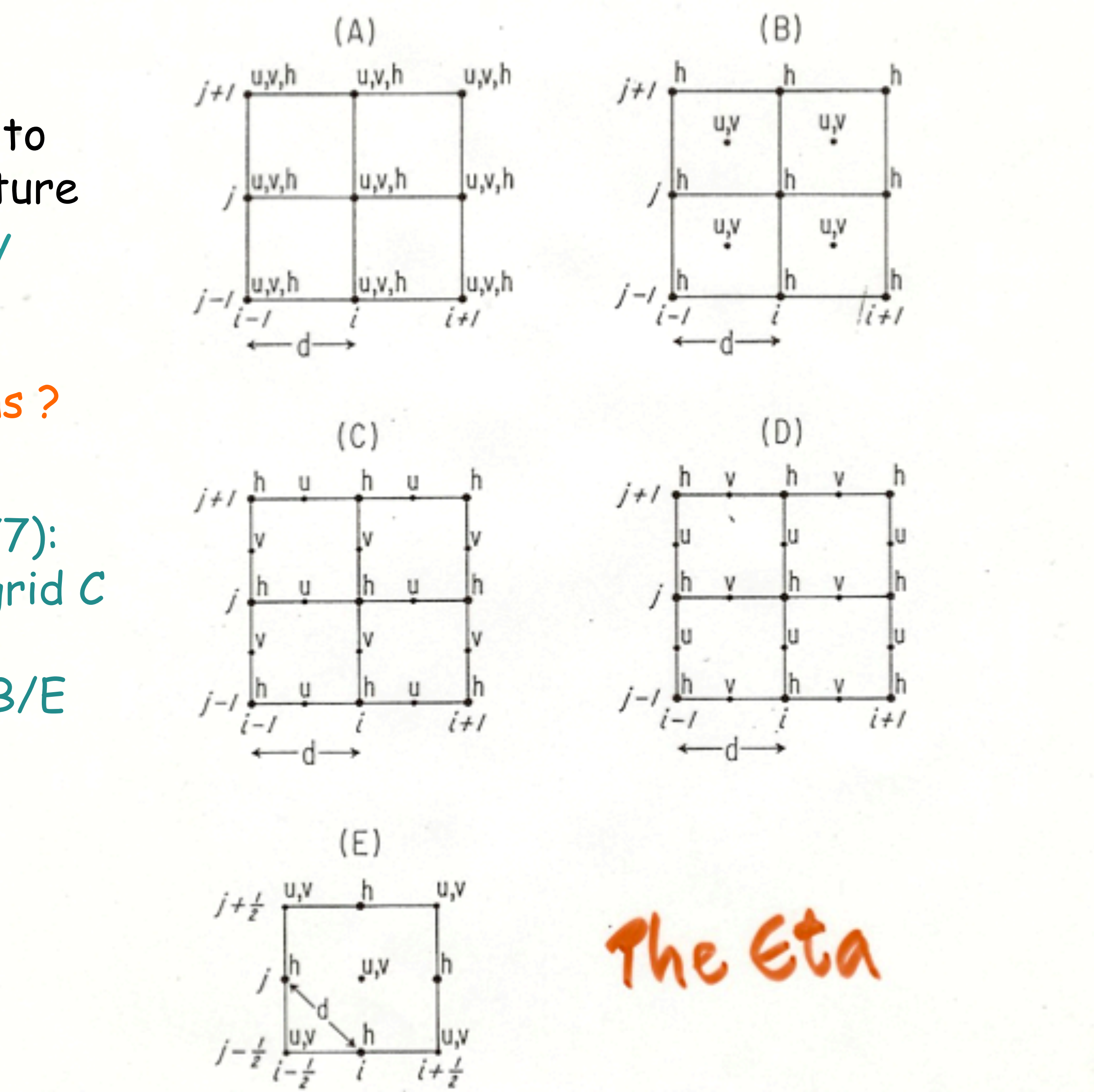


FIG. 3. Spatial distributions of the dependent variables on a square grid.

From ECMWF Seminar 1983:

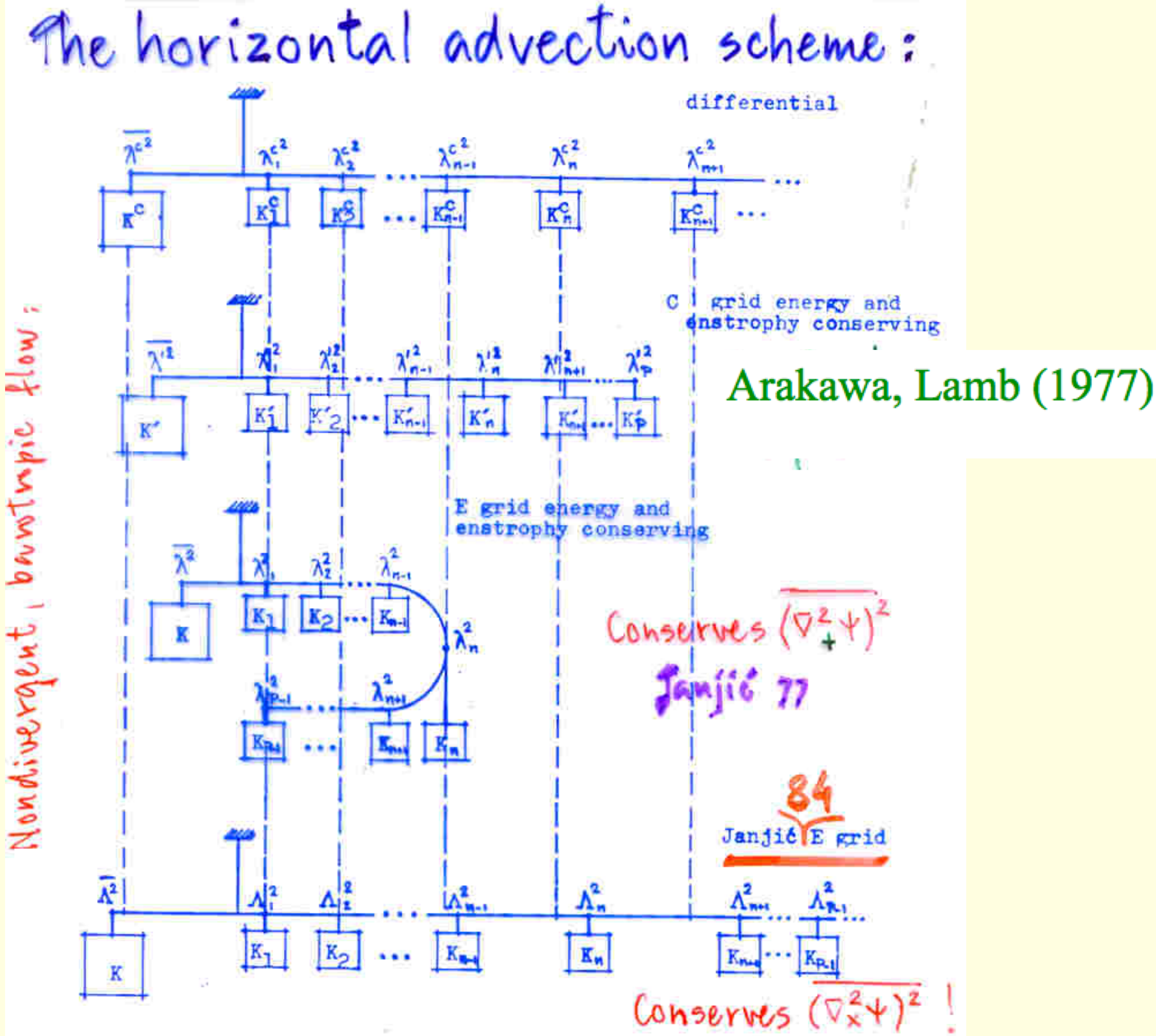


Fig. 3.12. Mechanical analogies of the constraints imposed on the non-linear energy cascade in the continuous case, in the case of the C-grid energy and enstrophy conserving scheme, in the case of the E-grid energy and enstrophy conserving scheme, and in the case of the scheme due to Janjić (1984).

(ECMWF Seminar '83)

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Horizontal advection: conserve enstrophy $(\Sigma \frac{1}{2}\zeta^2)$ and kinetic energy for nondivergent barotropic part of the flow!

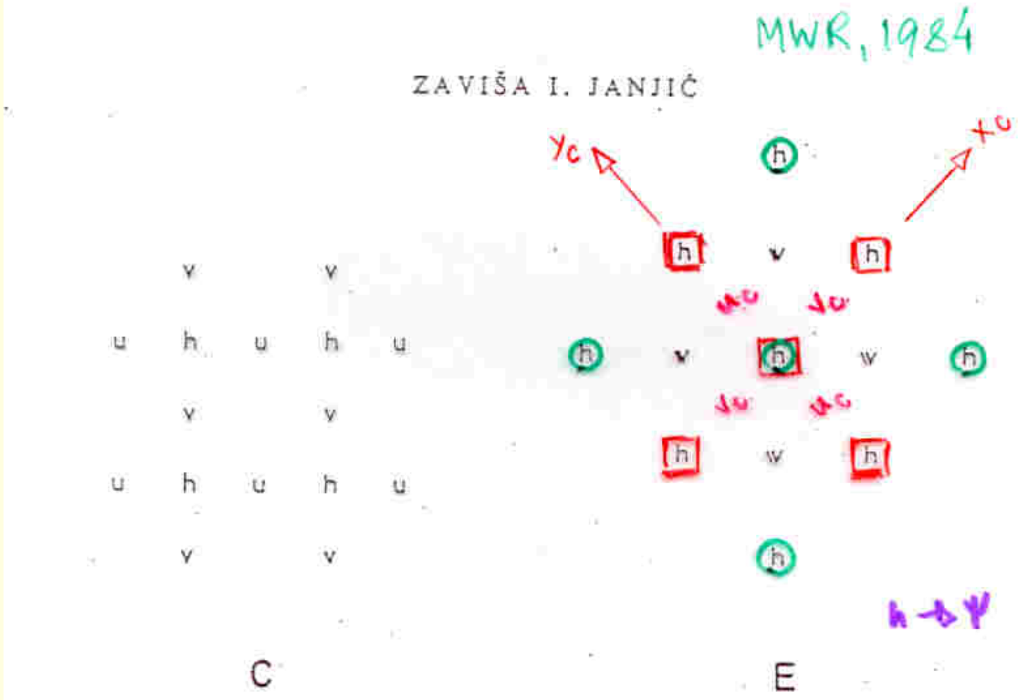

FIG. 1. Distributions of variables over grid points C and E.

Problem: ζ_E defined by simple differencing of the E grid u, v components eq. $\nabla^2_+\psi$, using ψ values at O points.

ζ_C, defined by differencing u_C, v_C, is equal to $\nabla^2_\times\psi$, using ψ values at □ points!

Janjic 1984:

- *Arakawa-Lamb C grid* scheme written in terms of u_C, v_C;
- write in terms of stream function values (at h points of the right hand plot);
- these same stream function values (square boxed in the plot) can now be transformed to u_E, v_E

Janjić adv. scheme

	Conserves: No inter. bnd.	Conserves: With int. bnd.
Nondivergent part of the flow		
C-grid enstrophy	✓	✓
vorticity	✓	✓
rotat. energy	✓	✓
Divergent part incl.		
mass	✓	✓
E-grid kin. energy	✓	✓
momentum	✓	O
Passive quantity (T, q, $q2$, hor. adv.)		
1st moment	✓	✓
2nd moment	✓	✓

From Janjic, MWR 1984: Initial field wavenumbers 1-3, but mostly 2;

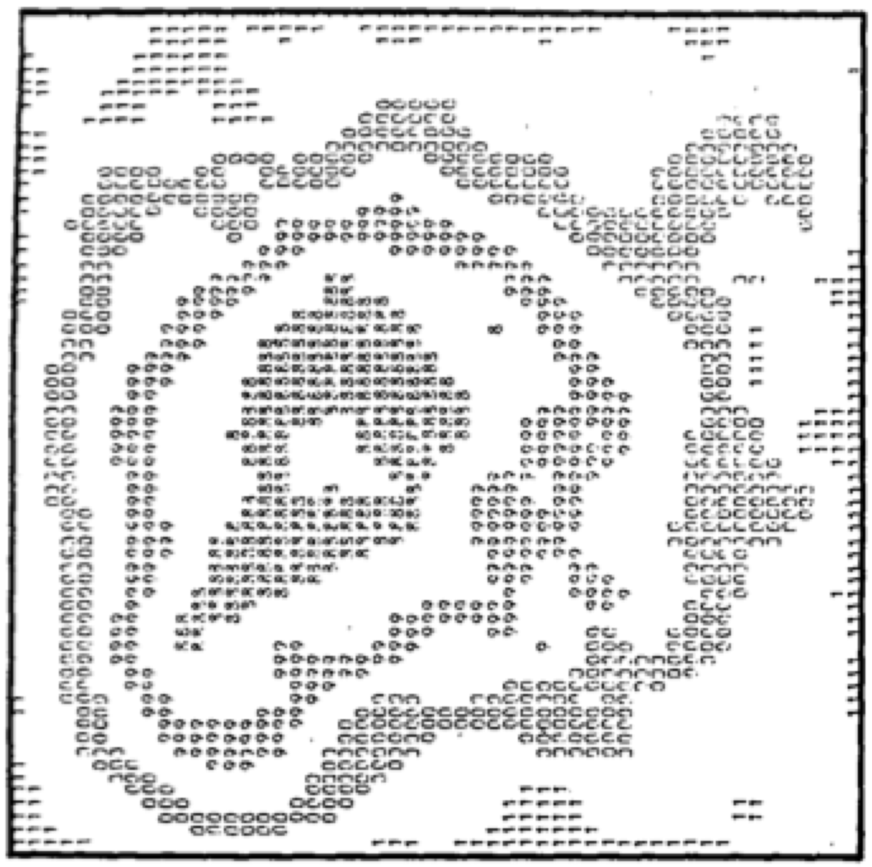

FIG. 13. Height field after 10 000 time steps in the control experiment. The shading interval is 160 m.

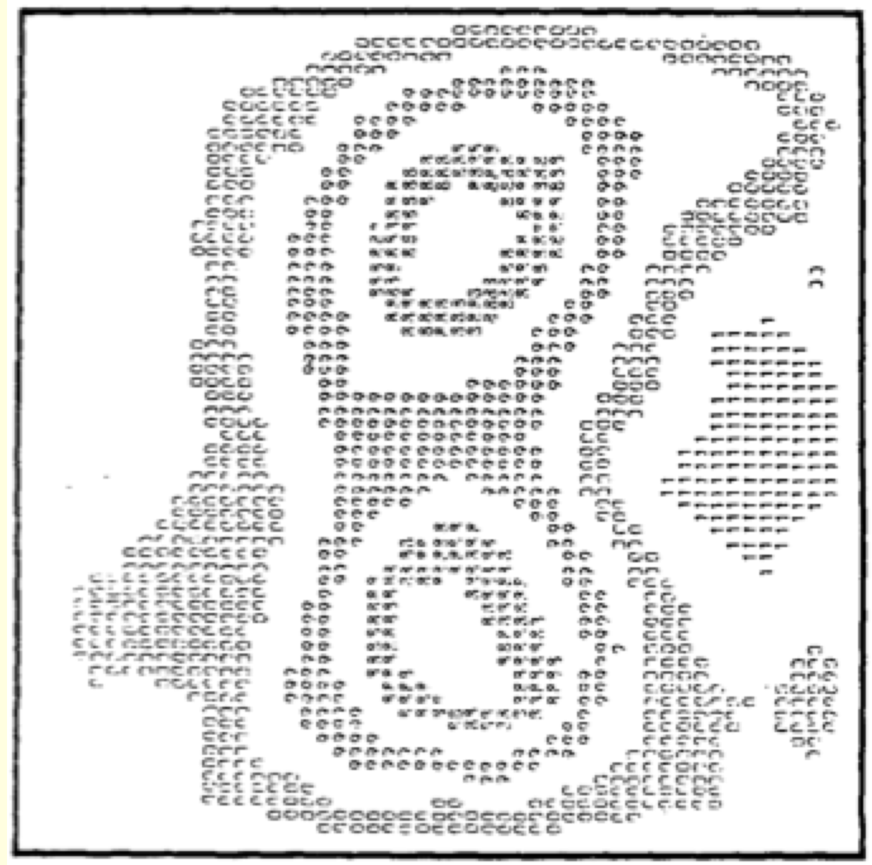

FIG. 12. Height field after 10 000 time steps in the main experiment. The shading interval is 160 m.

Left, Janjic 1977 – inaccurate (bent) analog of the Charney energy scale; Right, Janjic 1984 – a straight scale analog: no systematic transport to small scales (noise !), average wavenumber well maintained

• Conservation of energy in transformation kinetic to potential, in space differencing

- Evaluate generation of kinetic energy over the model's **v** points;
- Convert from the sum over **v** to a sum over T points;
- Identify the generation of potential energy terms in the thermodynamic equation, use appropriate terms from above

(2D: Mesinger 1984, reproduced and slightly expanded in

Mesinger, F., and Z. I. Janjic, 1985: Problems and numerical methods of the incorporation of mountains in atmospheric models. In: *Large-Scale Computations in Fluid Mechanics*, B. E. Engquist, S. Osher, and R. C. J. Somerville, Eds. Lectures in Applied Mathematics, Vol. 22, 81-120.

Downloadable in a bit earlier form at

http://www.ecmwf.int/publications/library/do/references/list/16111

3D: Dushka Zupanski in Mesinger et al. 1988)

Nonhydrostatic option (a switch available),

Janjic et al. 2001:

$$\left(\frac{\partial w}{\partial t}\right)^{\tau+1/2} \rightarrow \frac{w^{\tau+1} - w^{\tau}}{\Delta t}$$

Some of the references used (?) in Part I:

Arakawa, A., 1997: Adjustment mechanisms in atmospheric models. *J. Meteor. Soc. Japan*, **75**, No. 1B, 155-179.

Arakawa, A., and V. R. Lamb, 1977: Computational design of the basic dynamical processes of the UCLA general circulation model. *Methods in Computational Physics*, Vol. 17, J. Chang, Ed., Academic Press, 173-265.

Janjic, Z. I., J. P. Gerrity, Jr., and S. Nickovic, 2001: An alternative approach to nonhydrostatic modeling. *Mon. Wea. Rev.*, **129**, 1164-1178.

Janjic, Z. I., F. Mesinger, and T. L. Black, 1995: The pressure advection term and additive splitting in split-explicit models. *Quart. J. Roy. Meteor. Soc.*, **121**, 953-957.

Mesinger, F., 1973: A method for construction of second-order accuracy difference schemes permitting no false two-grid-interval wave in the height field. *Tellus*, **25**, 444-458.

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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://wwwt.emc.ncep.noaa.gov/officenotes).

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Mesinger, F., Z. I. Janjic, S. Nickovic, D. Gavrilov, and D. G. Deaven, 1988: The step-mountain coordinate: model description and performance for cases of Alpine lee cyclogenesis and for a case of an Appalachian redevelopment. *Mon. Wea. Rev.*, **116**, 1493-1518.

Zhang, H., and M. Rancic: 2007: A global Eta model on quasi-uniform grids. *Quart. J. Roy. Meteor. Soc.*, **133**, 517-528.

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,

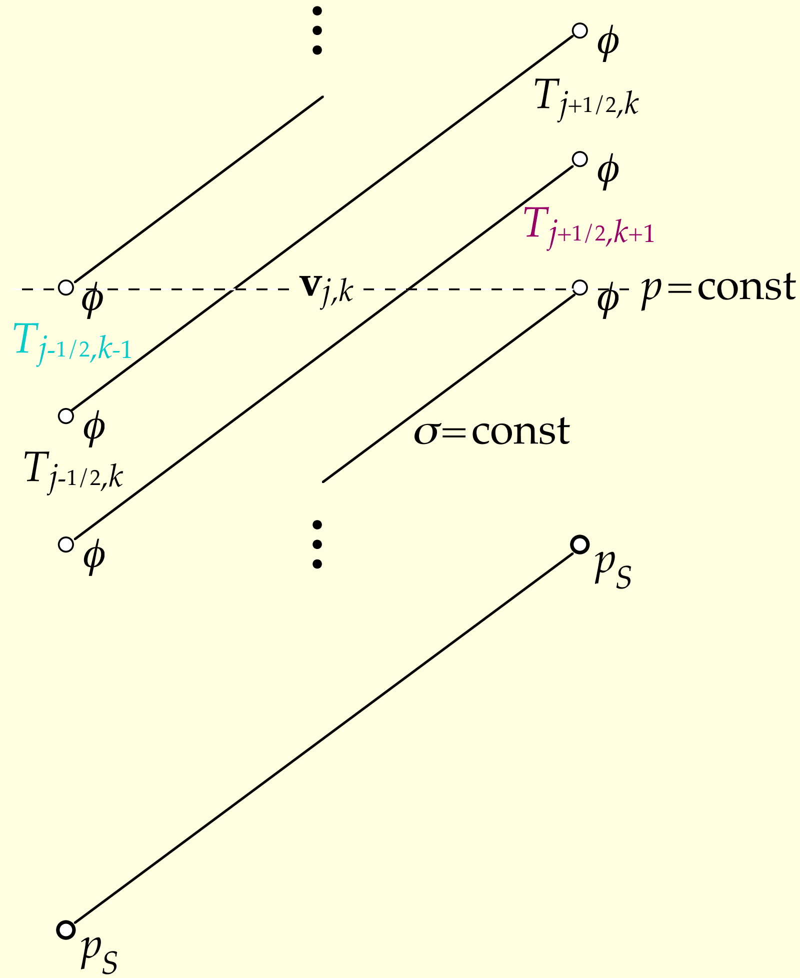
$$\phi = \phi_S - R_d \int_{p_S}^{p} T_v \, d \ln p$$

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:

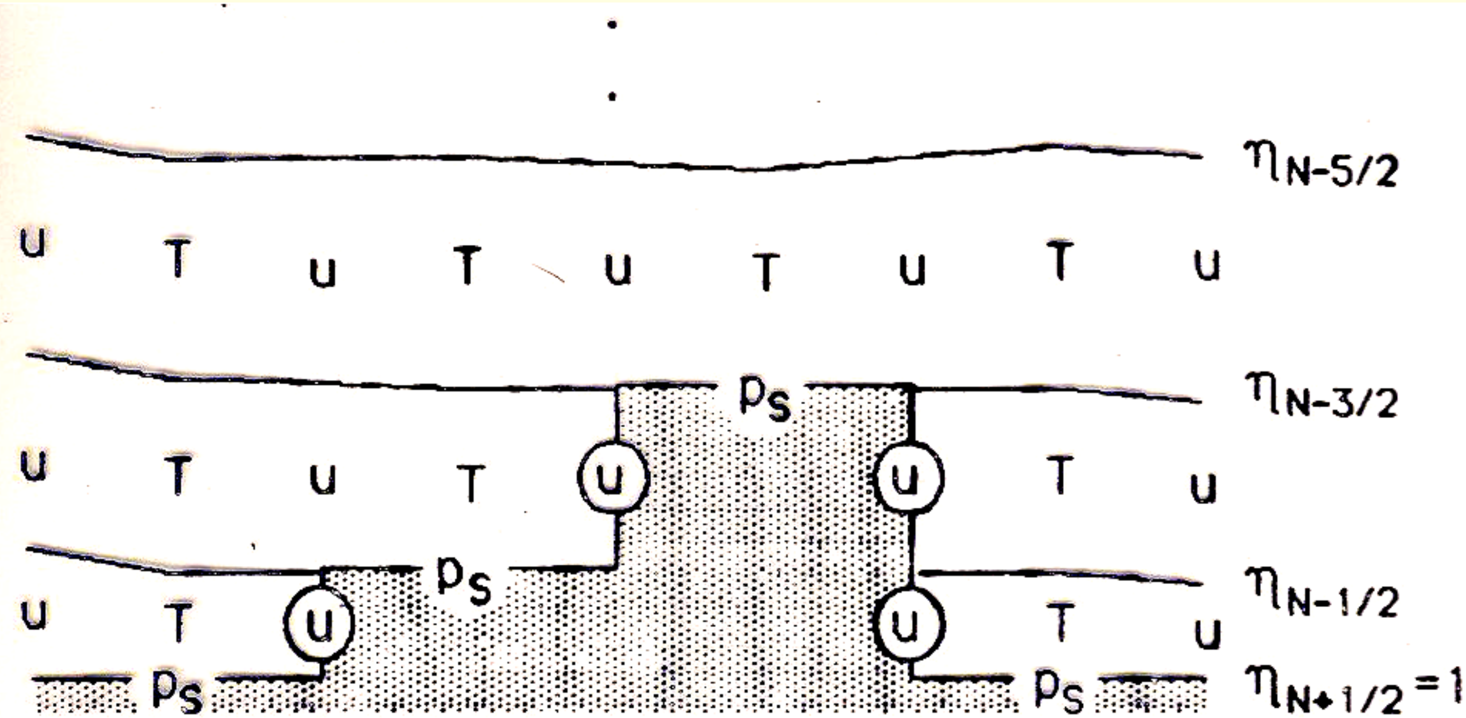


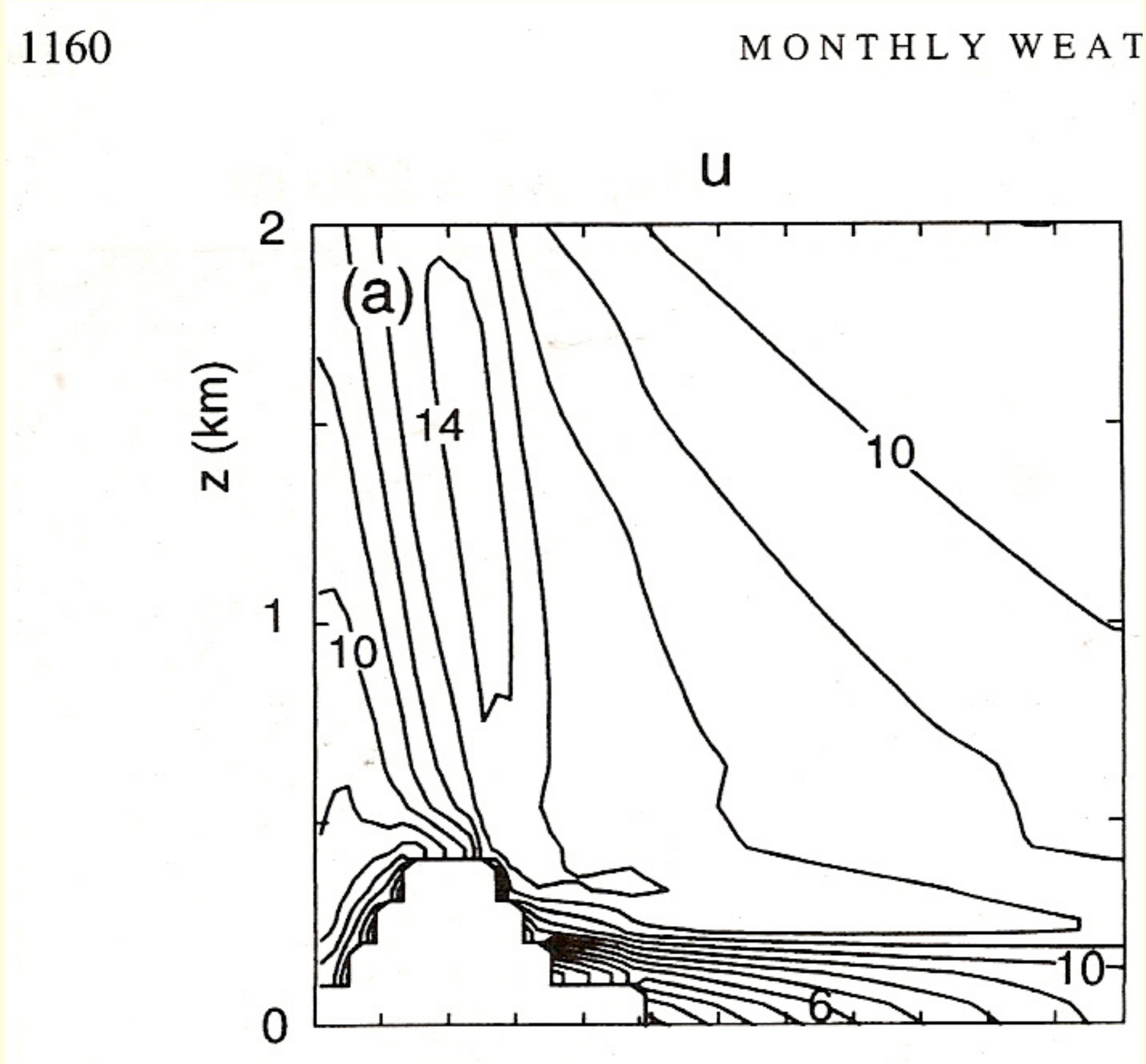
FIG. 1. Schematic representation of a vertical cross section in the eta coordinate using step-like representation of mountains. Symbols *u*, *T* and p_s represent the *u* component of velocity, temperature and surface pressure, respectively. *N* is the maximum number of the eta layers. The step-mountains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

#2:

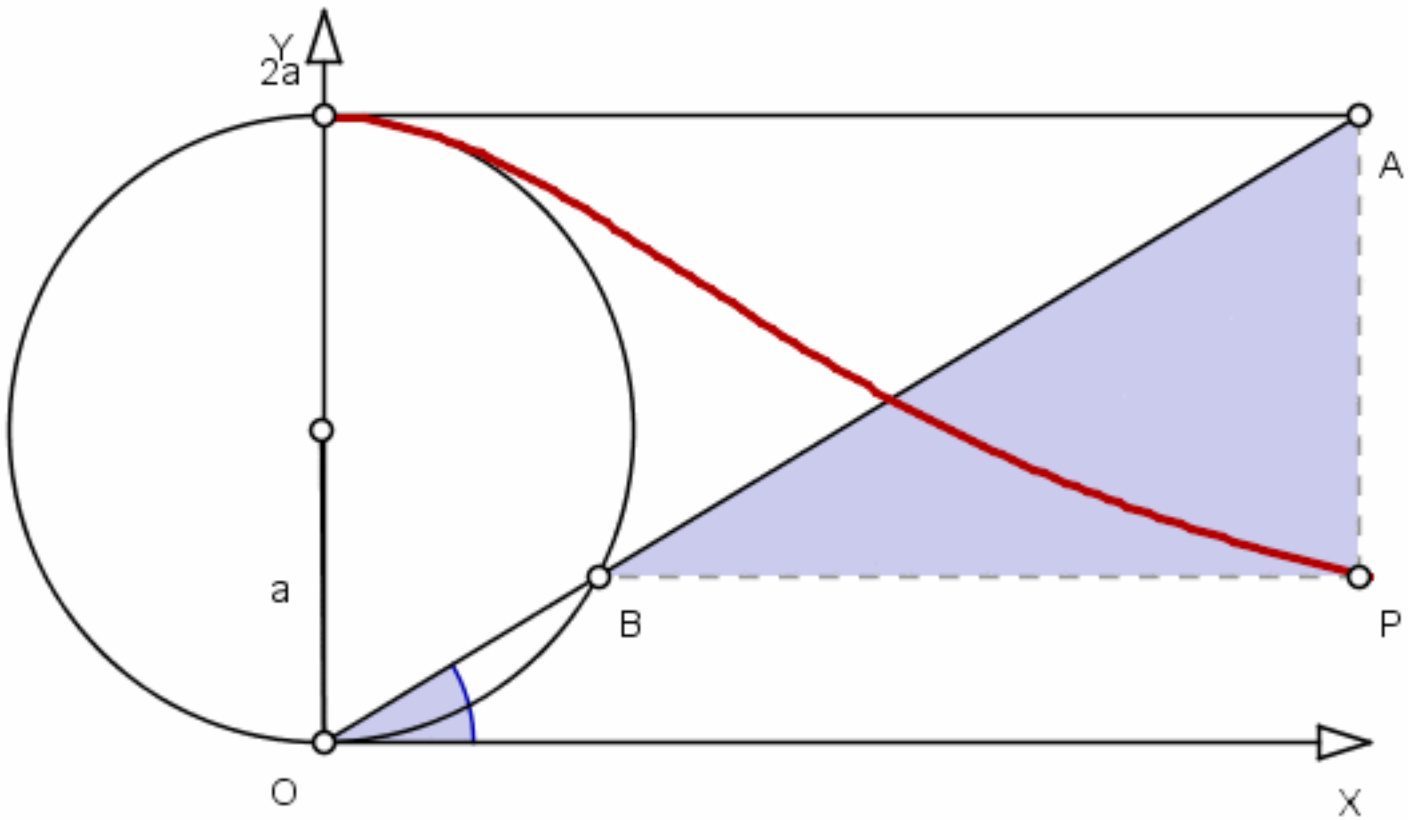
The flow down the slopes noticed to have been in some situations not realistic – tendency for flow separation. Wasatch downslope windstorm, Gallus, Klemp (MWR 2000), a case of Santa Ana wind. But a zonda case (Conf. Southern Hem. Meteor. Ocean. 1966, another later here) done adequately.



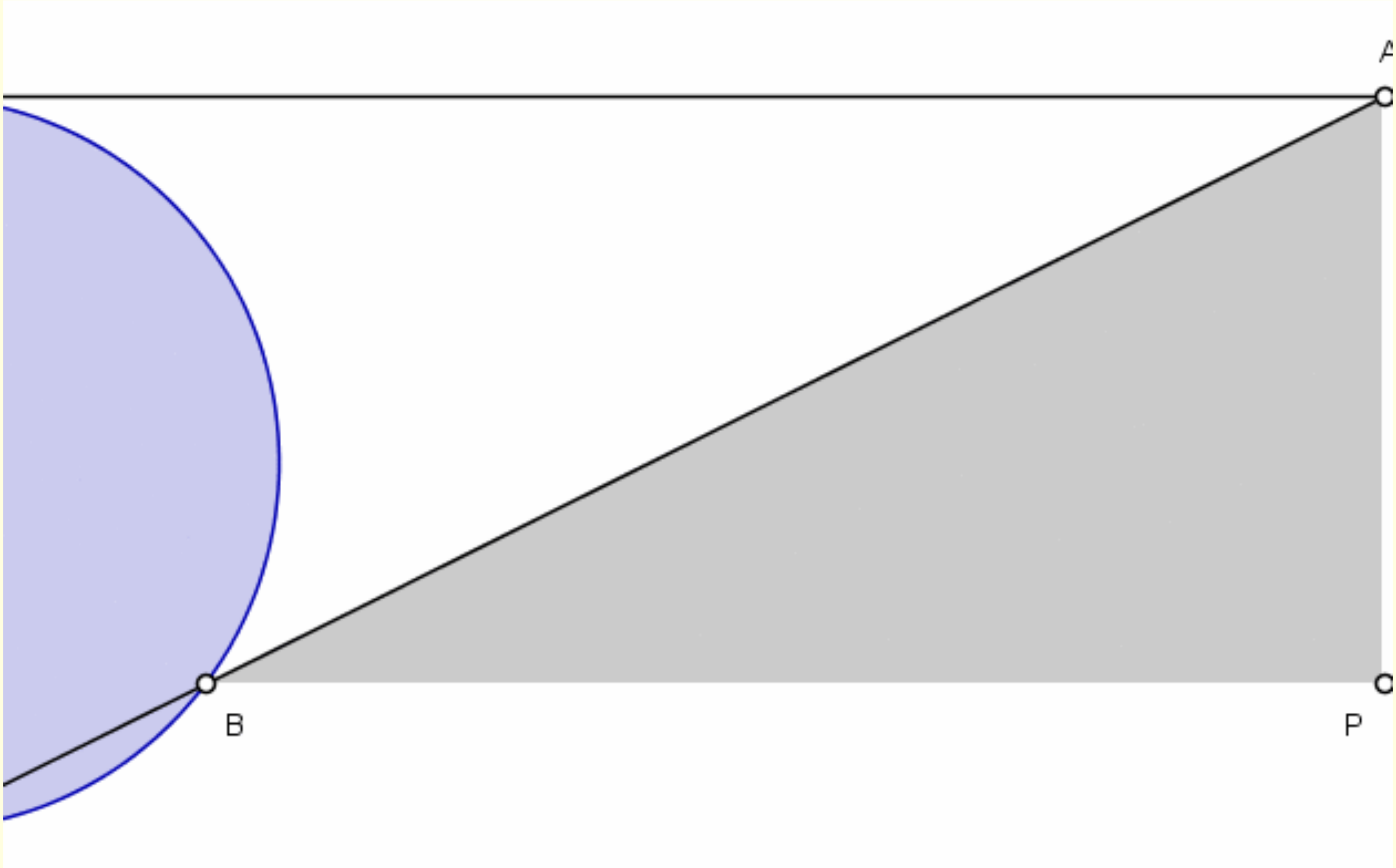
Gallus, Klemp, MWR 2000, Fig. 6 (a), horizontal velocity

("Witch of Agnesi" mountain)

"Witch of Agnesi":

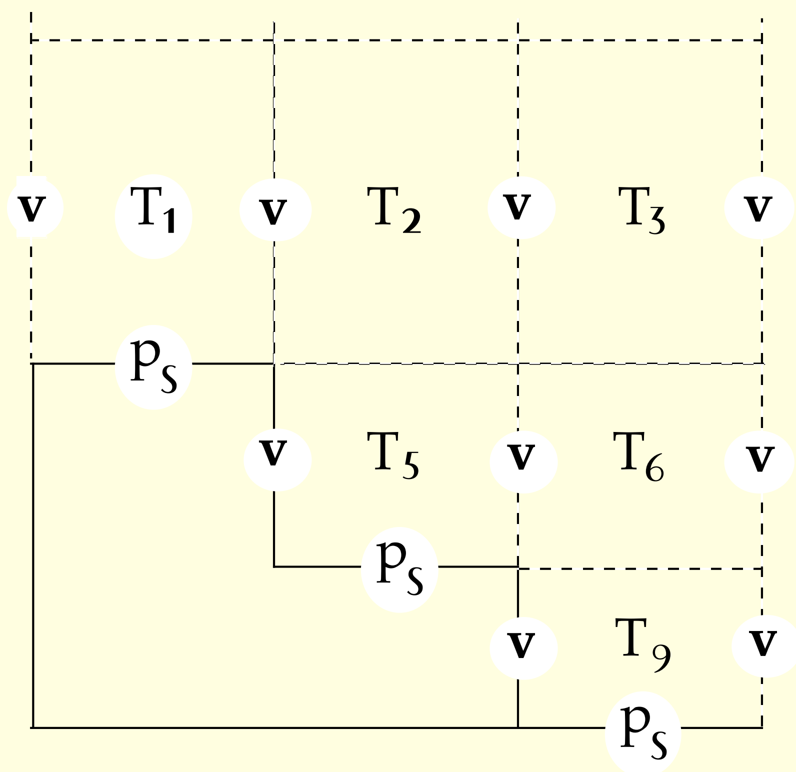


Acklowledgement: Wikipedia, Merrill



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



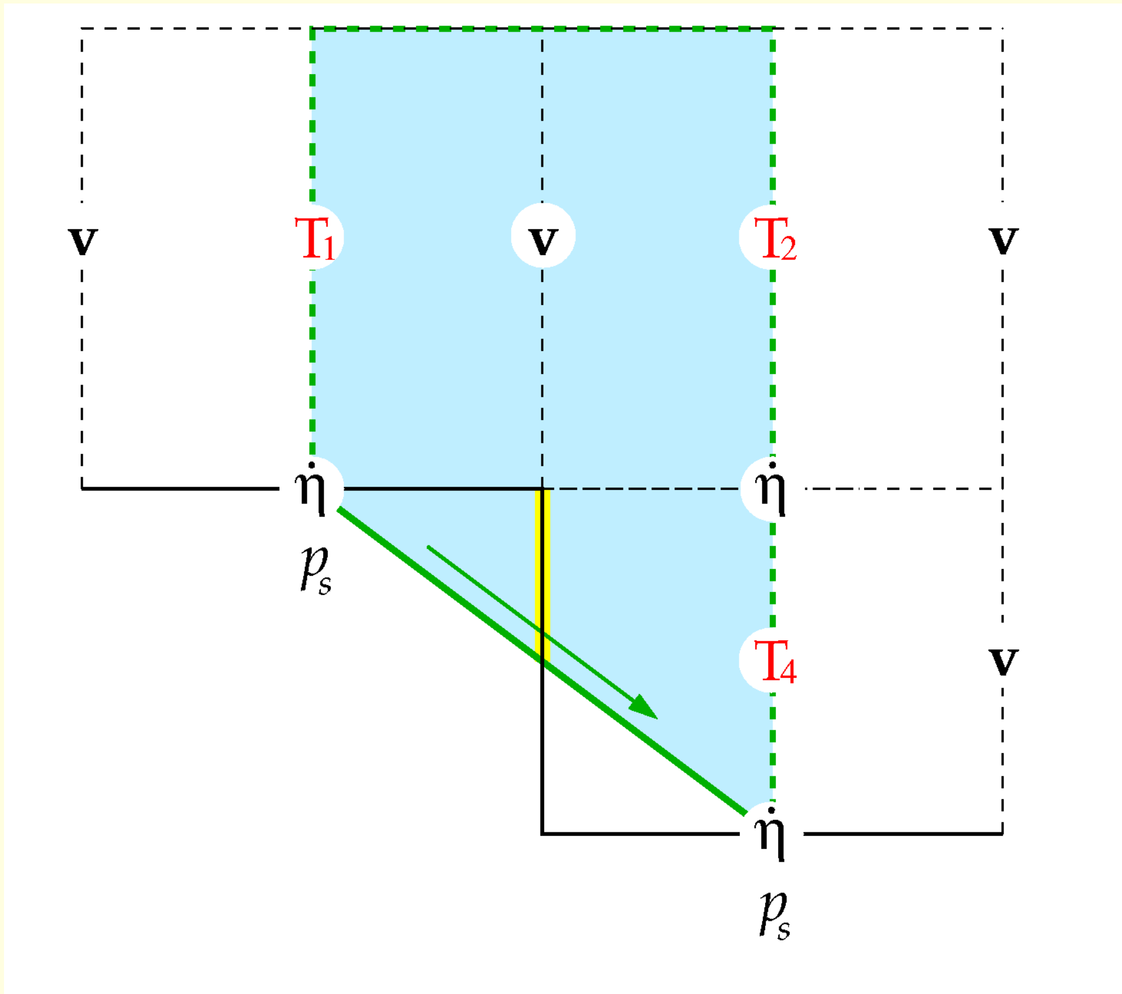
Flow attempting to move from box 1 to 5 is forced to enter box 2 first.

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.

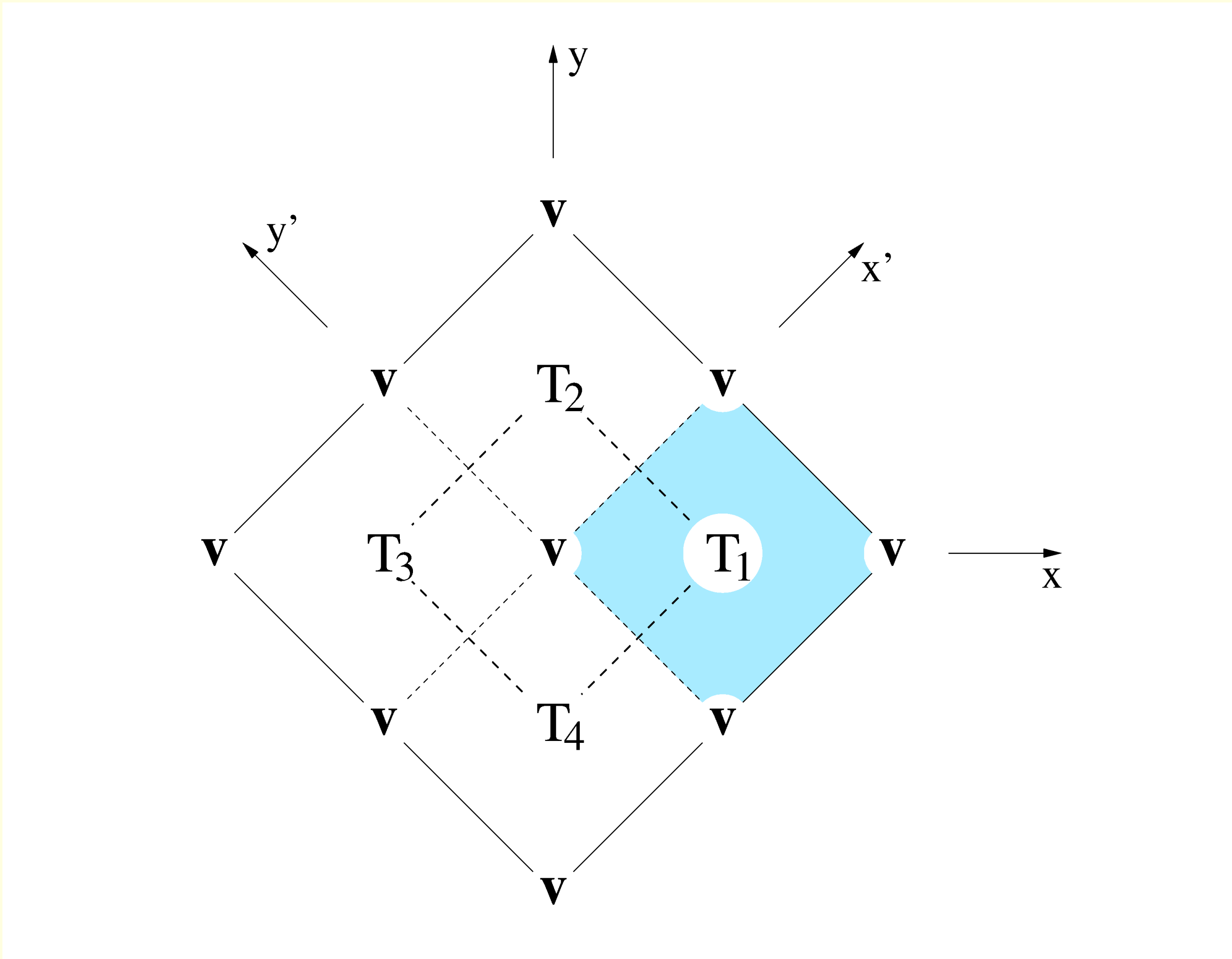
Remedy: The sloping steps, vertical grid

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



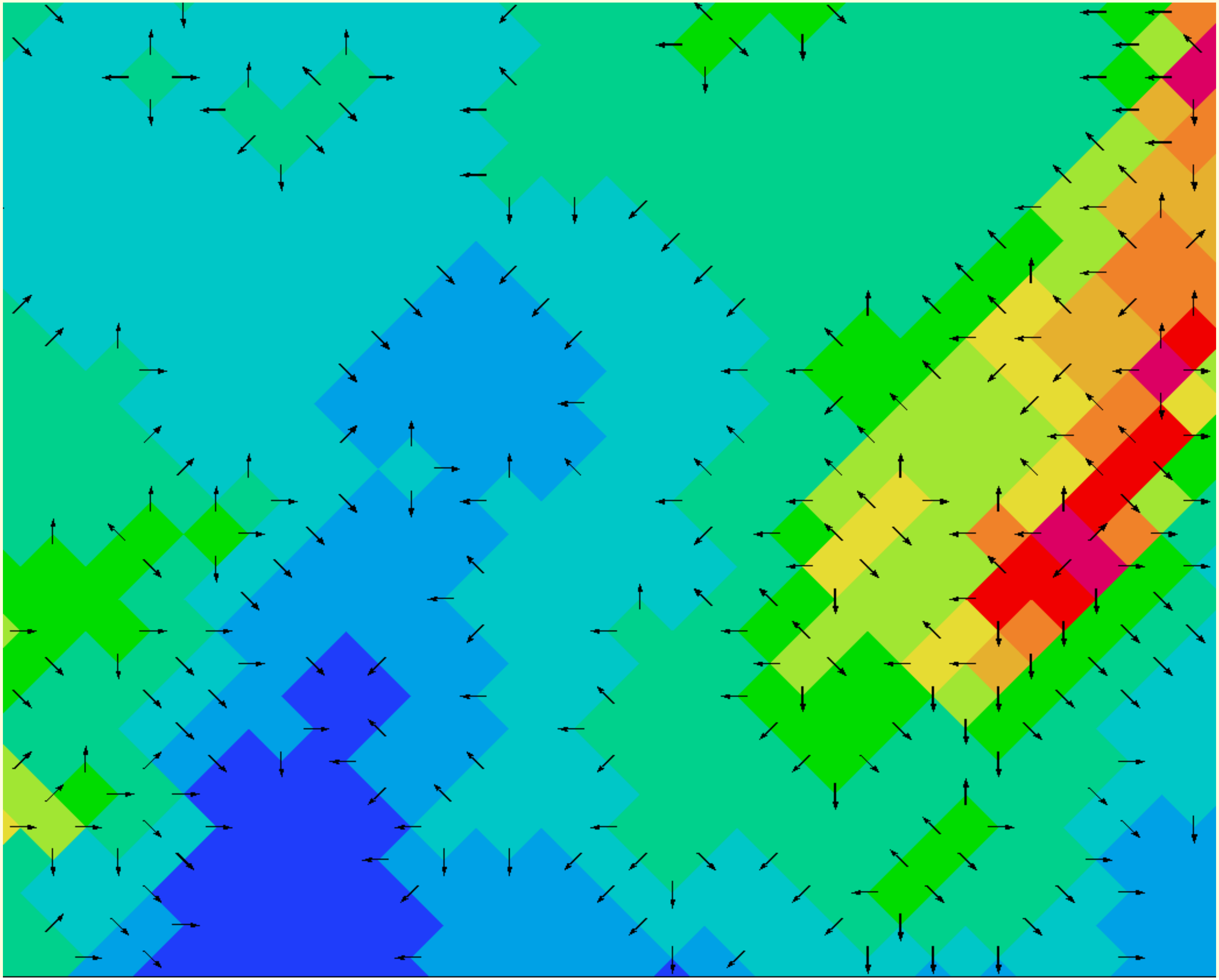
Horizontal treatment, 3D

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



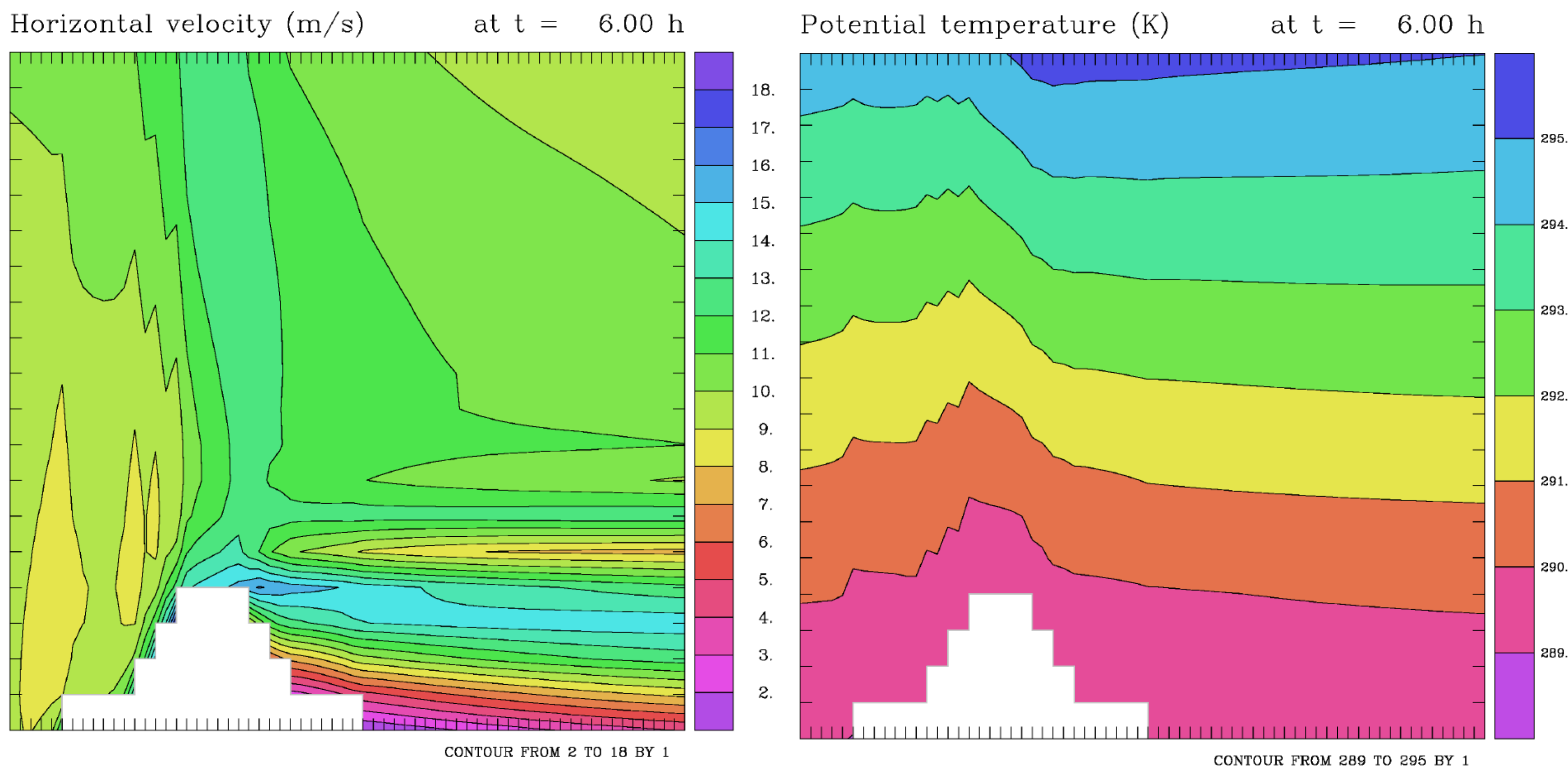
Inside the central **v** box, topography descends from the center of T1 box down by one layer thickness, linearly, to the centers of T2, T3 and T4

Example of slopes with an actual model topography:



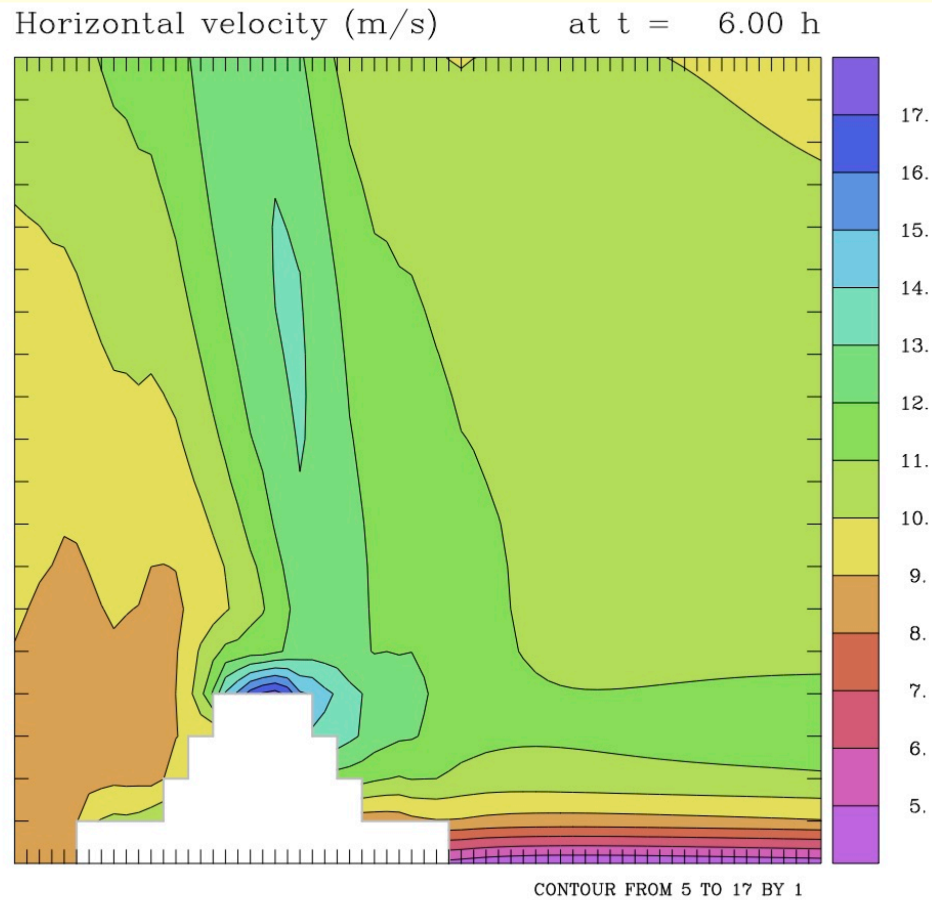
The Eta Gallus-Klemp Problem: before

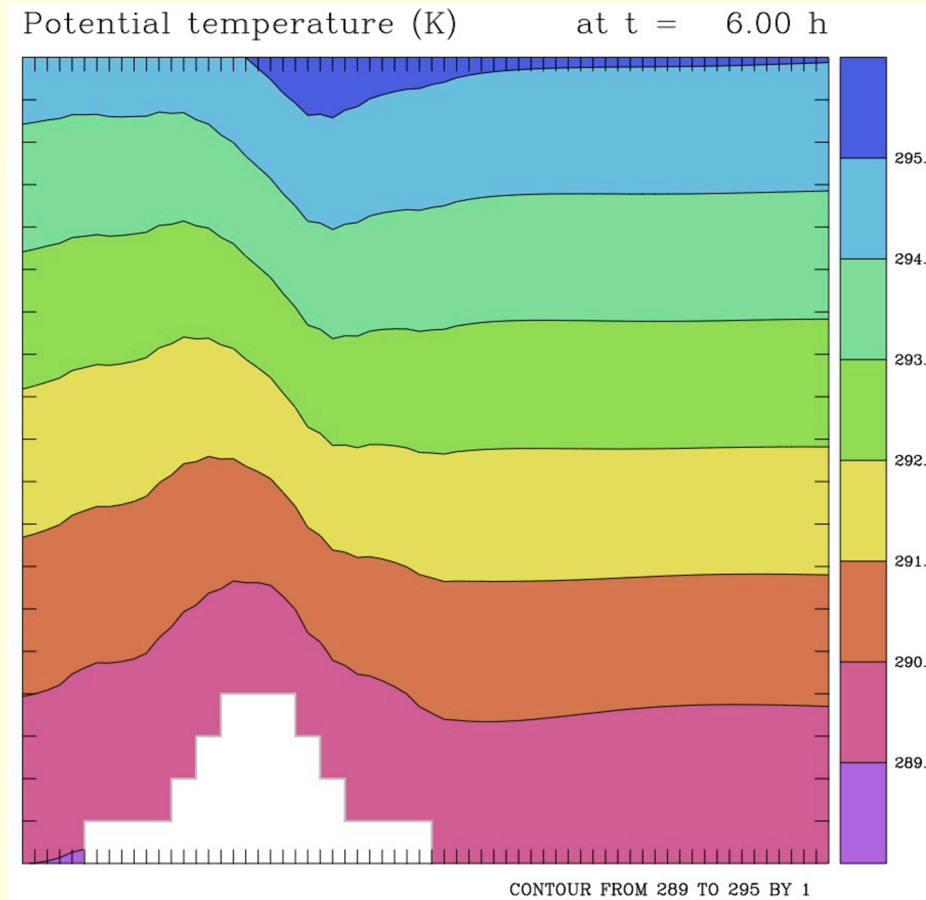
Flow separation on the lee side (à la Gallus and Klemp 2000)



(Hydrostatic; ought to be better nonhydrostatic, on “to do list”)

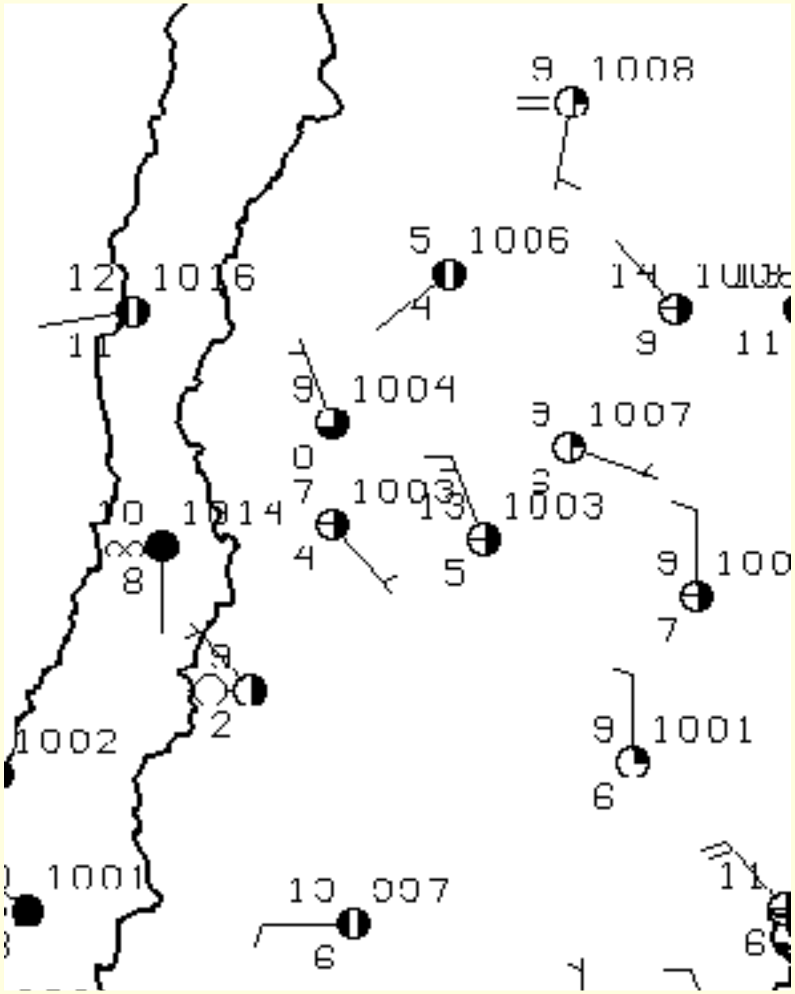
After: Emulation of the Gallus-Klemp experiment, Sloping steps code (“poor-man’s shaved cells”):



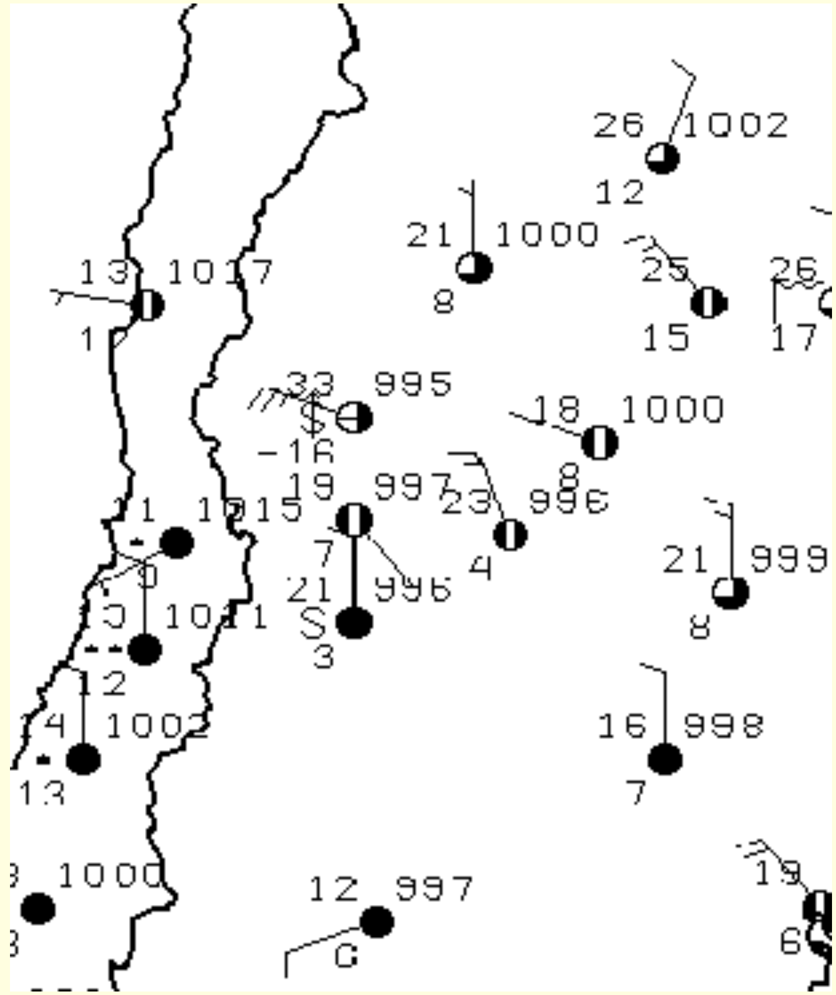


Velocity at the ground immediately behind the mountain increased from between 1 and 2, to between 4 and 5 m/s. “lee-slope separation” much reduced. Zig-zag features in isentropes at the upslope side removed.

Performance in a zonda downslope windstorm case



1200 UTC 11 July 2006



1800 UTC 11 July 2006

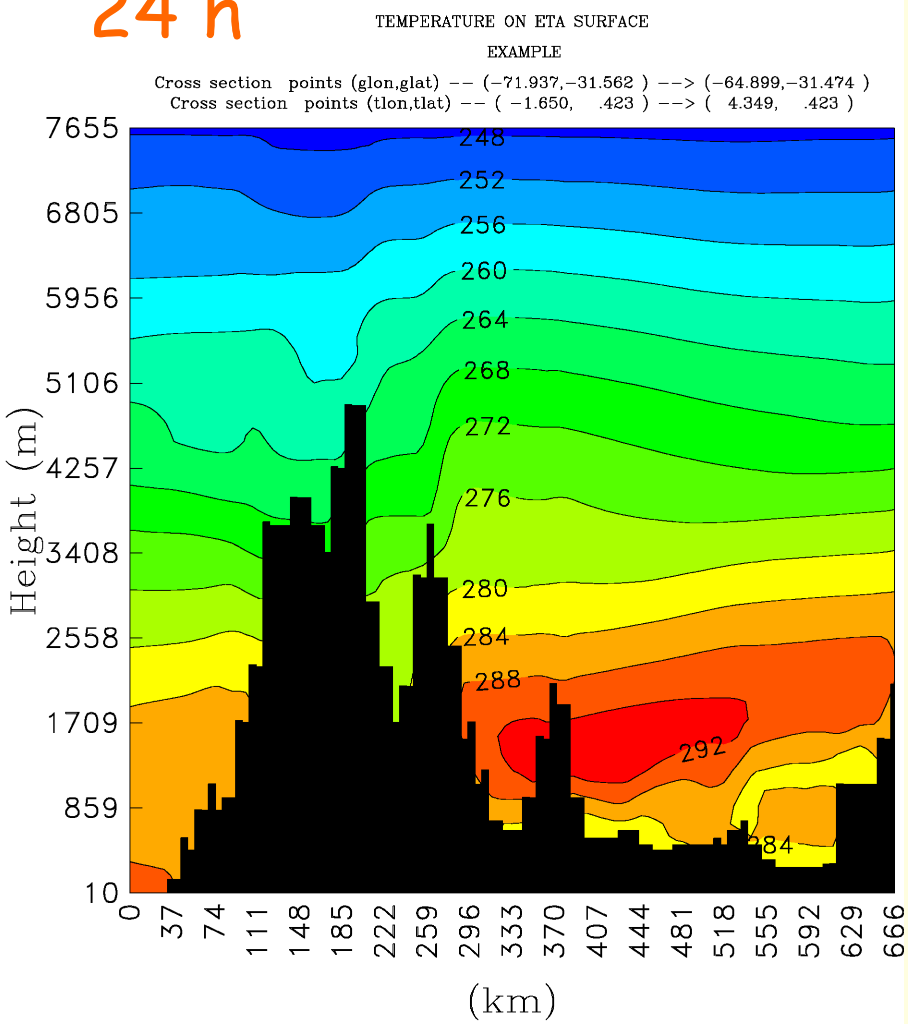
Note the station San Juan with the 2 m T increase from 9 to 33°C in 6 hours !

A real data experiment:
Zonda case of
11-12 July 2006

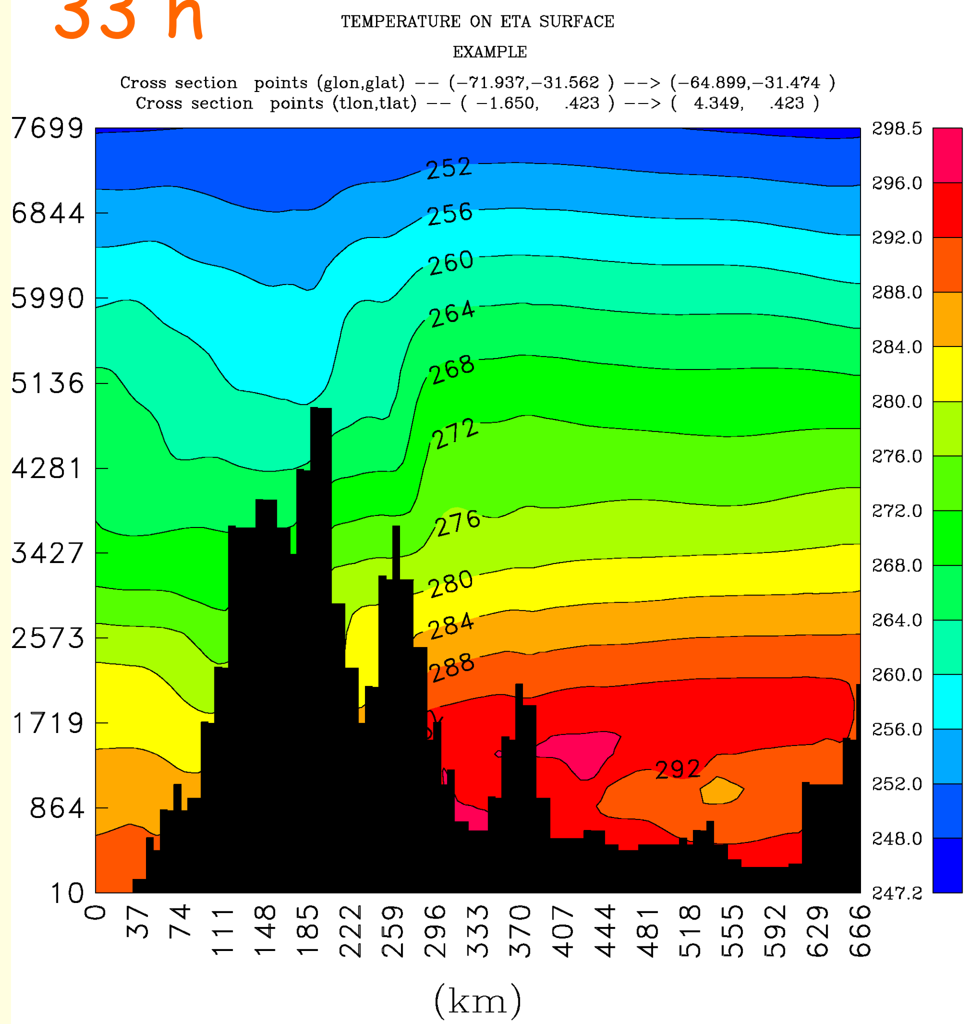
Acknowledgement:
. . .

Initial condition: 1200 UTC 10 July 2006 (8 km/ 60 layers run)

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

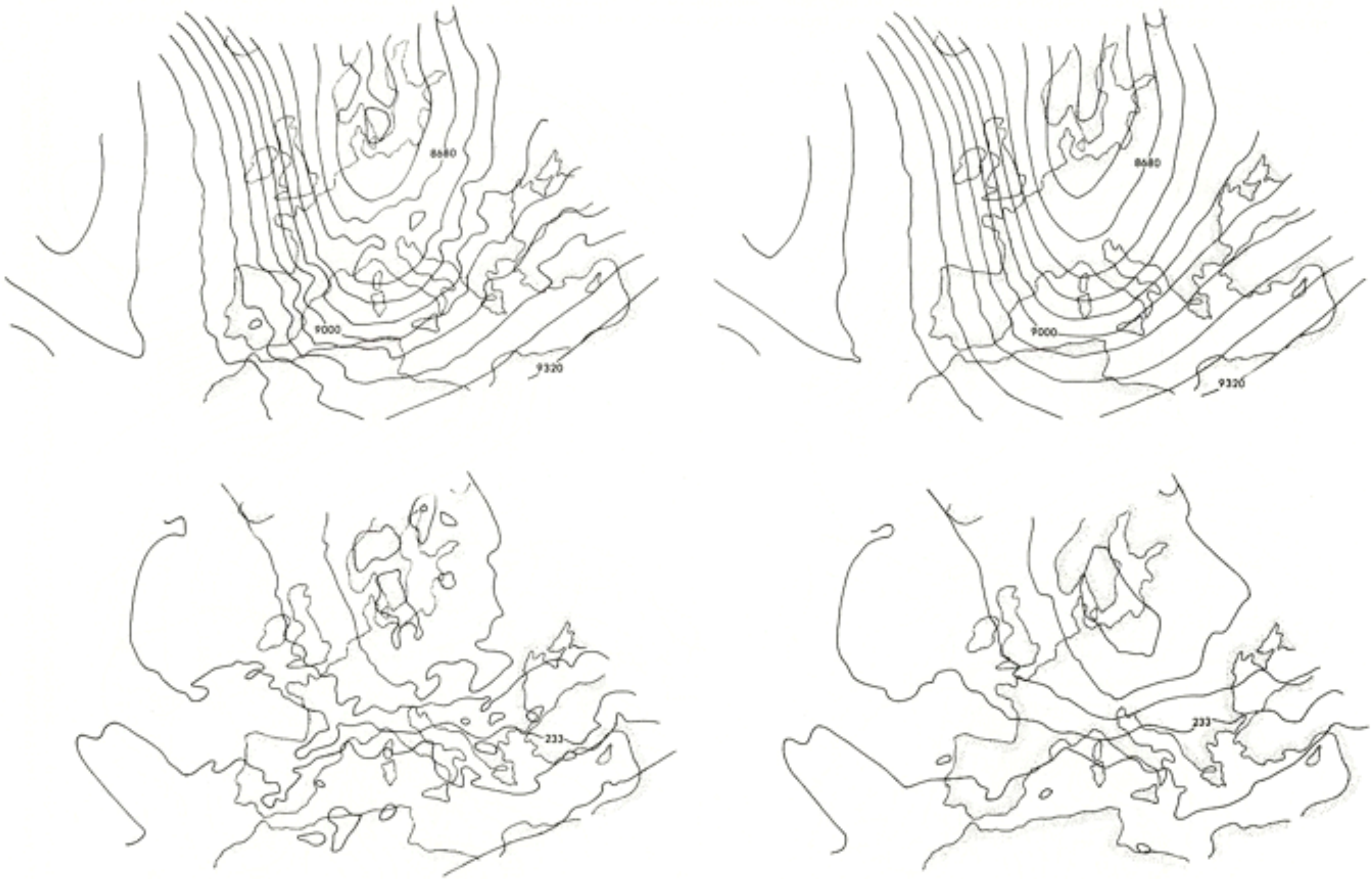


FIG. 6. 300 mb geopotential heights (upper panels) and temperatures (lower panels) obtained in 48 h simulations using the sigma system (left-hand panels) and the eta system (right-hand panels). Contour interval is 80 m for geopotential height and 2.5 K for temperature.

Some addressing precipitation scores, e.g.,

André Robert Memorial Volume:

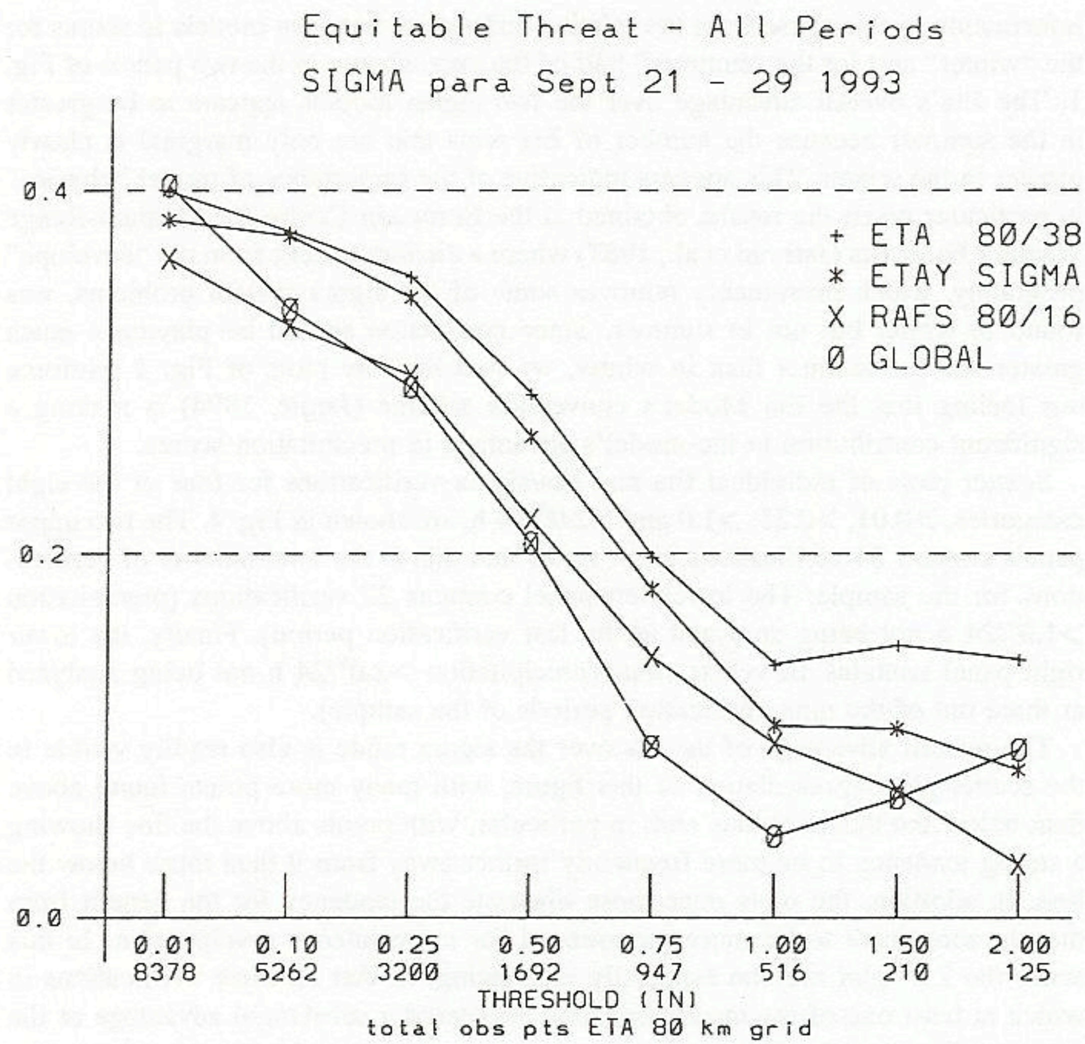


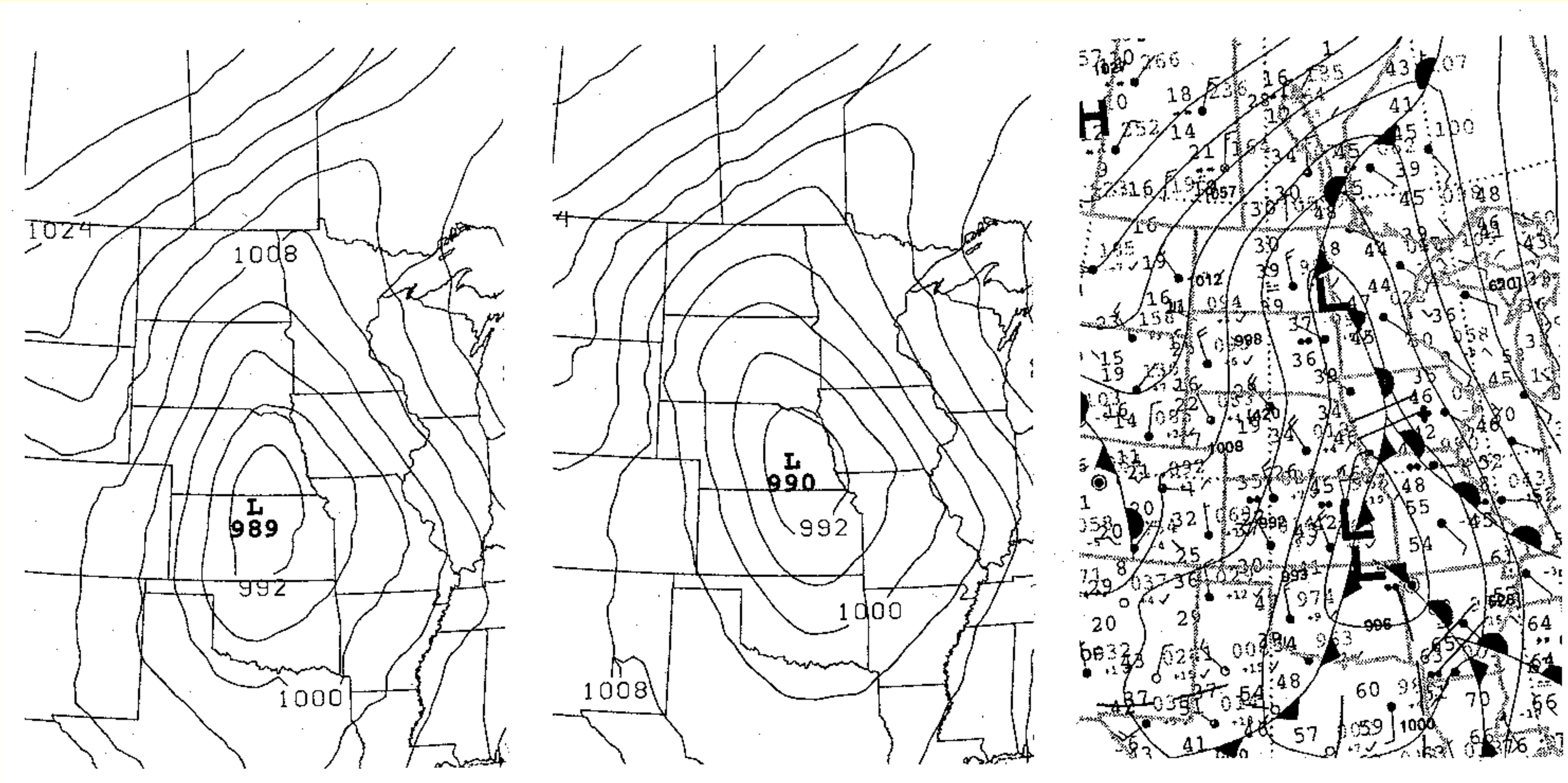
Fig. 3 Equitable precipitation threat scores for two versions of the Eta Model: Eta 80 km/38 layers ("ETA"), and the same version of the Eta Model but run using sigma coordinate ("ETAY"), and for the NGM (RAFS), and the Avn/MRF ("global") Model; for a sample of 16 forecasts verifying 1200 UTC 21 September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

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 :

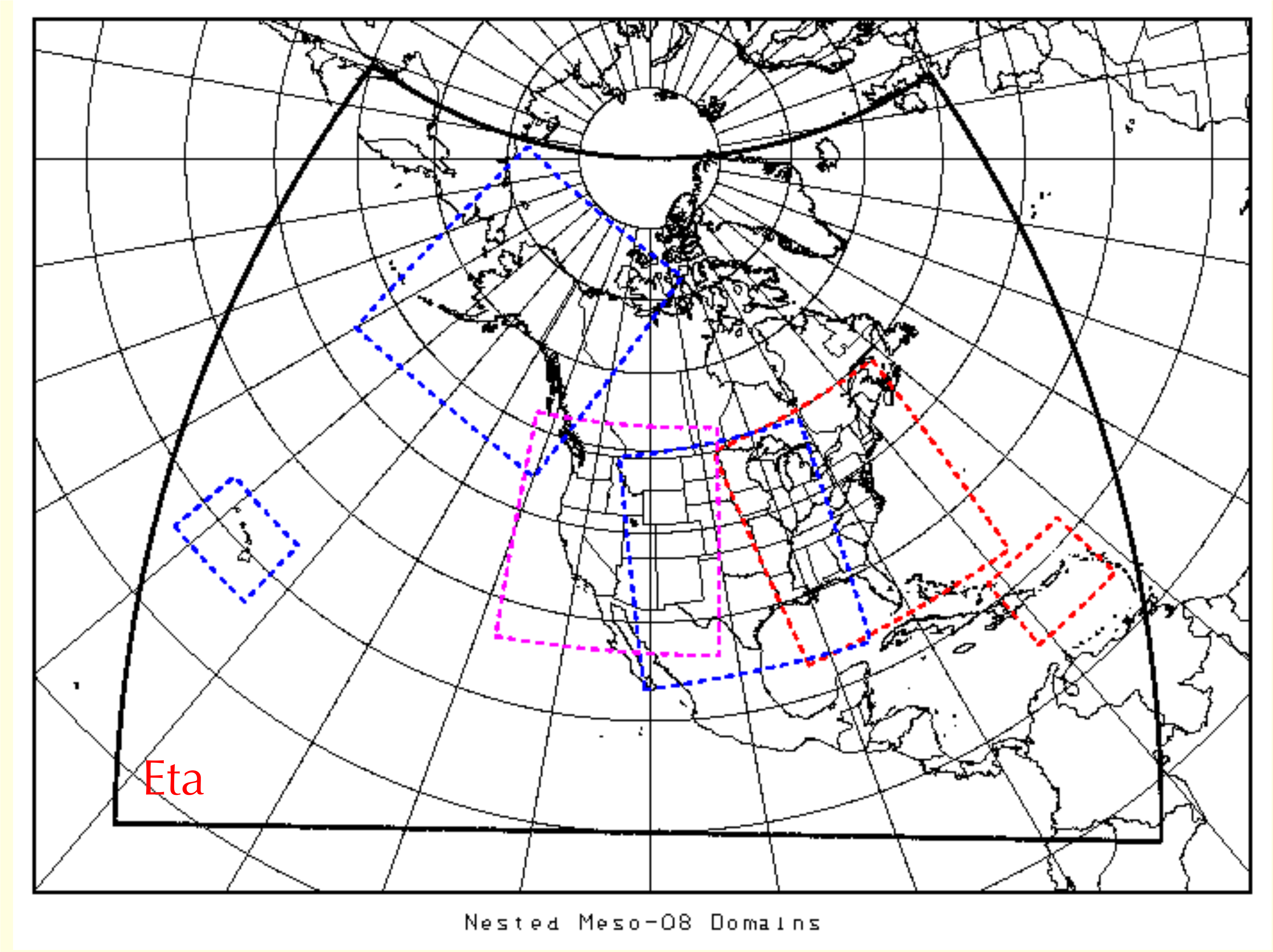


~ Just as in earlier experiments at lower resolution

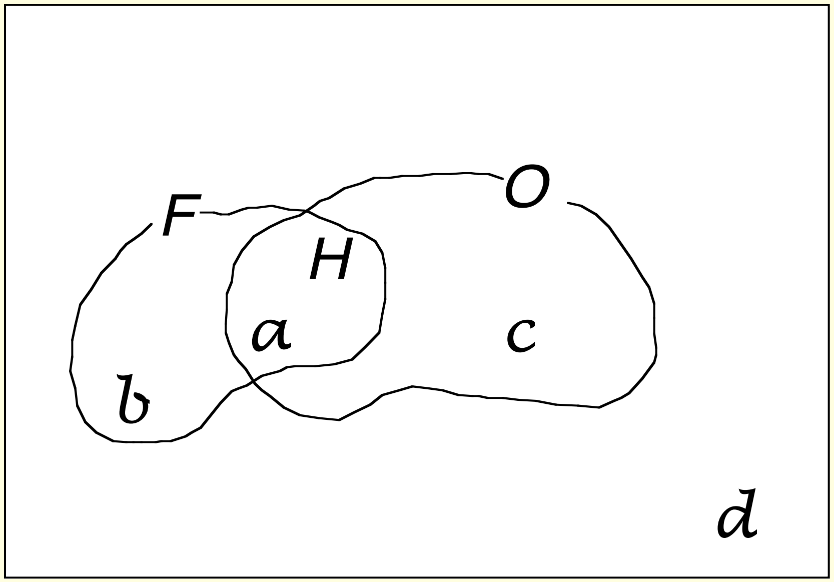
Examples which are not clear tests of one or the other feature, but for which it can be hopefully **convincingly argued** that the main contribution to the success **does come from one (the quasi-horizontal coordinate) or both of the preceding features**:

- 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;


Eta
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:

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

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

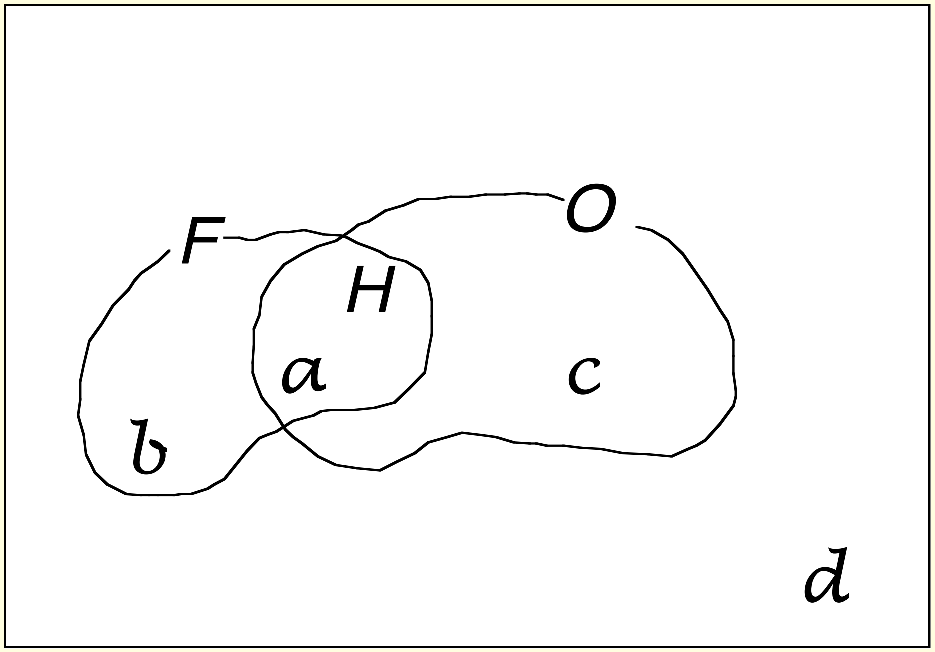
Methods to correct for bias:

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:

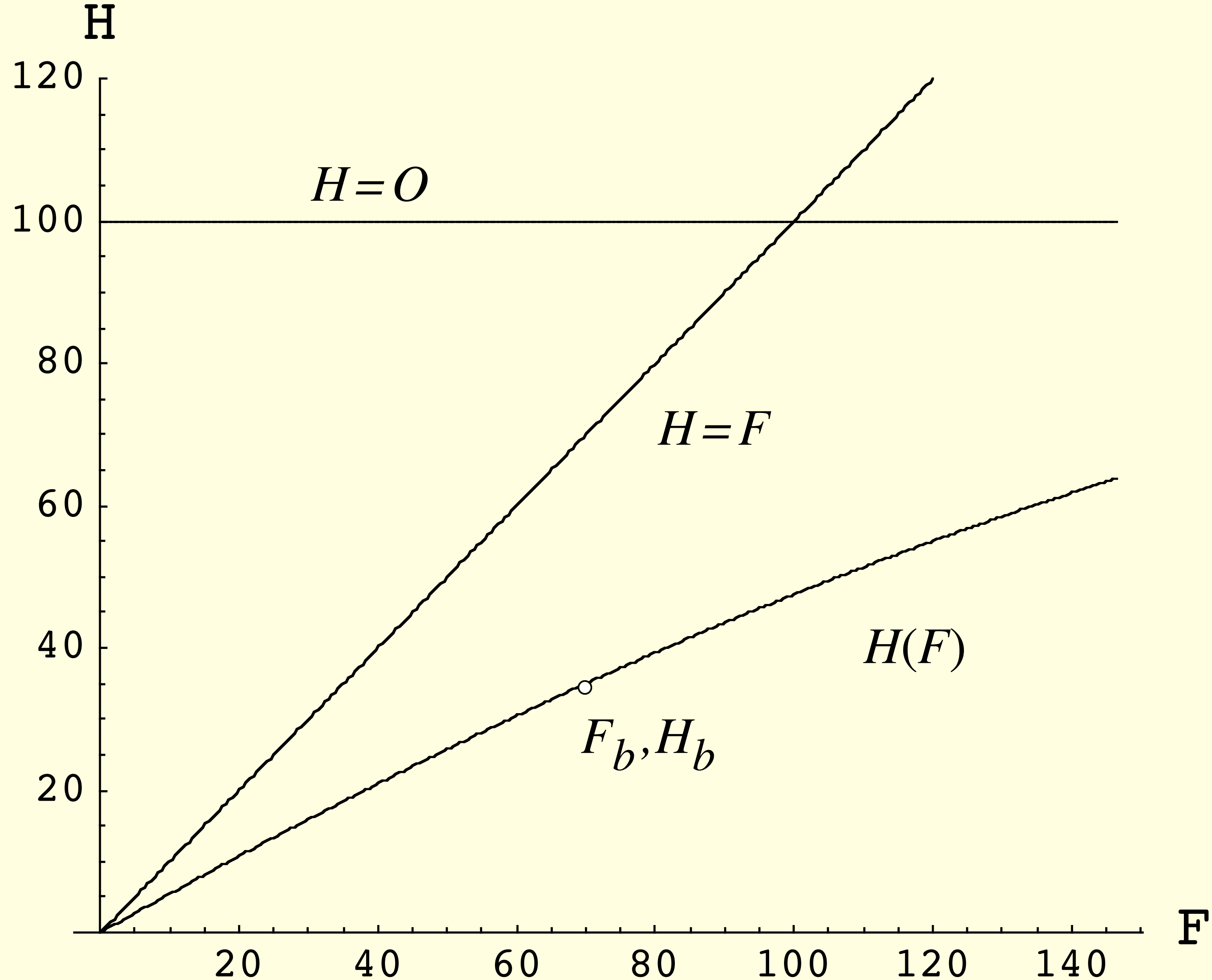
$$\frac{dH}{dA} = b(O - H) \qquad b = const$$

Differential equation, can be solved

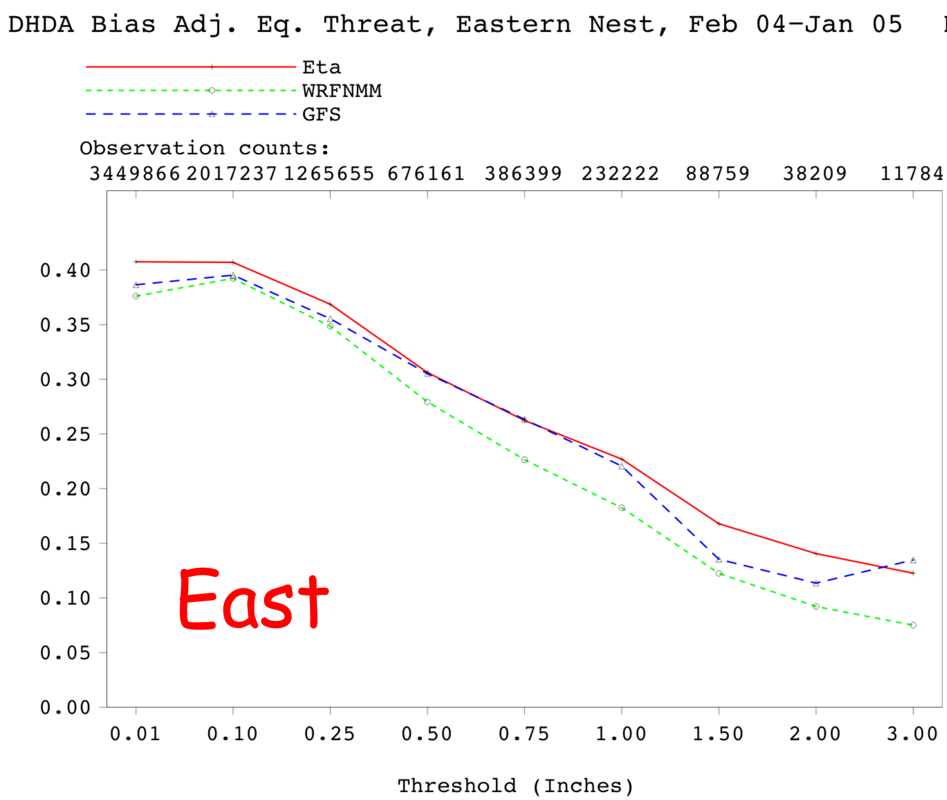
(Mathematica, or MATLAB)

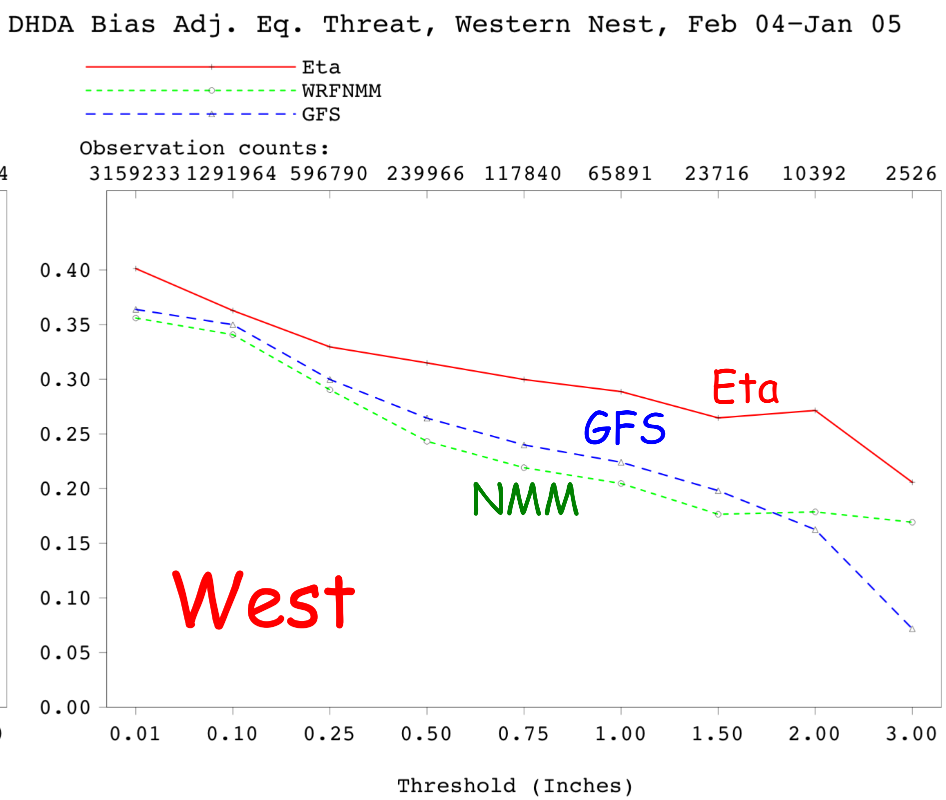
$H(F)$ obtained that now satisfies an additional requirement of dH/dF never > 1

dHdA method



ETS corrected for bias



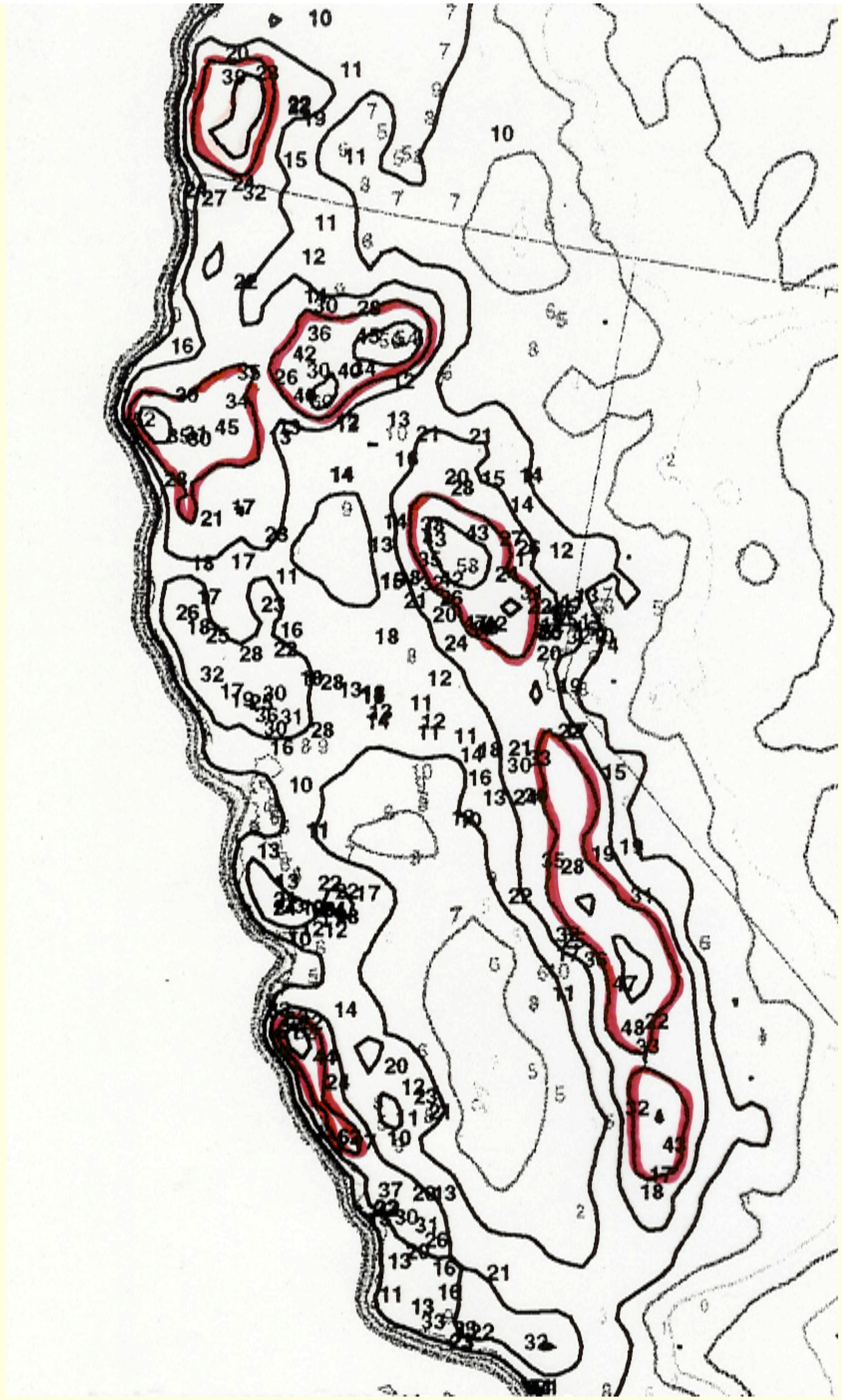


Correction for bias: Mesinger (Adv. Geosci. 2008): In order to obtain score that verifies placement of precipitation !

An example of precip at one of such events:

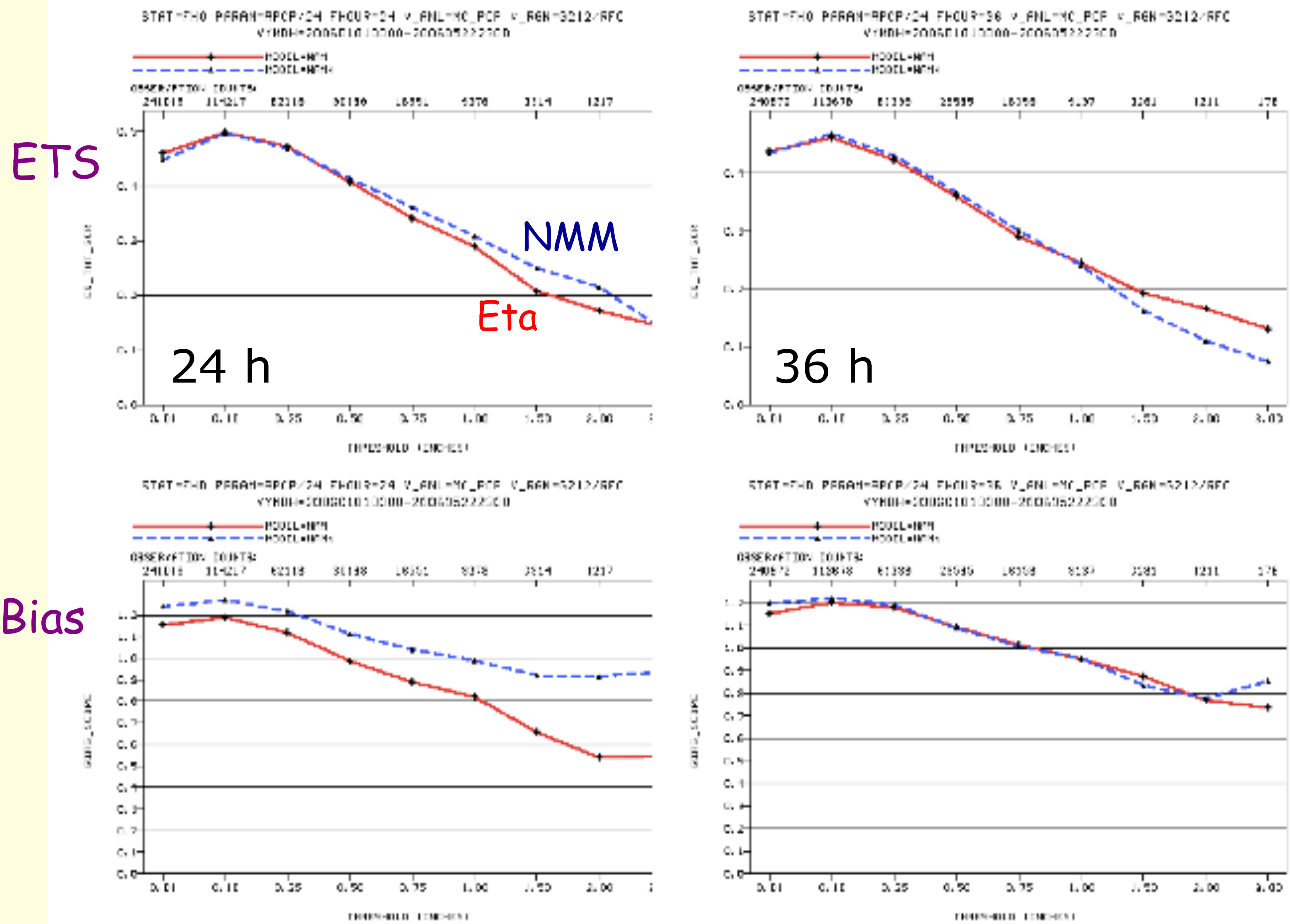
(8 Nov. 2002, red contours: 3 in/24 h)

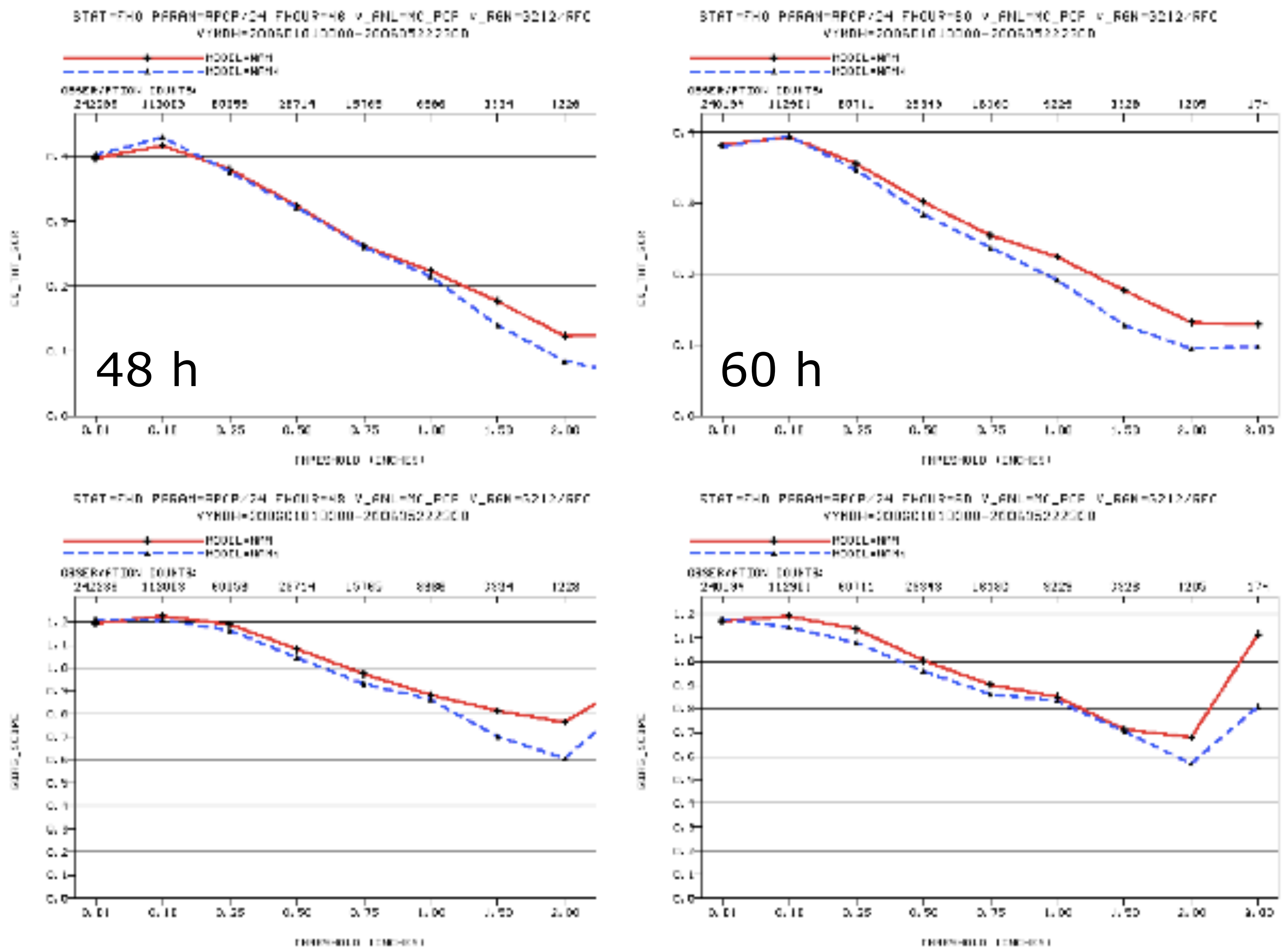
An extraordinary challenge to do well in QPF sense !

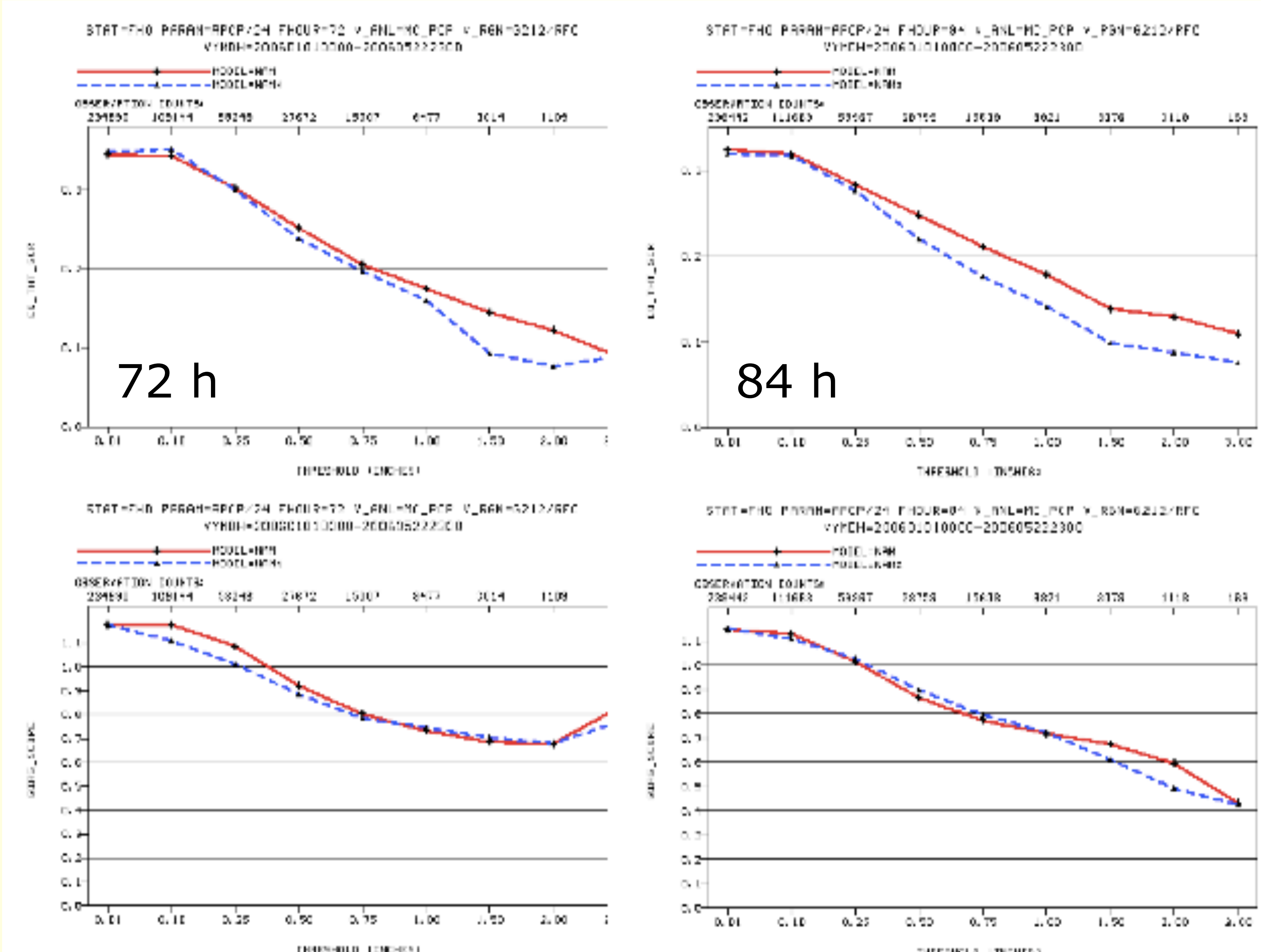


More recent results – comparison of Eta against the WRF-NMM, but with WRF-NMM using a new data assimilation system (from DiMego 2006)

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



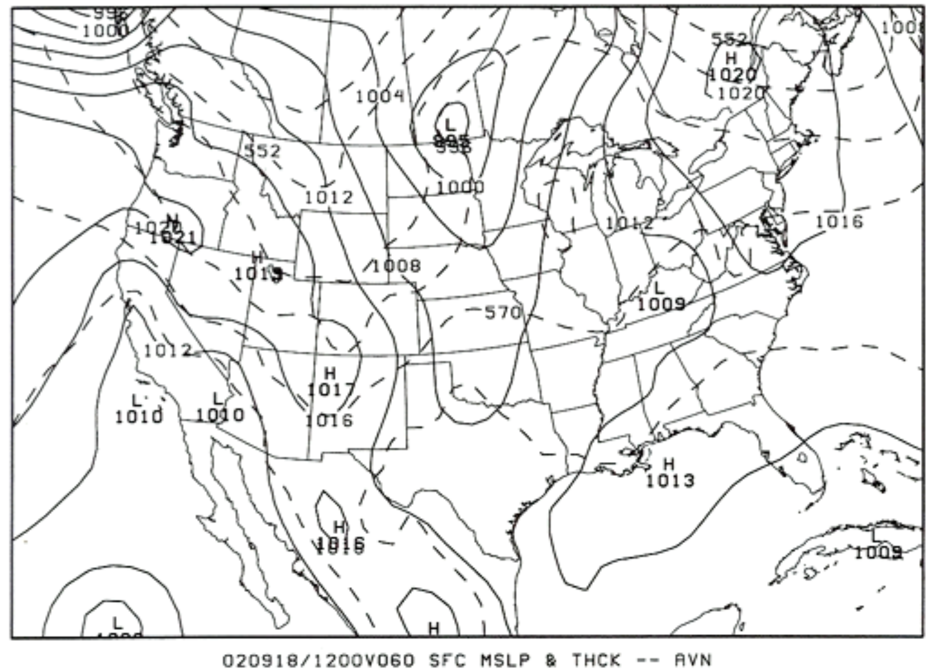
(From DiMego 2006)

The three low centers case

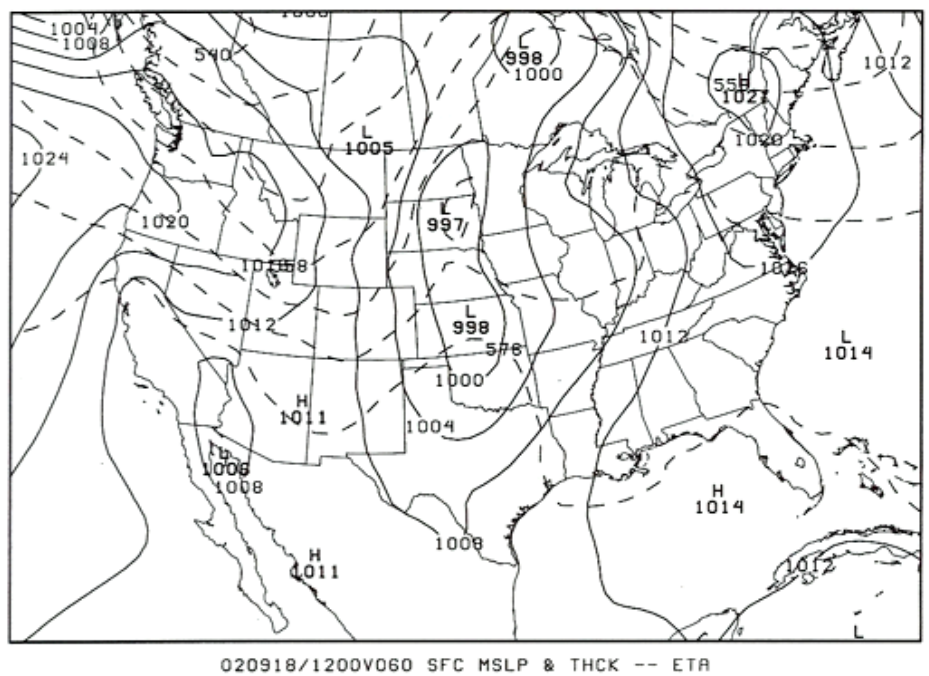
Valid at

12z 18 September 2002

Avn

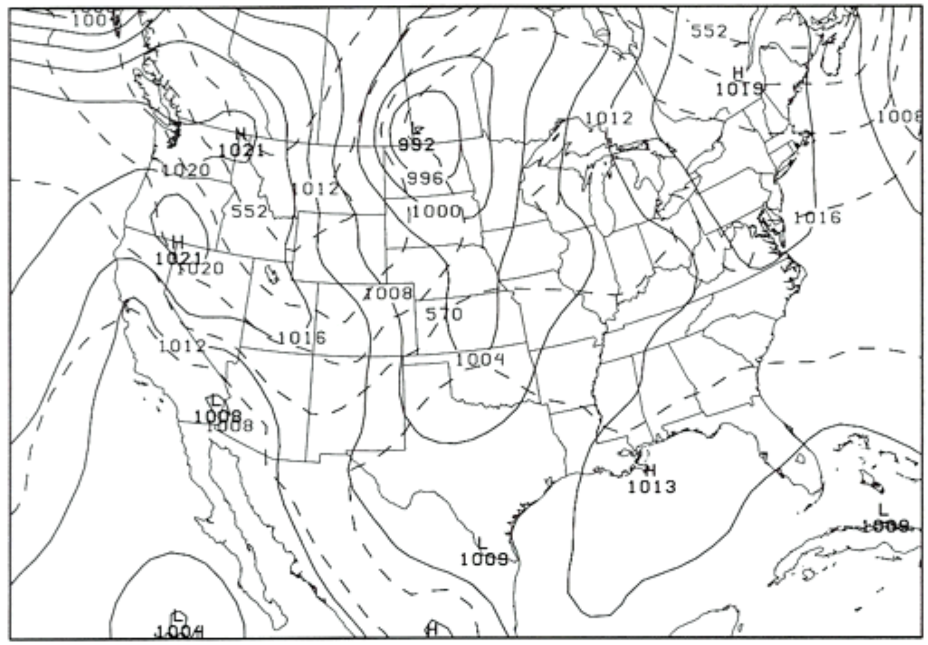


Eta



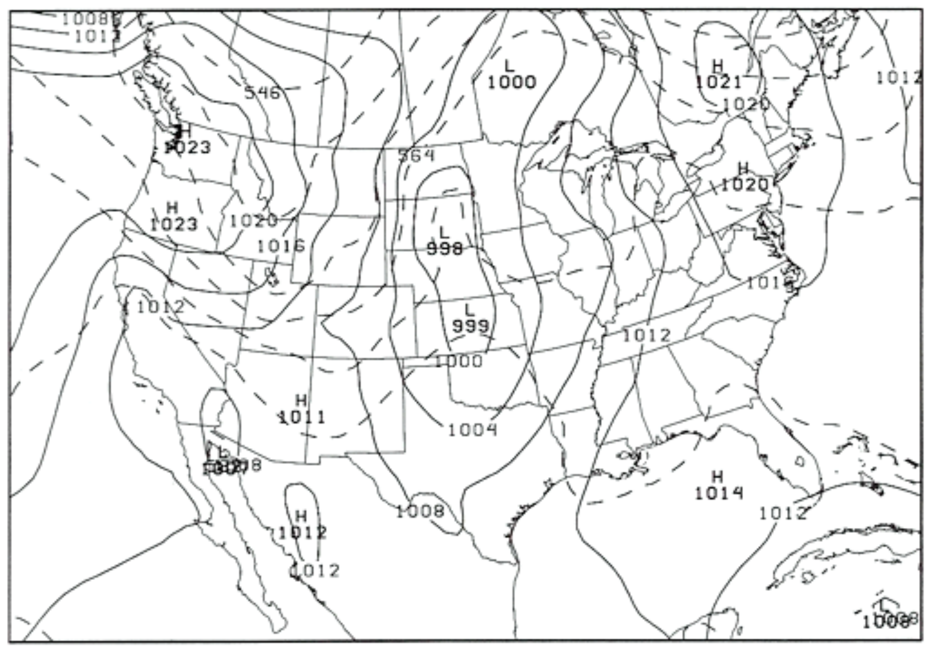
60 h fcsts

Avn



020918/1200V048 SFC MSLP & THCK -- AVN

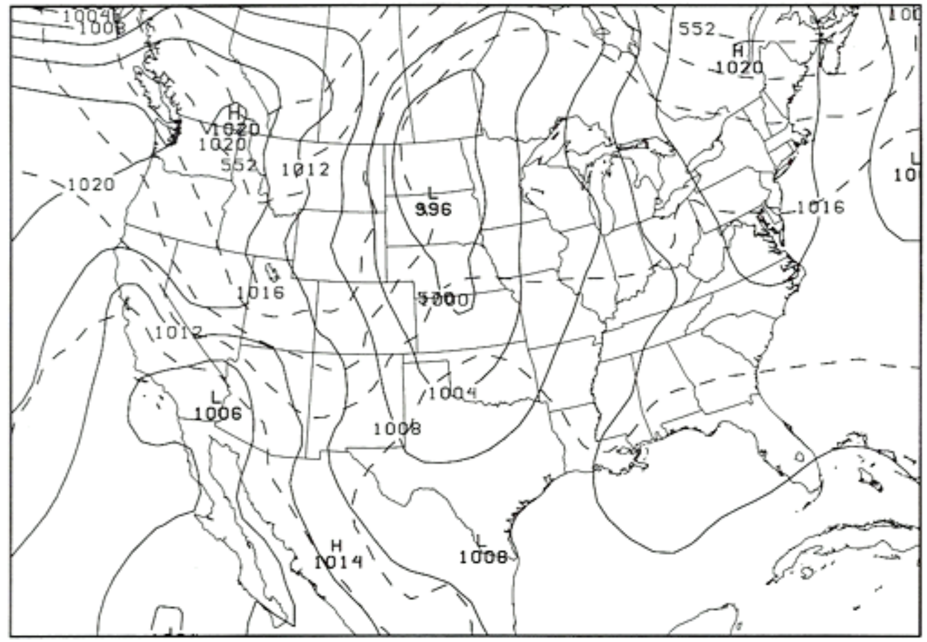
Eta



020918/1200V048 SFC MSLP & THCK -- ETA

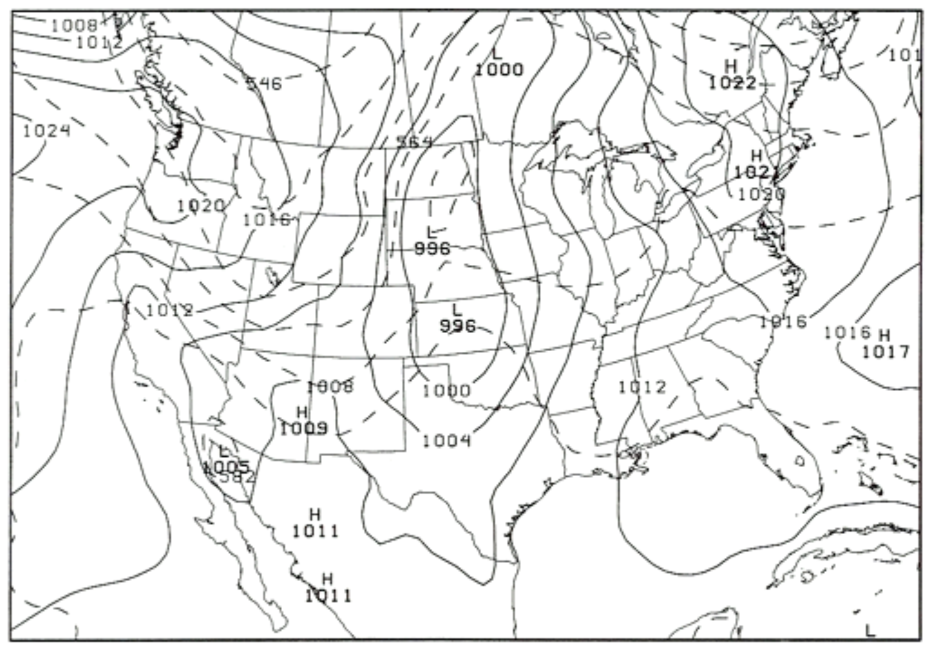
48 h fcsts

Avn



020918/1200V036 SFC MSLP & THCK -- AVN

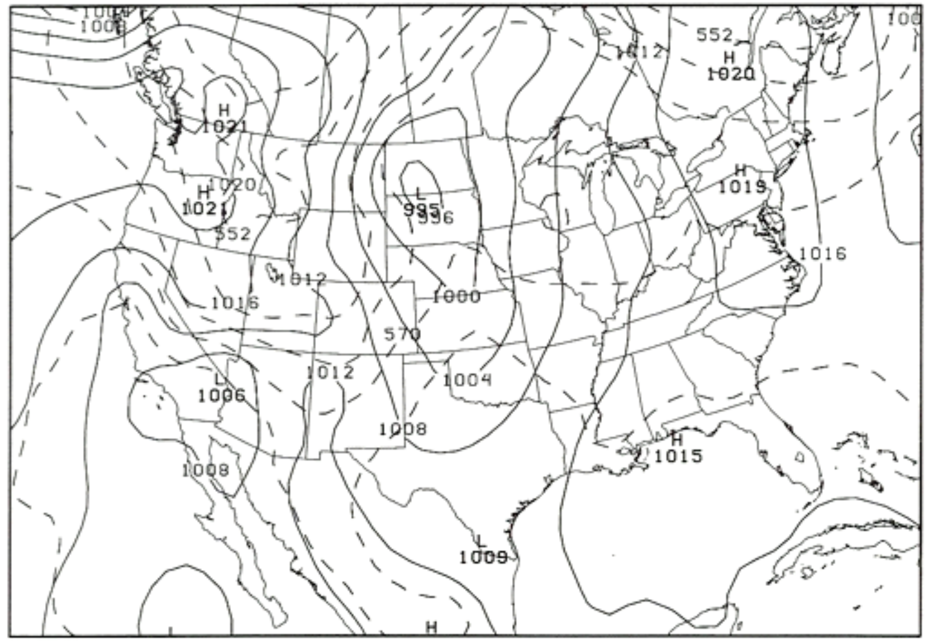
Eta



020918/1200V036 SFC MSLP & THCK -- ETA

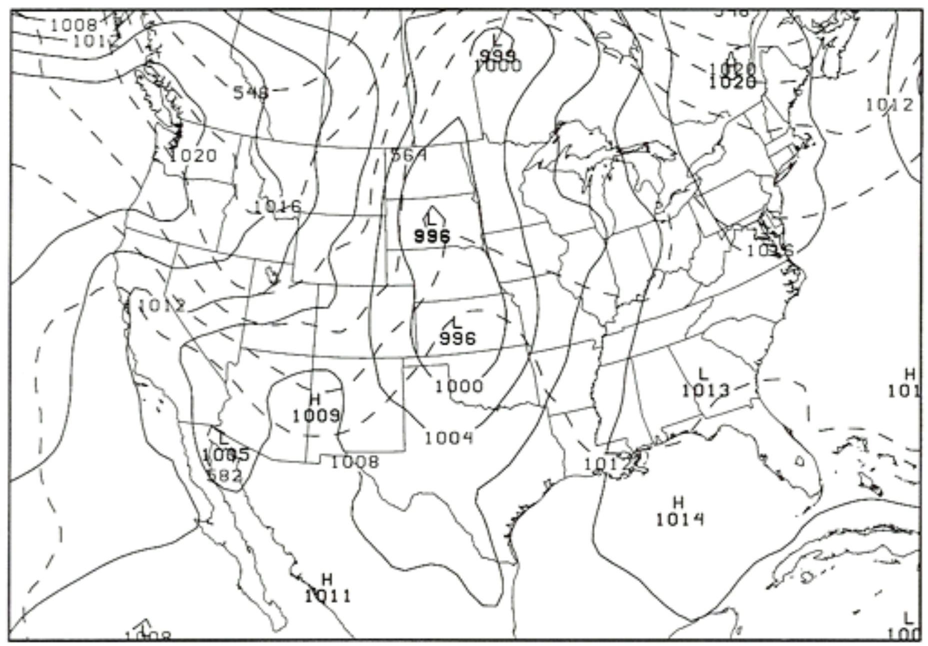
36 h fcsts

Avn



020918/1200V024 SFC MSLP & THCK -- AVN

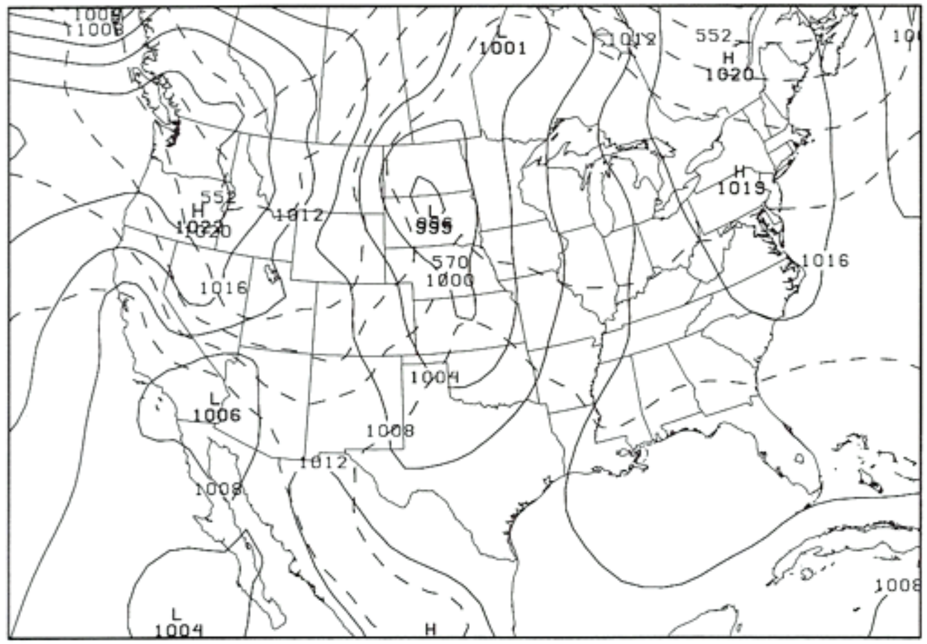
Eta



020918/1200V024 SFC MSLP & THCK -- ETA

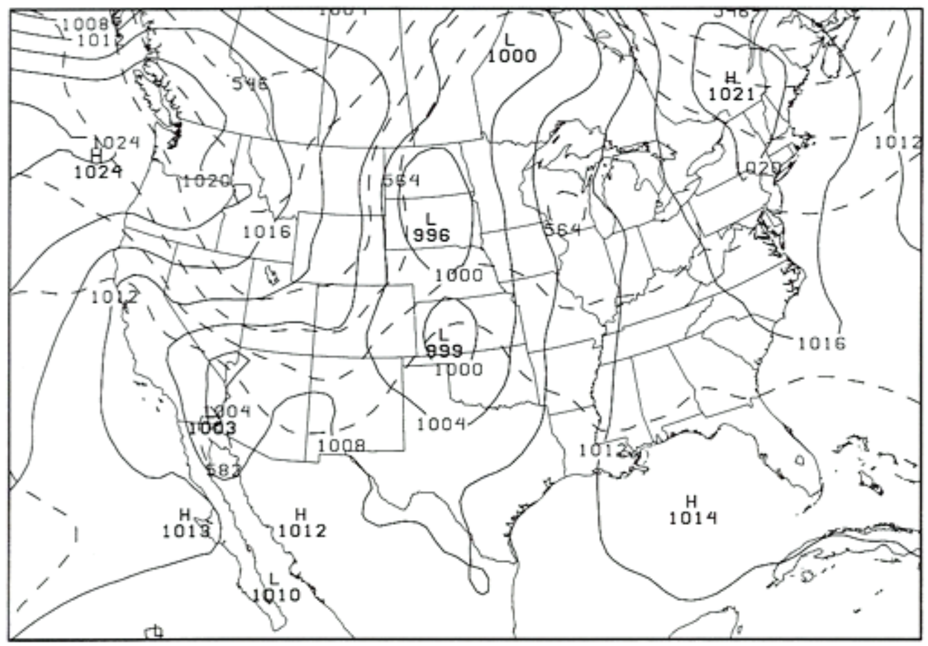
24 h fcsts

Avn



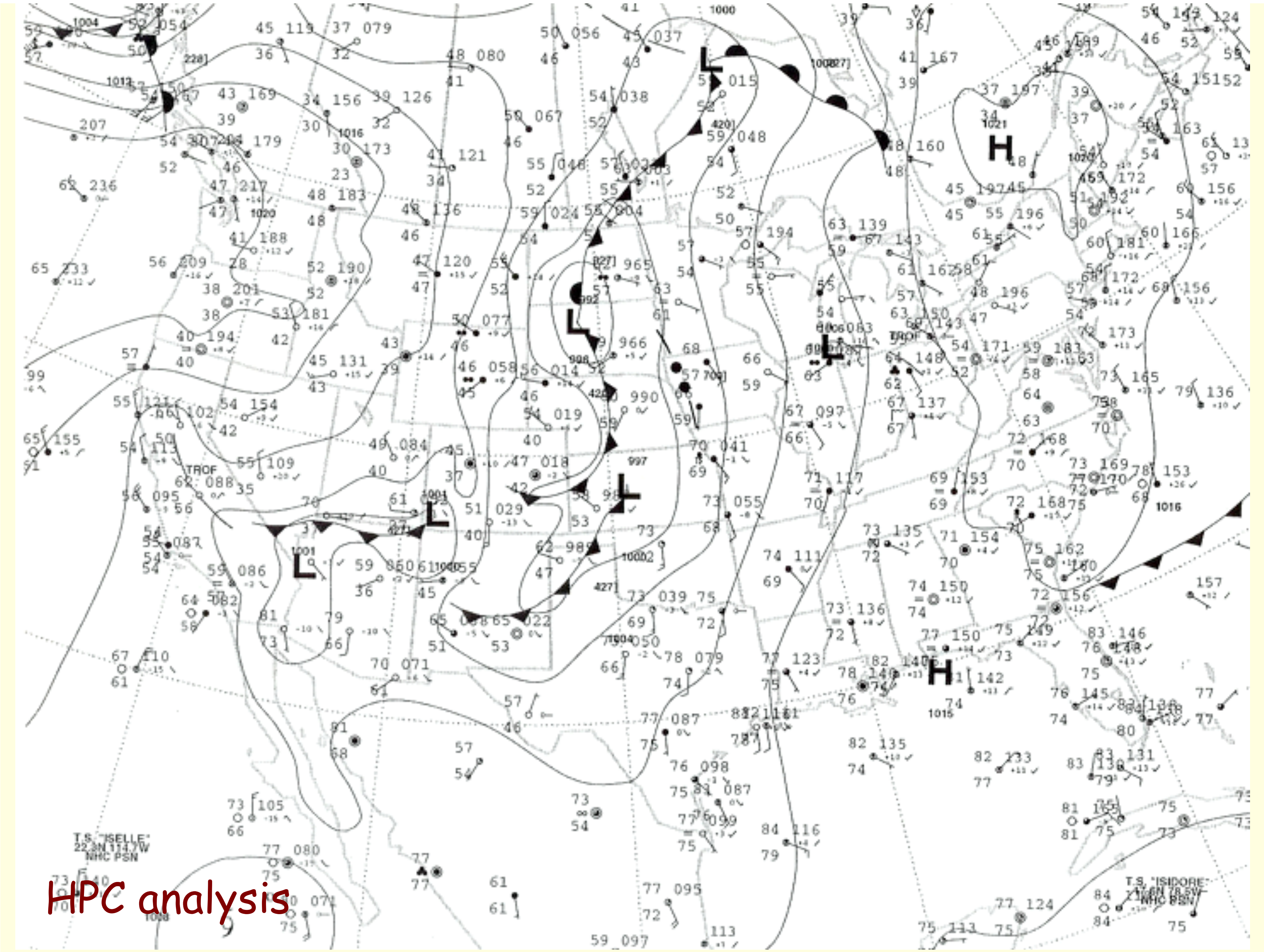
020918/1200V012 SFC MSLP & THCK -- AVN

Eta

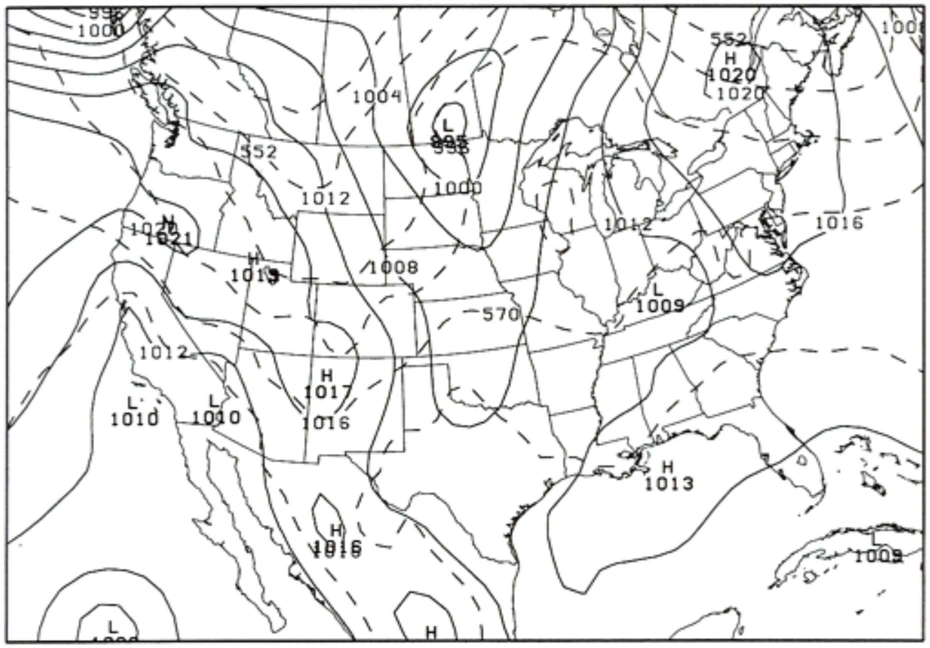


020918/1200V012 SFC MSLP & THCK -- ETA

12 h fcsts

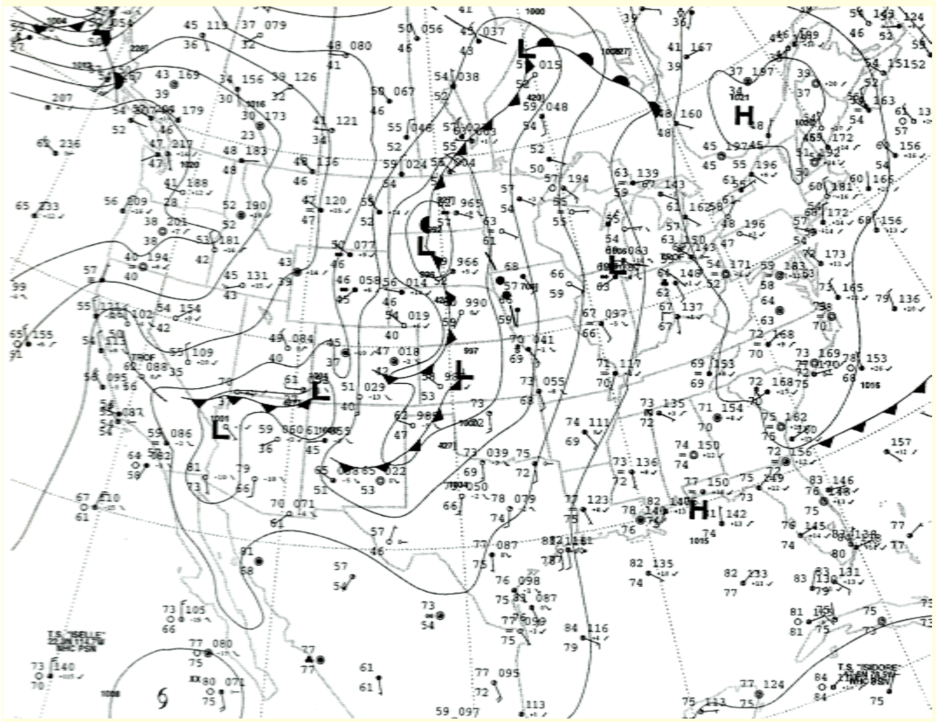


HPC analysis

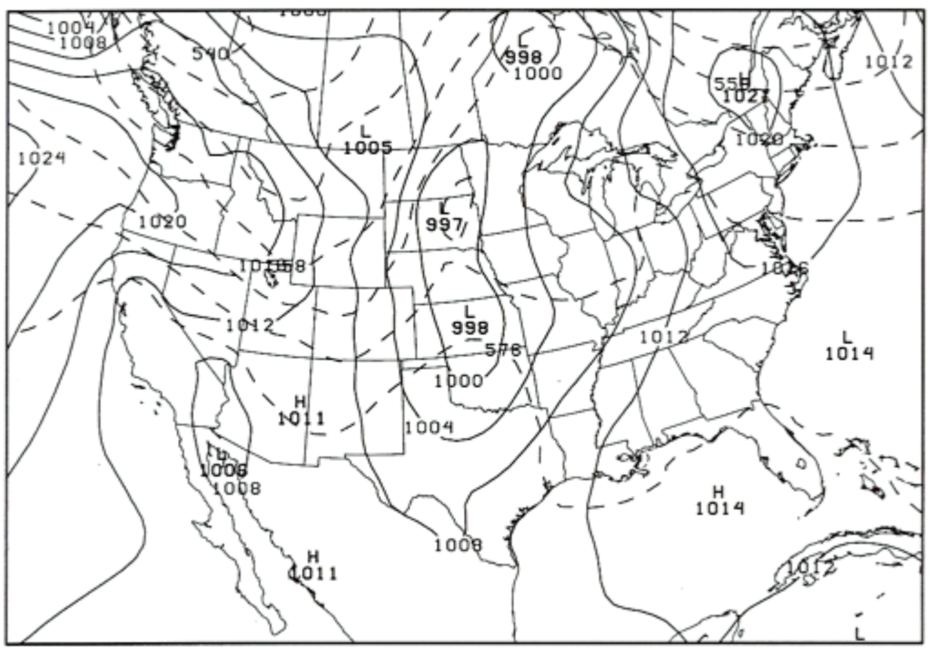


020918/1200V060 SFC MSLP & THCK -- AVN

Avn, 60 h fcst



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

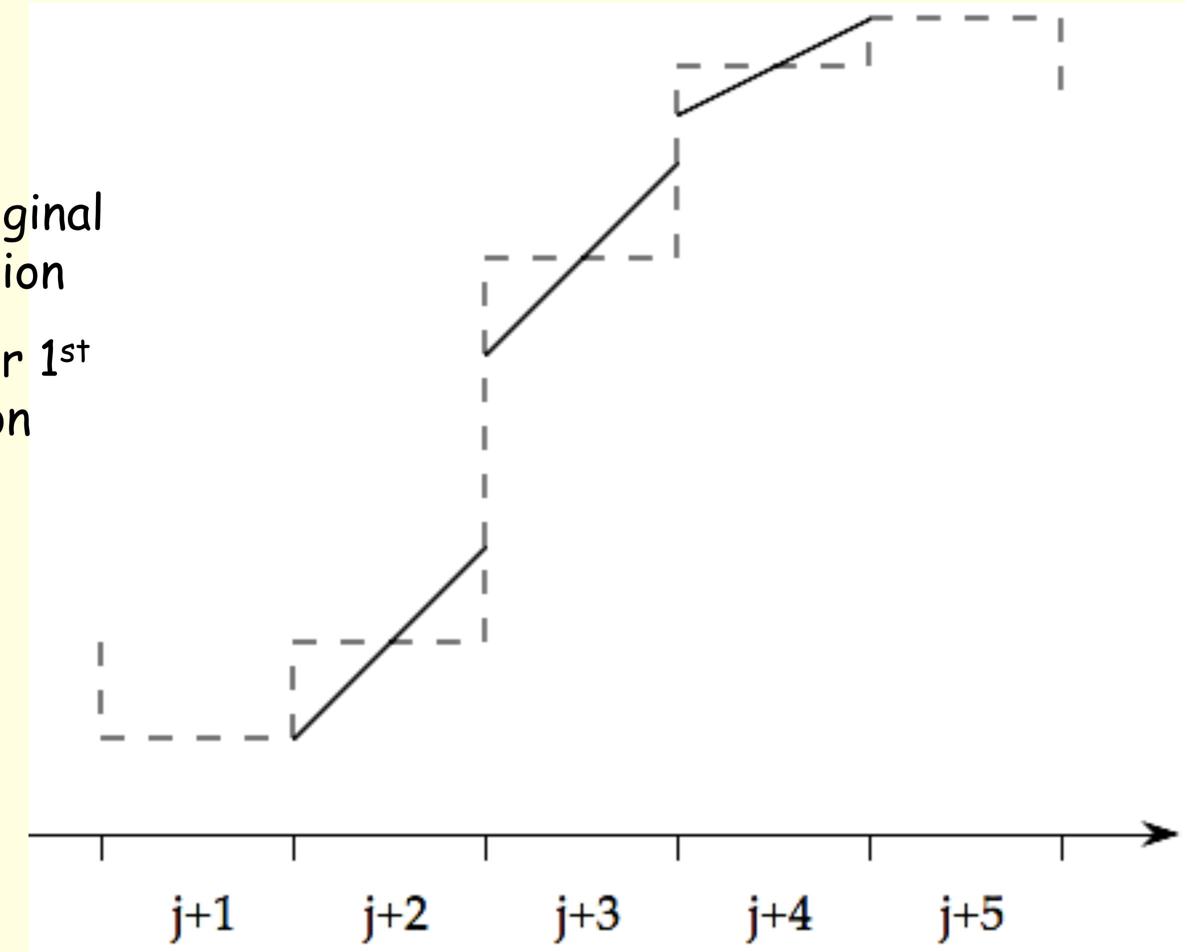


Figure 1. An example of the Eta iterative slope adjustment algorithm. The initial distribution is illustrated by the dashed line, with slopes in all five zones shown equal to zero. Slopes resulting from the first iteration are shown by the solid lines. See text for additional detail.

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:

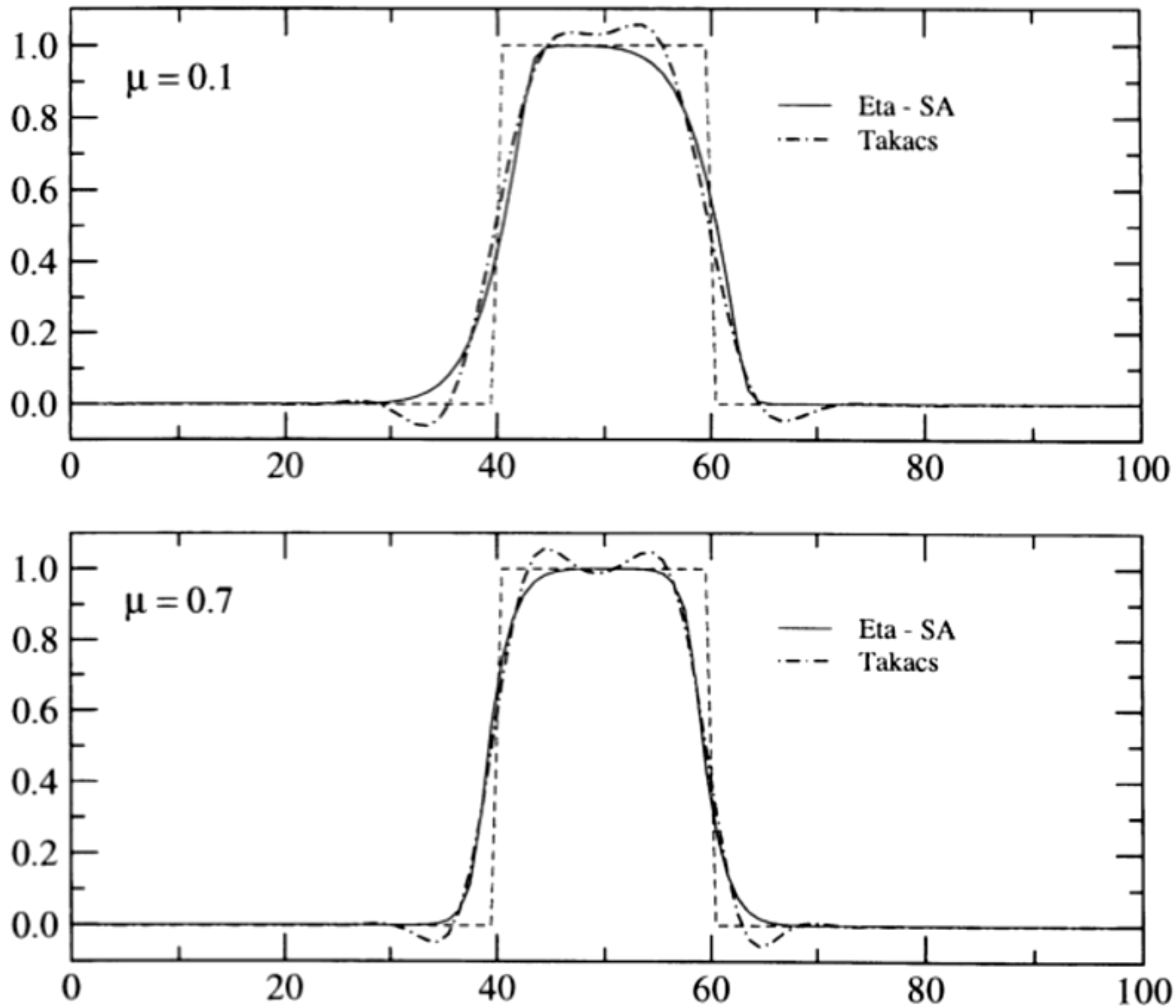


Figure 9. Same as Fig. 2, except for the Eta slope-adjustment scheme results (SA, solid line) compared against those using the Takacs (1985) third-order "minimized dissipation and dispersion errors" scheme (dot-dashed line). See text for definitions of schemes.

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/ .

Gallus, W. A., Jr., and J. B. Klemp, 2000: Behavior of flow over step orography. *Mon. Wea. Rev.*, **128**, 1153-1164.

Janjic, Z. I., 1997: Advection scheme for passive substances in the NCEP Eta Model. *Res. Activities Atmos. Oceanic Modelling*, Rep. 25, WMO, Geneva, 3.14.

Janjic, Z. I., 2003: A nonhydrostatic model based on a new approach. *Meteor. Atmos. Phys.*, **82**, 271-301.

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

Mesinger, F., and Z. I. Janjic, 1985: Problems and numerical methods of the incorporation of mountains in atmospheric models. In: *Large-Scale Computations in Fluid Mechanics*, B. E. Engquist, S. Osher, and R. C. J. Somerville, Eds. Lectures in Applied Mathematics, Vol. 22, 81-120.

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.

Steppeler, J., H. W. Bitzer, Z. Janjic, U. Schättler, P. Prohl, U. Gjertsen, L. Torrisi, J. Parfinievicz, E. Avgoustoglou, and U. Damrath, 2006: Prediction of clouds and rain using a *z*-coordinate nonhydrostatic model. *Mon. Wea. Rev.*, **134**, 3625–3643.

Takacs, L. L., 1985: A two-step scheme for the advection equation with minimized dissipation and dispersion errors. *Mon. Wea. Rev.*, **113**, 1050-1065.

Code etc. downloadable at http://etamodel.cptec.inpe.br/

This was NWP; what about after say 6-7 days ?

"Ensemble forecasting": start a number of forecasts that initially differ to a degree that mimics our insufficient knowledge of the initial state

Can one also benefit from running a limited area model?

One should certainly be able to get additional detail

However: Can a nested regional model have large-scale skill comparable to / better than that of the driver global forecasts ?

Should one attempt
improving on the large scales ?)

Upgraded Eta
driven by ECMWF 32-day
ensemble members
(Katarina Veljovic, ..., MetZ 2010)

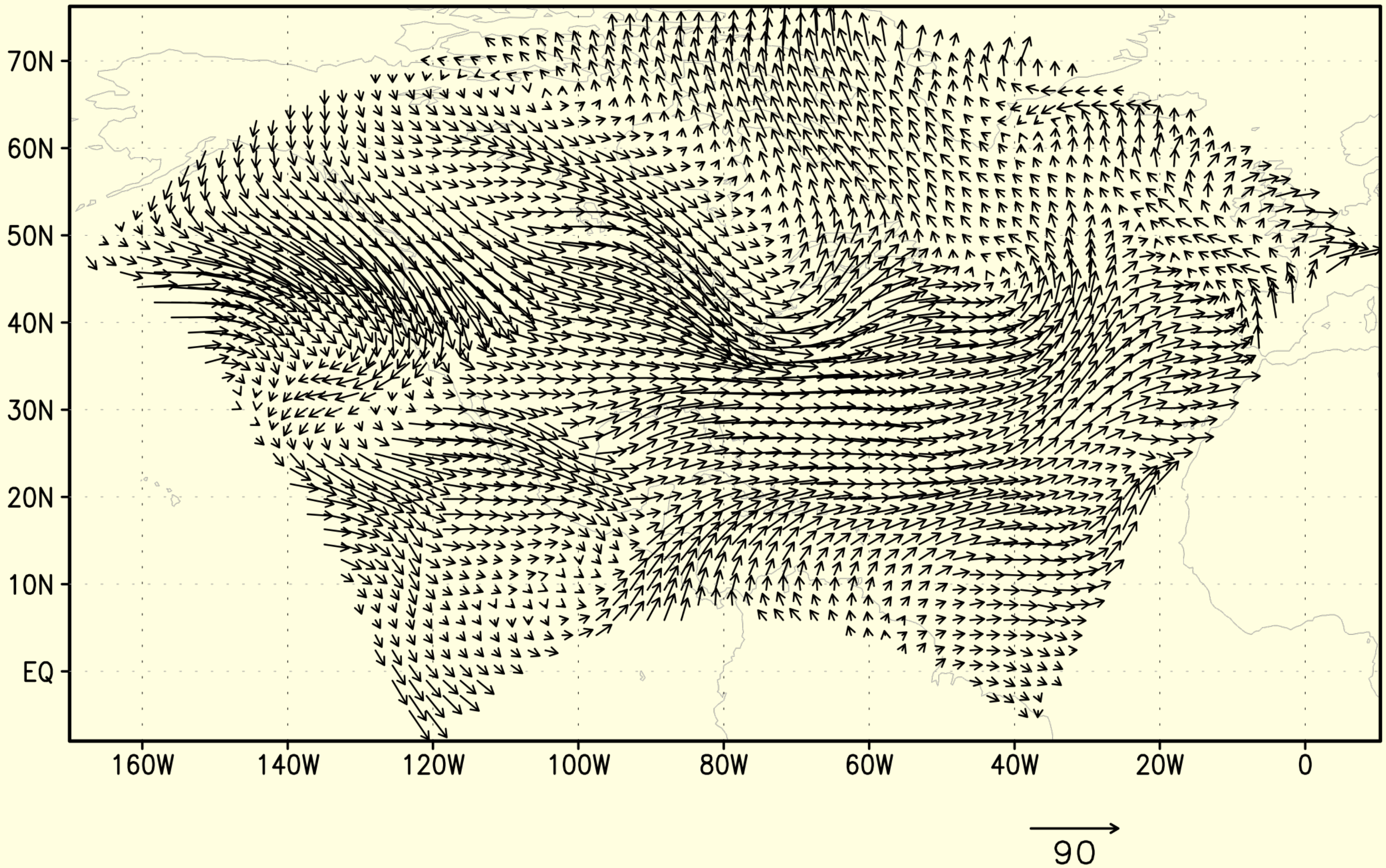
T399 (~50 km)/62 level to 15 days, lower resolution later;

Eta RCM: 31 km/45 layer, 12,000 x 7,580 km domain

Verification against ECMWF analyses

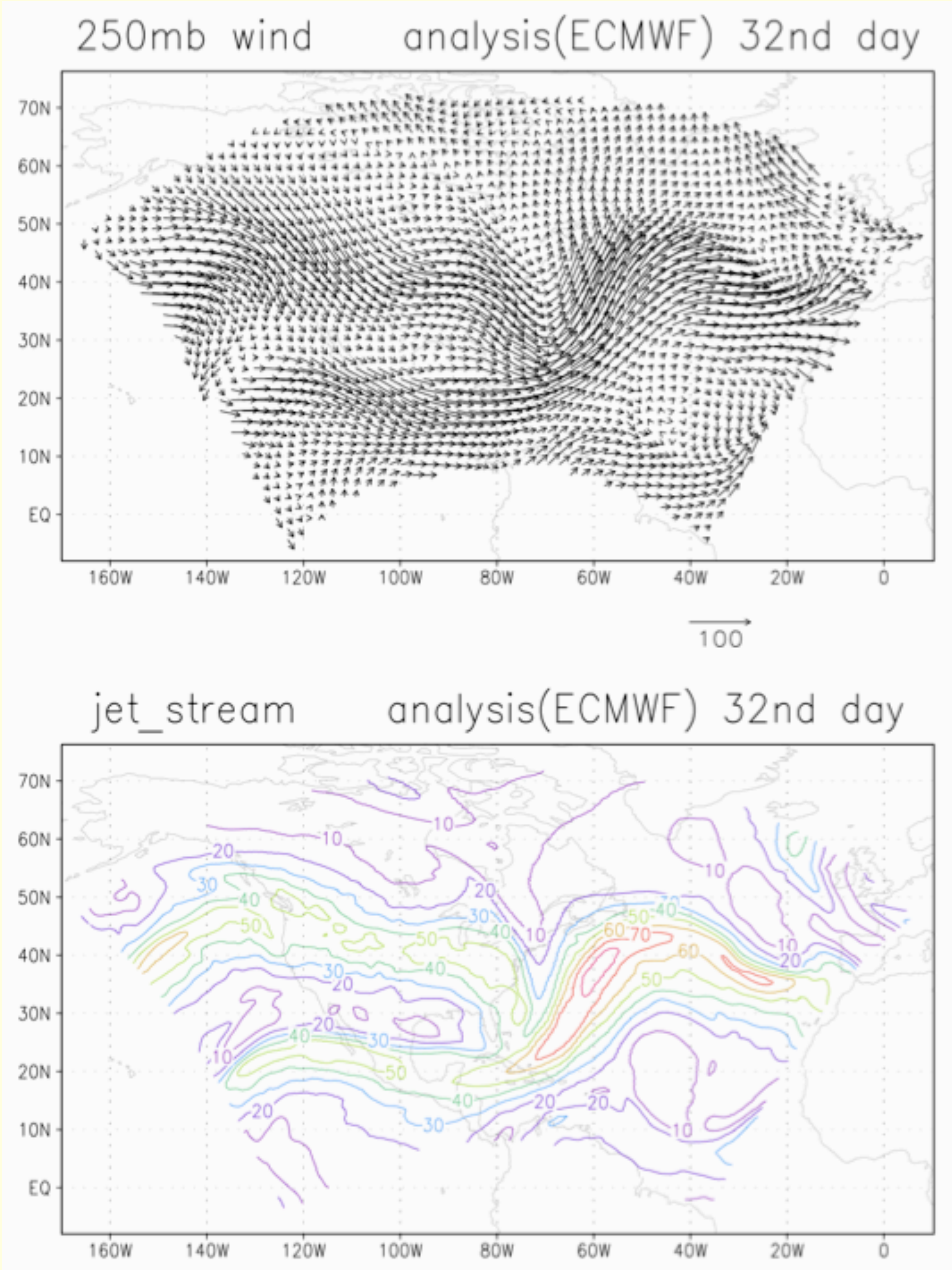
Eta driven by ECMWF 32 day ensemble, control + 25 ensemble members; the domain:

250 hPa wind at the initial time:

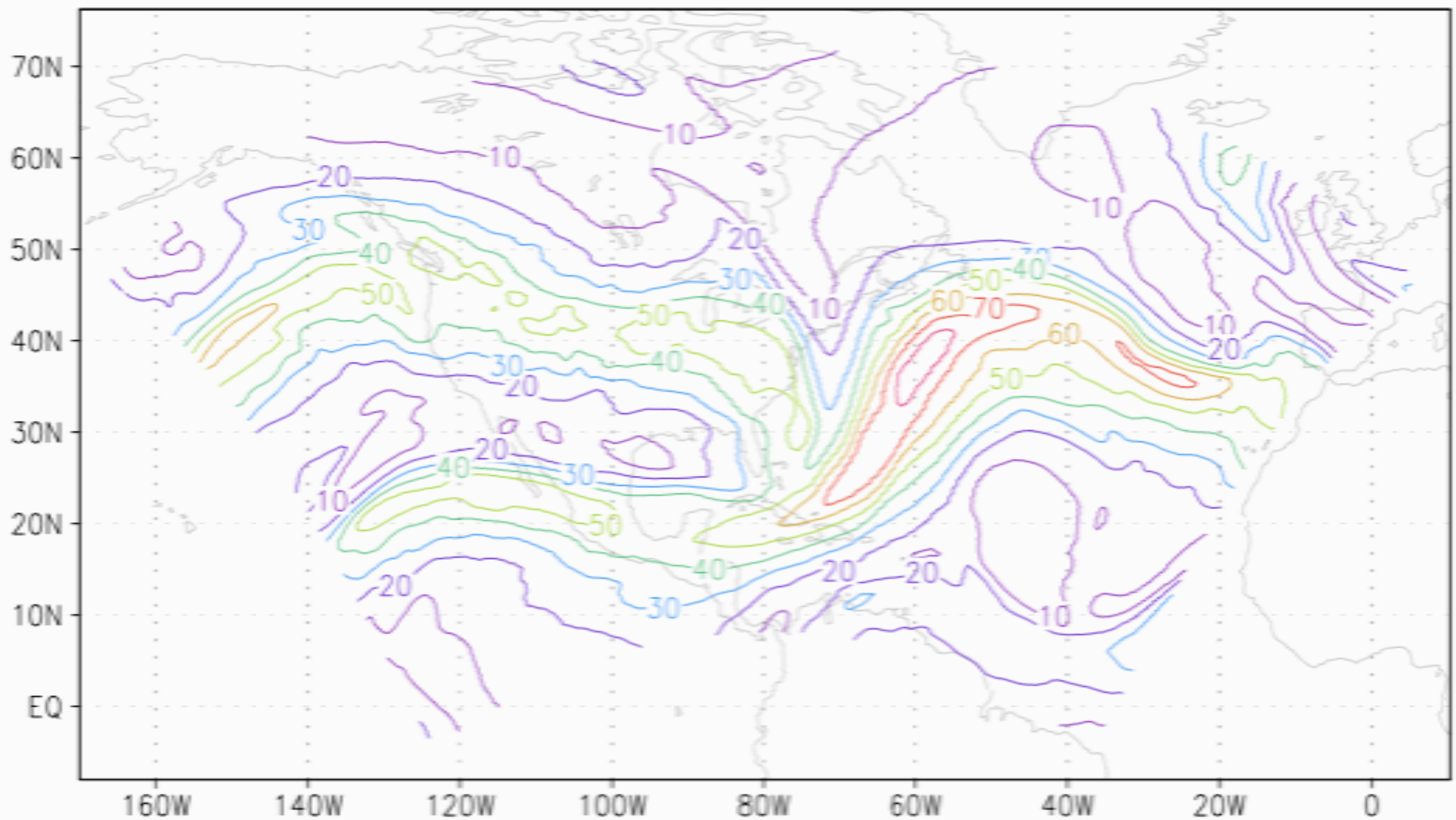


(12,000 x 7,550 km)

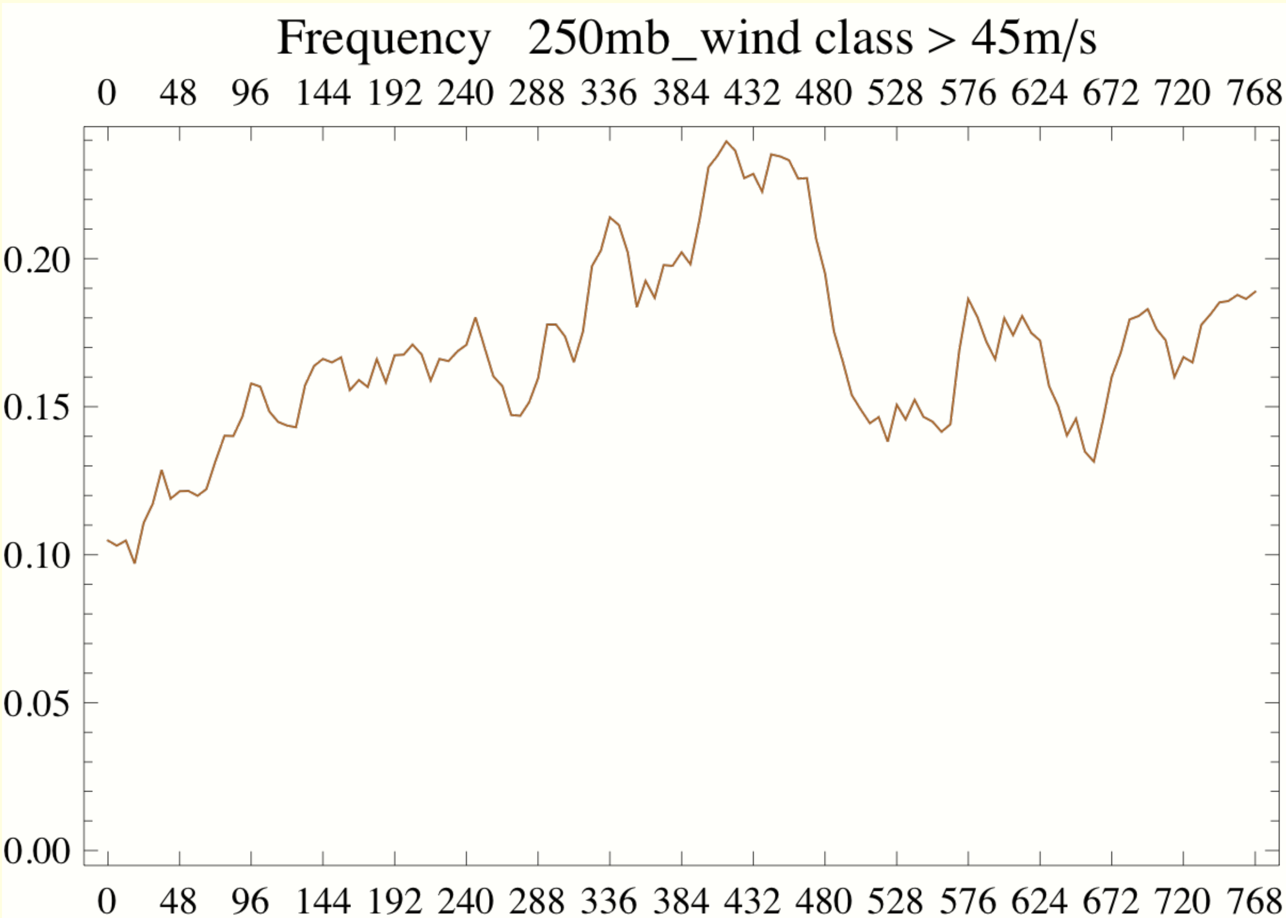
To identify “large scales”, we look at the placement of jet stream level winds, (taken as 250 hPa) with speeds > chosen threshold



jet_stream analysis(ECMWF) 32nd day



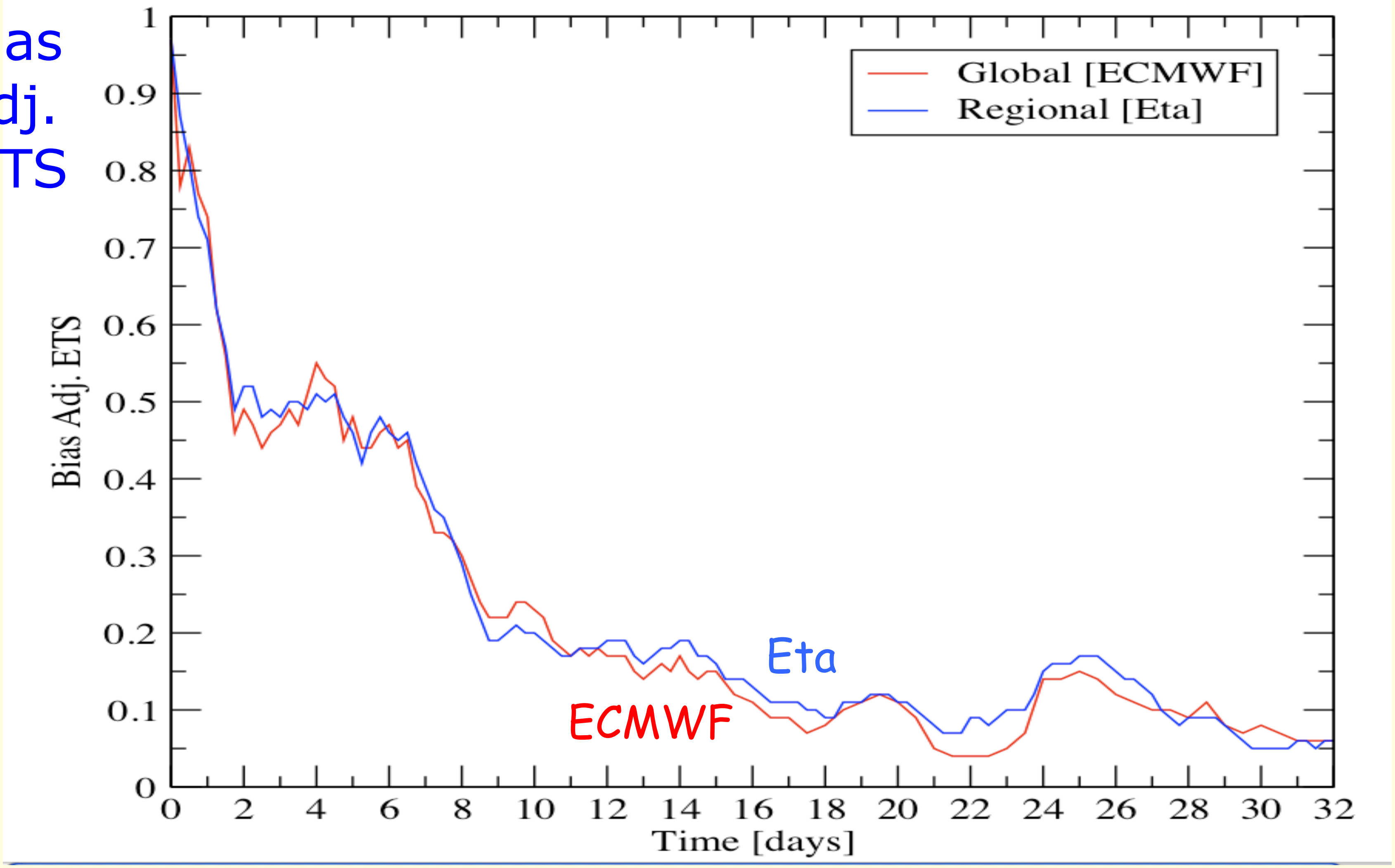
What speeds should we look at ?



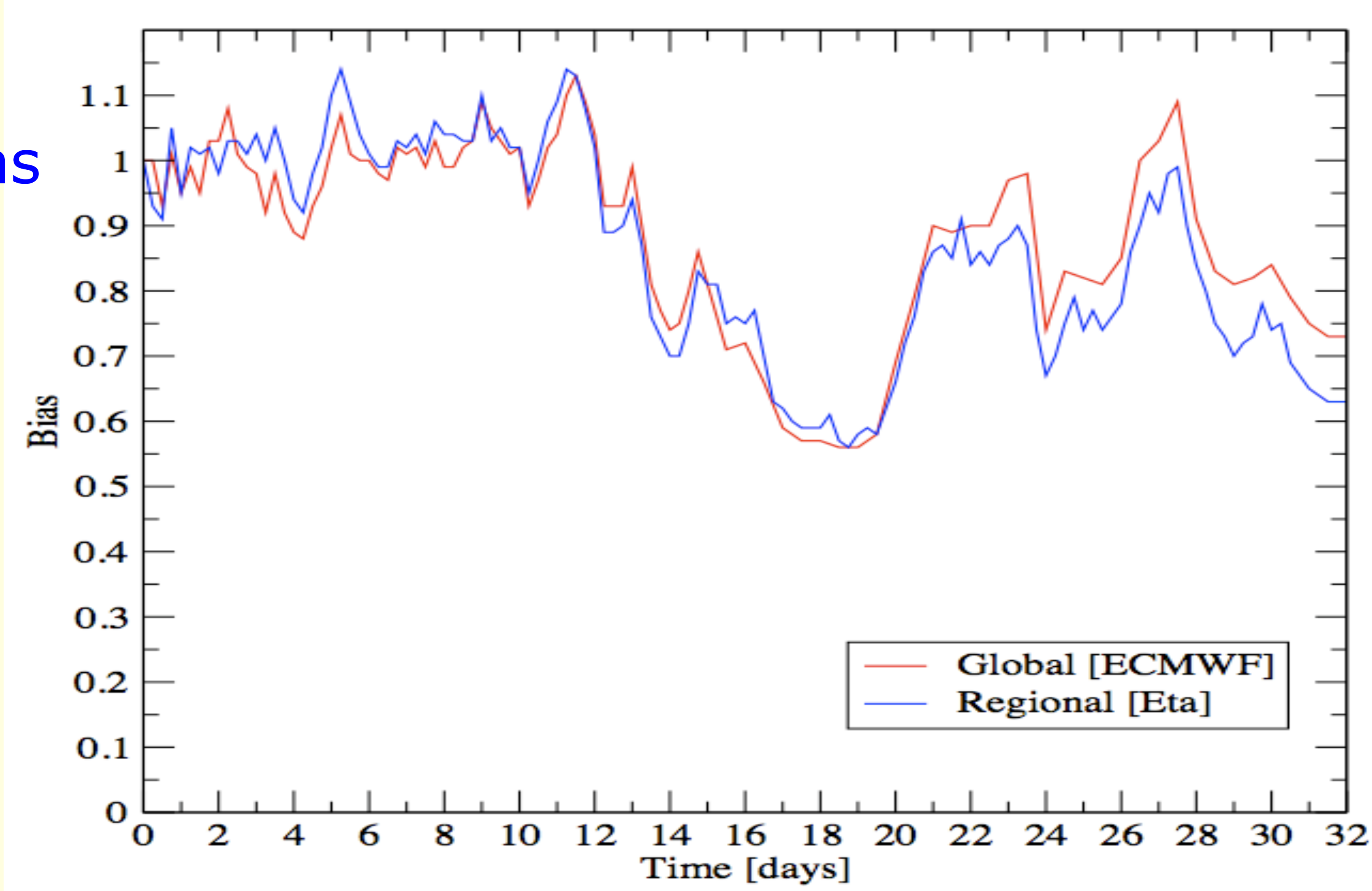
> 45 m/s

Results: 26 (25 members + control) 32-day forecasts:

Bias adj. ETS

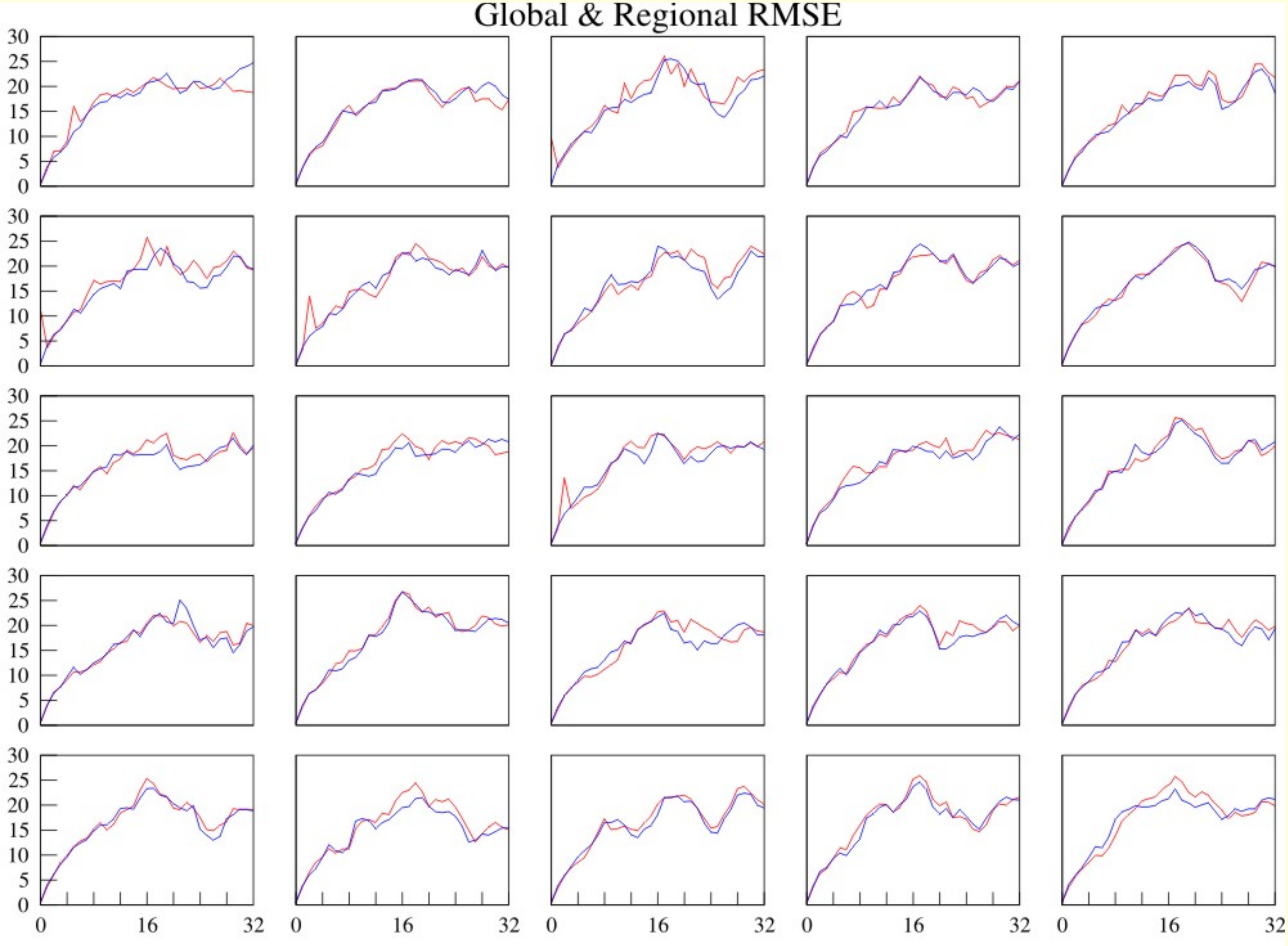


Bias



Bias
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32
Time [days]
Global [ECMWF]
Regional [Eta]

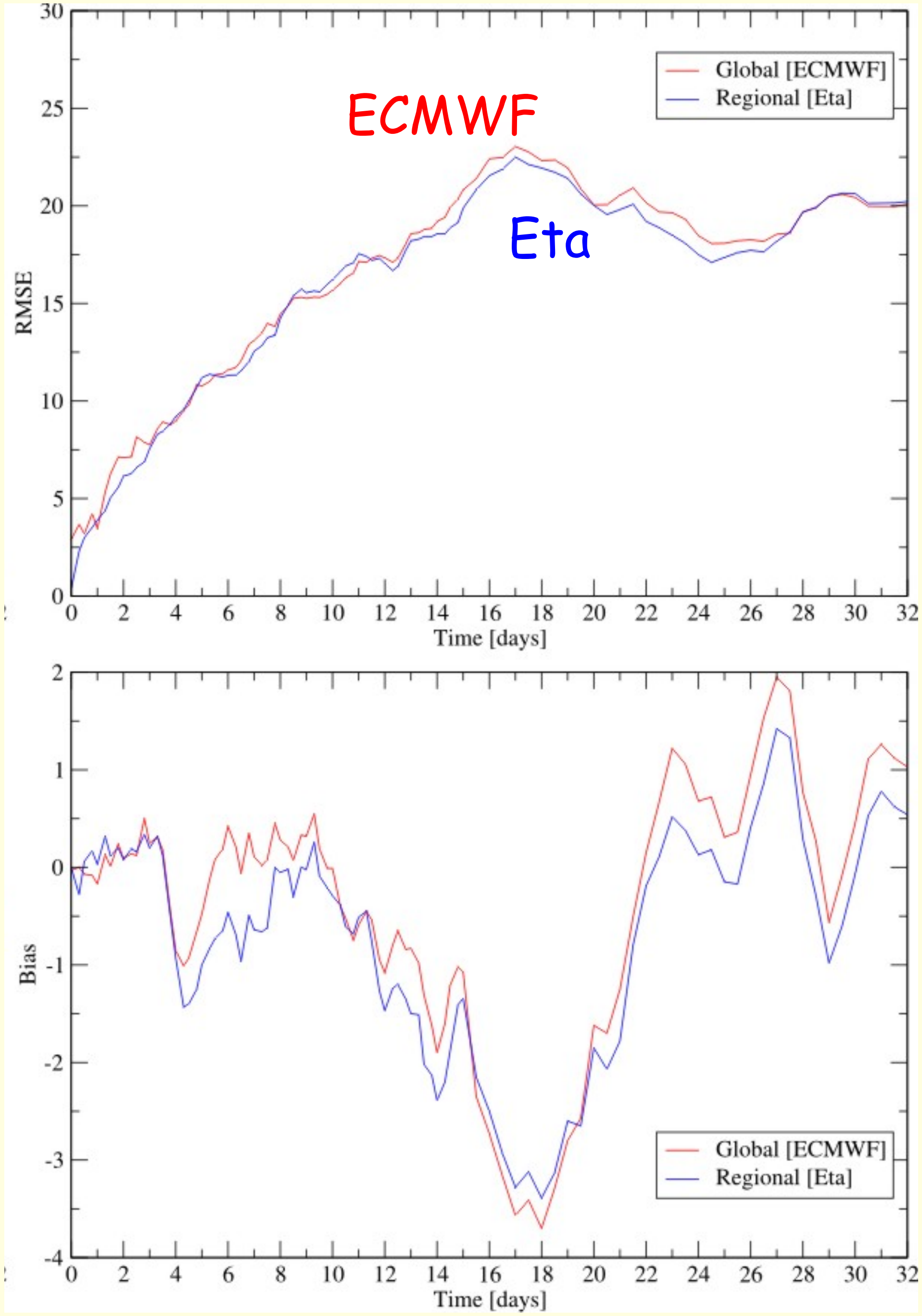
More traditional verification: root mean square 250 mb wind differences:



All 26 forecasts:

RMSE

Bias



Thus,

- The Eta RCM skill in forecasting large scales (with no interior nudging) just about the same as that of the driver model; most times even higher !!!!!

- This despite the Eta absorbing its lateral boundary error;

and certainly not benefiting from verification being done using ECMWF analyses, with assimilation system sharing its model with the driver global ensemble members!

Current work / the future ?

"Seamless prediction": coupled global models: oceans, land-surface, CO_2, ice, "dynamic vegetation", . . .

Monthly, seasonal prediction, climate "projection" "regional climate change", . . .