Eta Model Dynamics

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Entrenamiento en Modelado Numérico de
Escenarios de Cambio Climático

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Part I:

- Approach;
- Gravity-wave coupling/ time differencing;
- Nonhydrostatic effects;
- Advection:
- Energy transformations

"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:

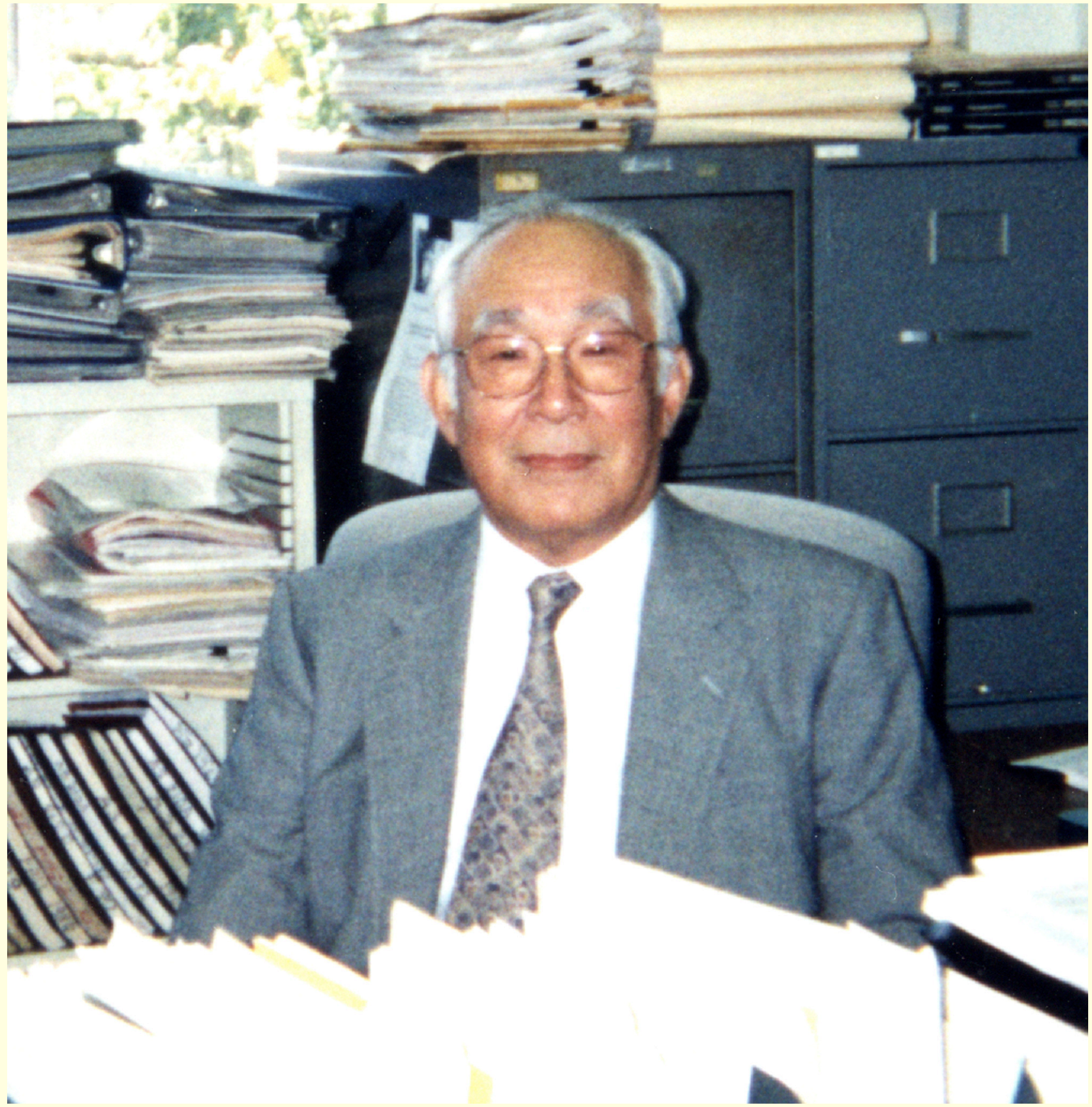
- Conservation of energy and enstrophy;
- Avoidance of computational modes;
- Dispersion and phase speed;
- . . .

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:

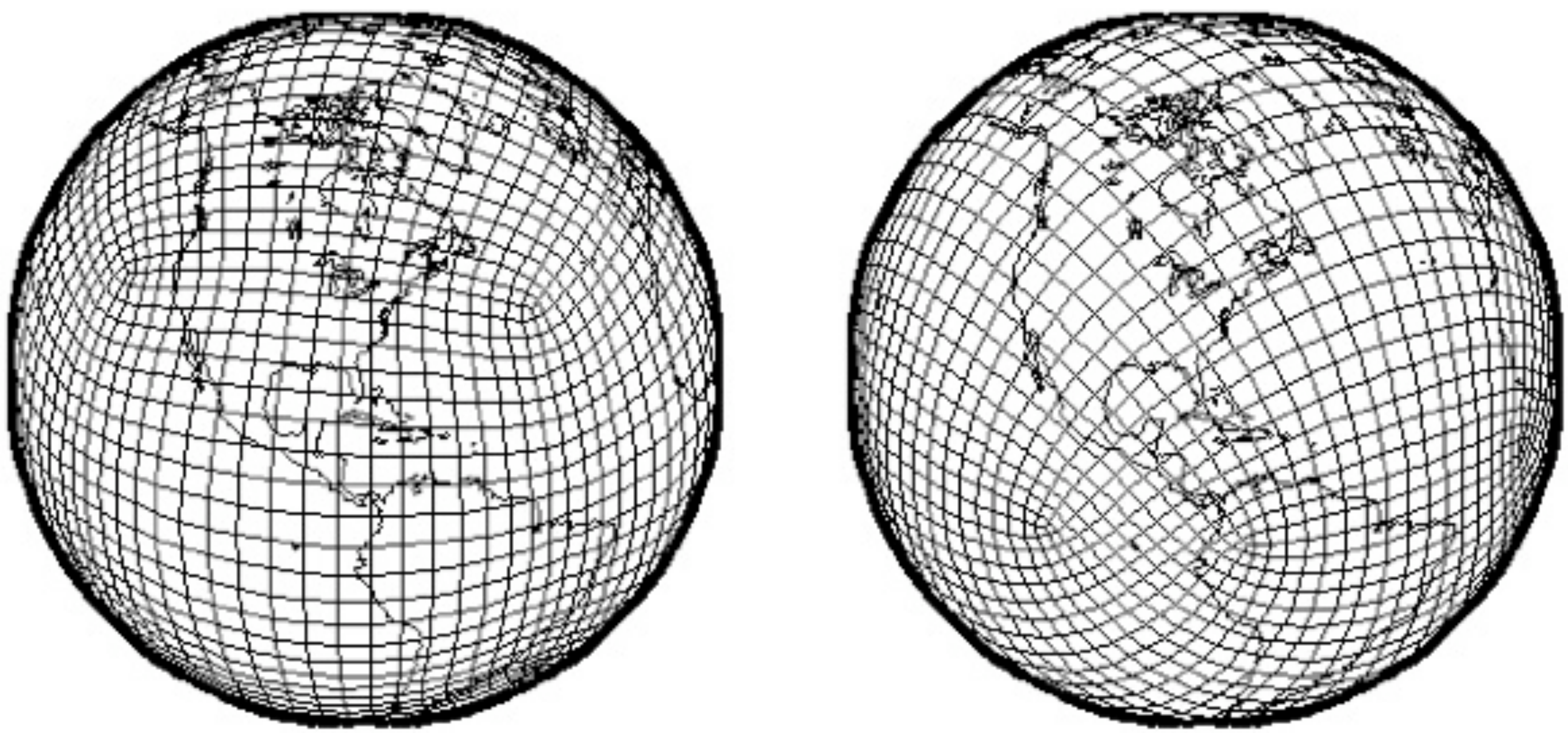


The Eta (as mostly used up to now) is a regional model:

Lateral boundary conditions (LBCs) are needed (to be briefly summarized later)

There is now also a global Eta Model:

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;

- Nonhydrostatic option;

- 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;

- The eta vertical coordinate, ensuring hydrostatically consistent calculation of the pressure gradient ("second") term of the pressure-gradient force (PGF);

- . . . . .

- Gravity-wave coupling scheme

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"

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

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

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

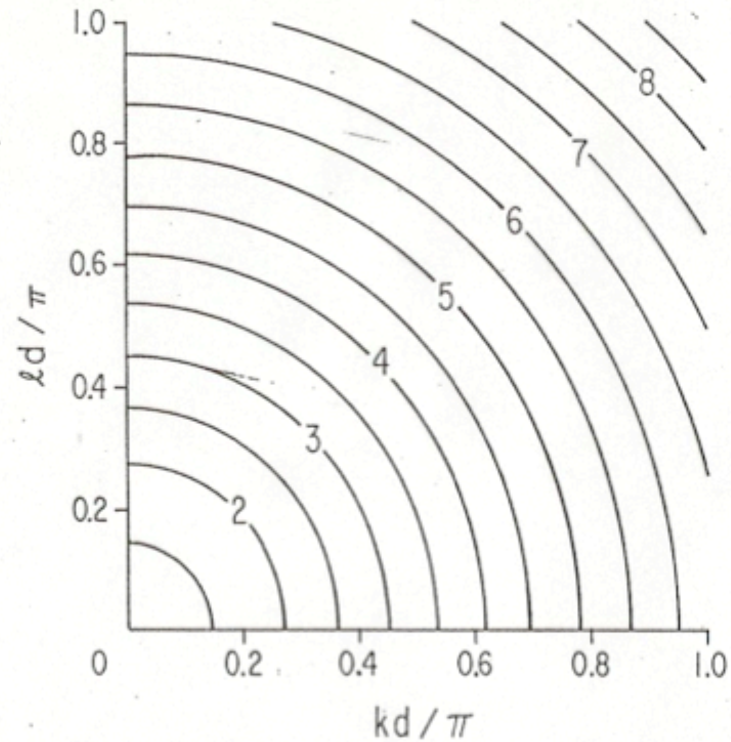


FIG. 9. Contours of the (nondimensional) frequency as a function of the (nondimensional) horizontal wave numbers for the differential shallow water equation for $\lambda/d = 2$, presented for comparison with Fig. 8.

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

Arakawa, dynamics:

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

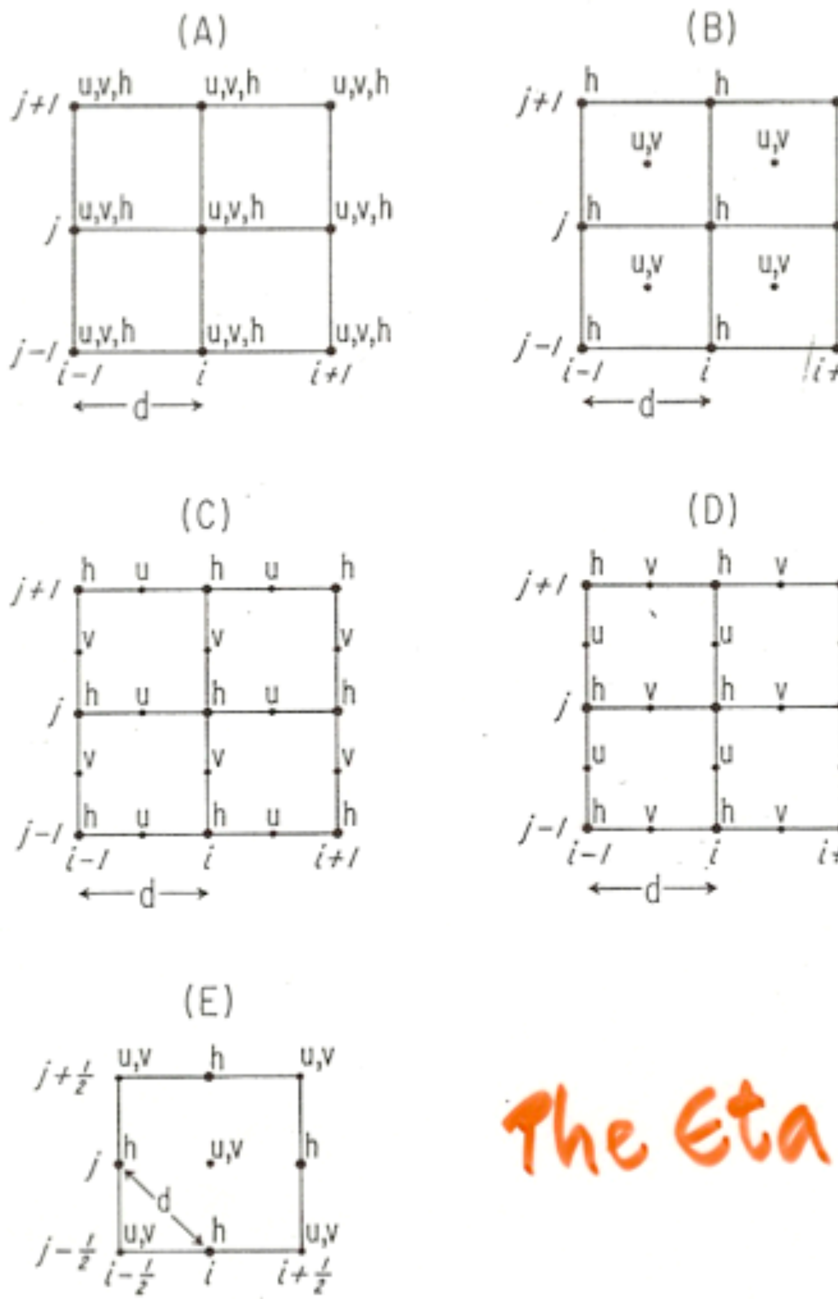
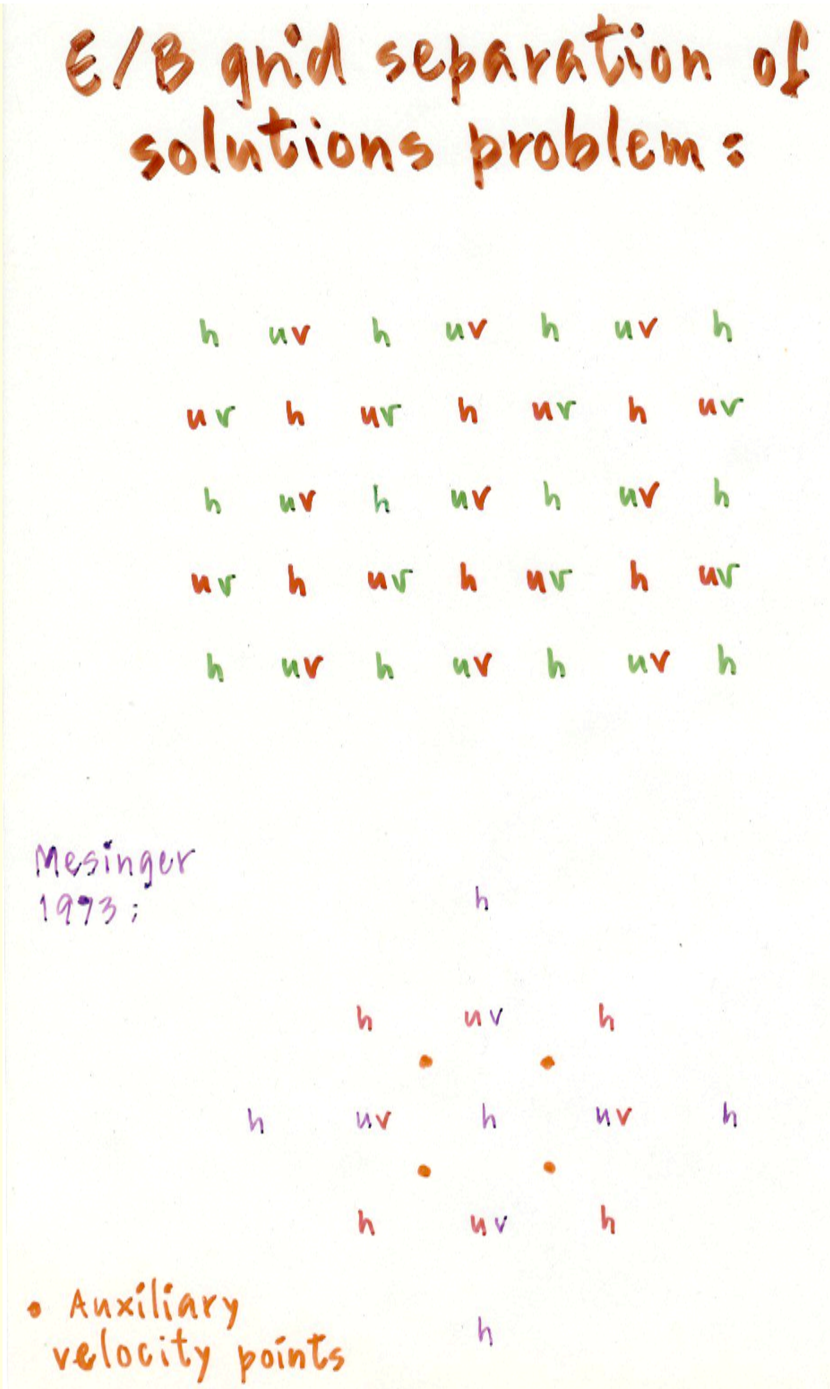


FIG. 3. Spatial distributions of the dependent variables on a square grid.

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

Linearized shallow-water equations:

The forward-backward scheme:

(Richtmyer ?)

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

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

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

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, (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

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

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

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

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.

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

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

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, while the time step required for linear stability with the leapfrog scheme was half that with the forward-backward scheme, (5.9) shows that we can omit the variables at every second time step, and thus achieve the same computation time as using the forward-backward scheme with double the time step.

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:

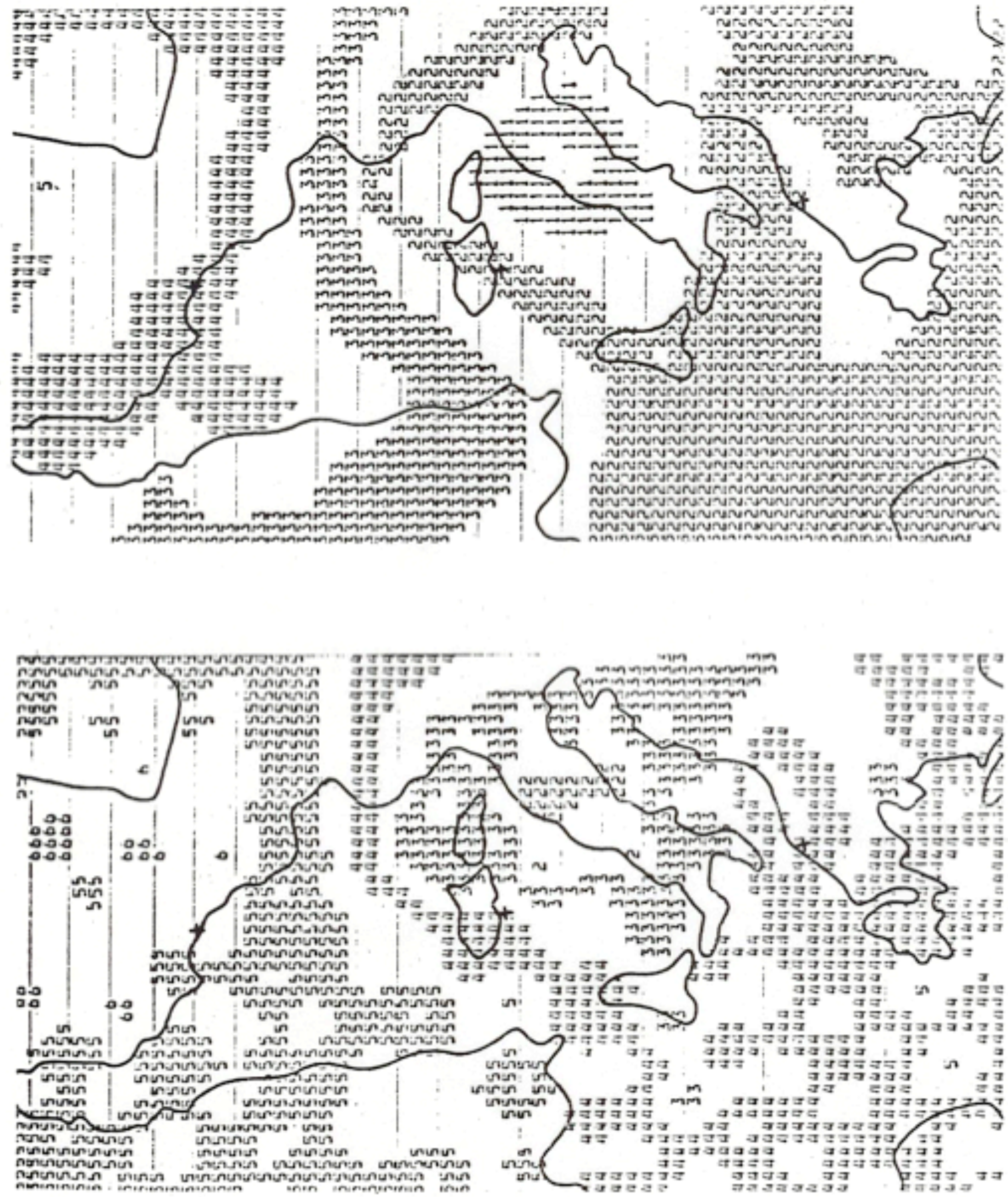
Experiments recently (2006) made, doing 48 h forecasts, with full physics, at two places, comparing

continuity eq. forward, vs momentum eq. forward

No visible difference ! (Why?)

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 might still be a little better?)

Vertical advection over 2 adj. time steps

Horizontal diffusion;

Repeat (except no vertical advection now, if 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;

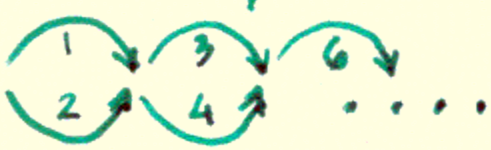
. . . . .

Time differencing: split explicit

A variety of time steps:

time

Cont. eq.



"forward-backward" sch.

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

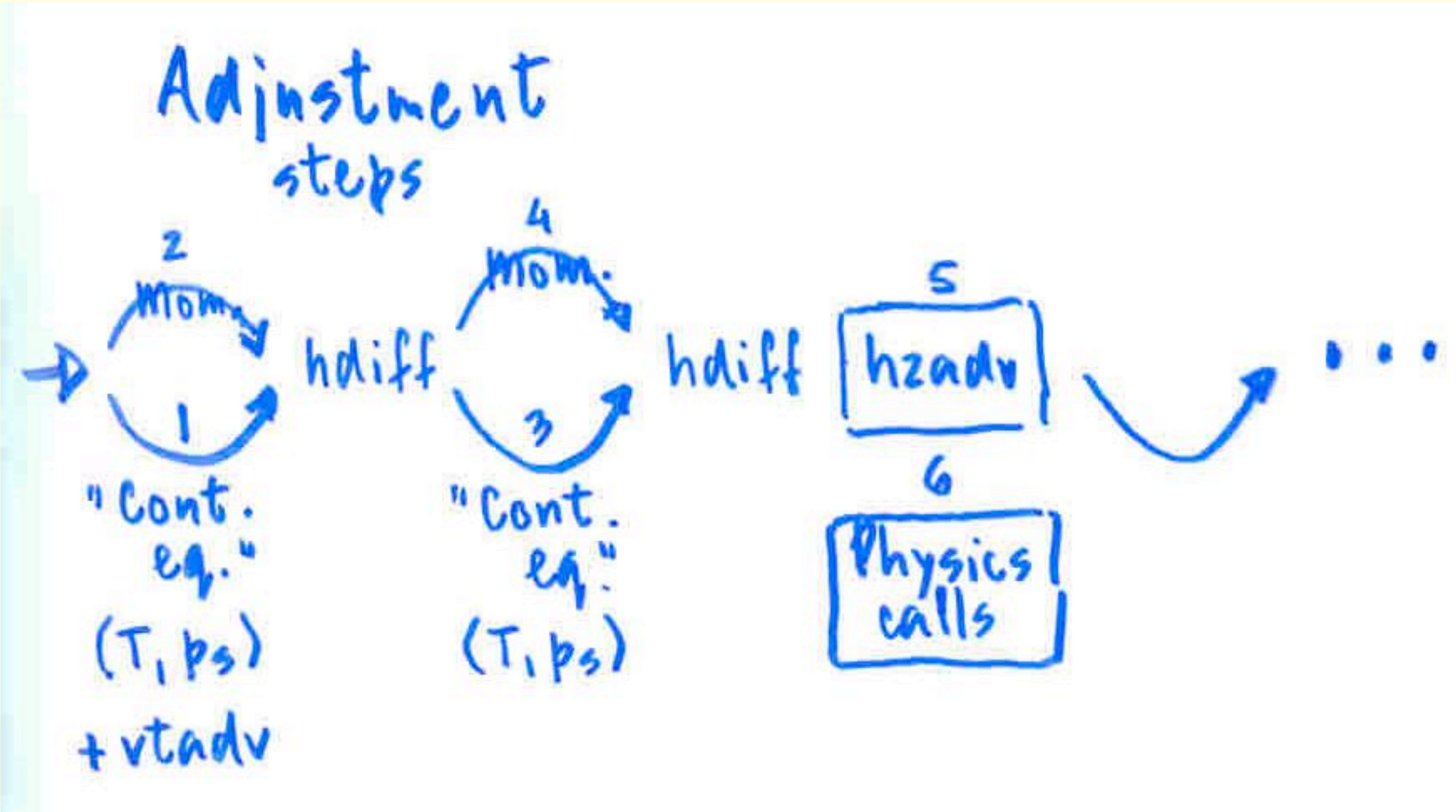
5

Horiz. adv. (~Heun)

Some physics
(incl. convection)

More physics

F. Mesinger


Adjustment steps
2
Mom.
4
Mom.
5
hdiff
hdiff
hzadv
1
3
6
"Cont. eq."
(T, ps)
+ vtadv
"Cont. eq."
(T, ps)
Physics calls
. . .

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, slides that follow). Energy conservation in the Eta, in transformation between potential and kinetic energy is achieved in space differencing.

Time differencing in the Eta: two steps of (2) are followed by one, over 2Δt, step of (3).

How is this figured out?

To achieve energy conservation in time differencing one needs to replicate what happens in the continuous case. Energy conservation in the continuous case, still shallow water eqs. for simplicity:

$$\frac{\partial \mathbf{v}}{\partial t}+(\mathbf{v}\cdot\nabla)\mathbf{v}=-f\,\mathbf{k}\times\mathbf{v}-g\nabla h, \qquad (1.1)$$

$$\frac{\partial h}{\partial t}+\nabla\cdot(h\mathbf{v})=0. \qquad (1.2)$$

To get the kinetic energy eq., multiply (1.1) by $h\,\mathbf{v}$, multiply (1.2) by $\frac{1}{2}\mathbf{v}\cdot\mathbf{v}$, and add,

$$\frac{\partial}{\partial t}\frac{1}{2}h\mathbf{v}\cdot\mathbf{v}+h(\mathbf{v}\cdot\nabla)\frac{1}{2}\mathbf{v}\cdot\mathbf{v}+\frac{1}{2}\mathbf{v}\cdot\mathbf{v}\nabla\cdot(h\mathbf{v})=-gh\mathbf{v}\cdot\nabla h \qquad (4)$$

For the potential energy eq., multiply (1.2) by *gh,*

$$\frac{\partial}{\partial t}\frac{1}{2}gh^2+gh\nabla\cdot(h\mathbf{v})=0 \qquad (5)$$

Adding (3) and (4) we obtain

$$\frac{\partial}{\partial t}\left(\frac{1}{2}h\mathbf{v}\cdot\mathbf{v}+\frac{1}{2}gh^2\right)+\nabla\cdot\left(\frac{1}{2}\mathbf{v}\cdot\mathbf{v}\,h\mathbf{v}\right)+\nabla\cdot(gh^2\mathbf{v})=0\,. \qquad (6)$$

Thus, the total energy in a closed domain is conserved

For conservation in time differencing terms that went into one and the other divergence term have to be available at the same time;

- Kinetic energy in horizontal advection (the 1st divergence term):

Formed of contributions of horizontal advection of **v** in (1.1), and mass divergence in (1.2)
Not available at the same time with the split-explicit approach;

cannot be done;

- Energy in transformations potential to kinetic (the 2nd divergence term):

Formed of the advection of *h* term on the right side of (4), coming from the pressure-gradient force, and the mass divergence term of (5), coming from the continuity eq.;

Both are done in the adjustment stage with the splitting as in (2) and (3);
cancellation is thus possible if the two are done at the same time

However: they are done separately with the forward-backward scheme;

Thus, with the forward-backward scheme, cannot be done;

Time steps used for the adjustment stage very small;
not considered a serious weakness

(Eta at 10 km resolution is typically using adjustment time step of 20 s)

Nonhydrostatic option (a switch available),

Janjic et al. 2001:

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

- *Advection*

Horizontal velocity components:

The horizontal advection scheme:

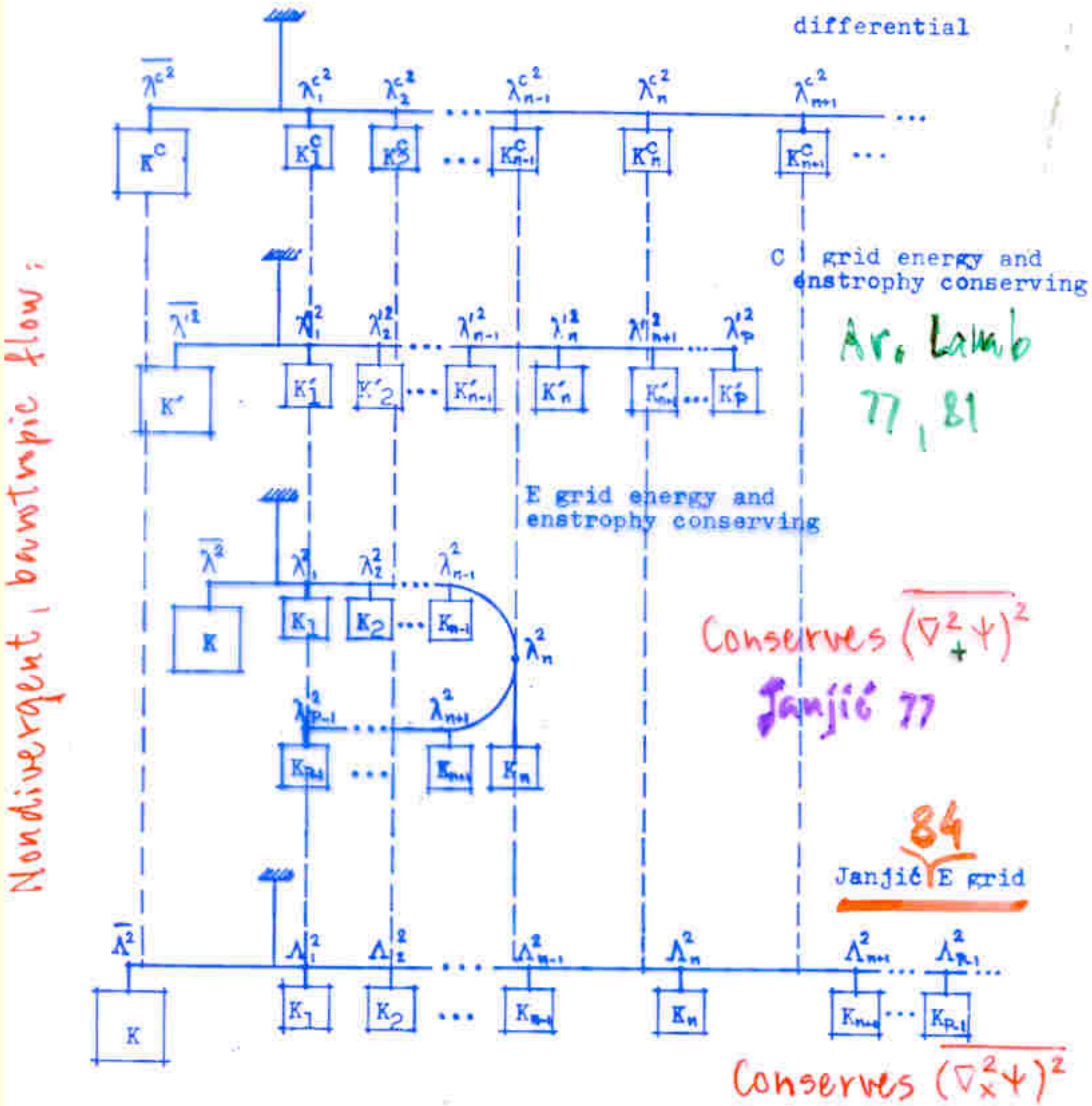


Fig. 3.12. Mechanical analogies of the constraints imposed on the non-linear energy cascade in the continuous case, in the case of the C-grid energy and enstrophy conserving scheme, in the case of the E-grid energy and enstrophy conserving scheme, and in the case of the scheme due to Janjić (1984).

96 (ECMWF Seminar '83)

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

MWR, 1984

ZAVIŠA I. JANJIĆ

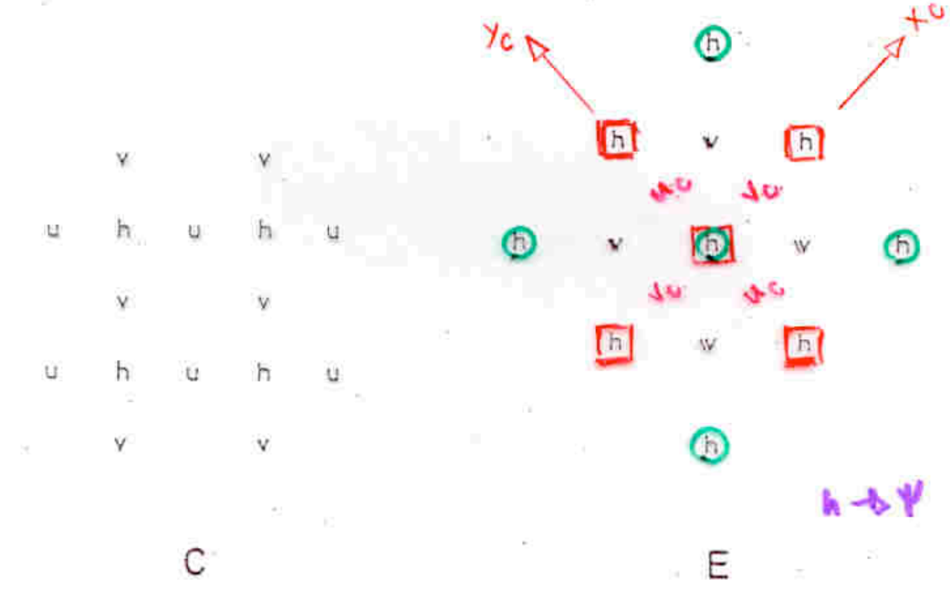


FIG. 1. Distributions of variables over grid points C and E.

Problem: ζ_E defined by simple differencing of the E grid u, v components eq. $\nabla^2_+ \psi$, using ψ values at ○ 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 (θ, q, q2, hor. adv.)		
1st moment	✓	✓
2nd moment	✓	✓

Vertical: "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)

Advection of passive scalars (moisture, cloud water/ice):

In "standard" Eta:

Horizontal: Janjic (1997) "antidiffusion scheme"
Vertical: Piecewise-linear (Mesinger and Jovic 2002)

From Mesinger and Jovic :

Dashed: original distribution

Solid: after 1st iteration

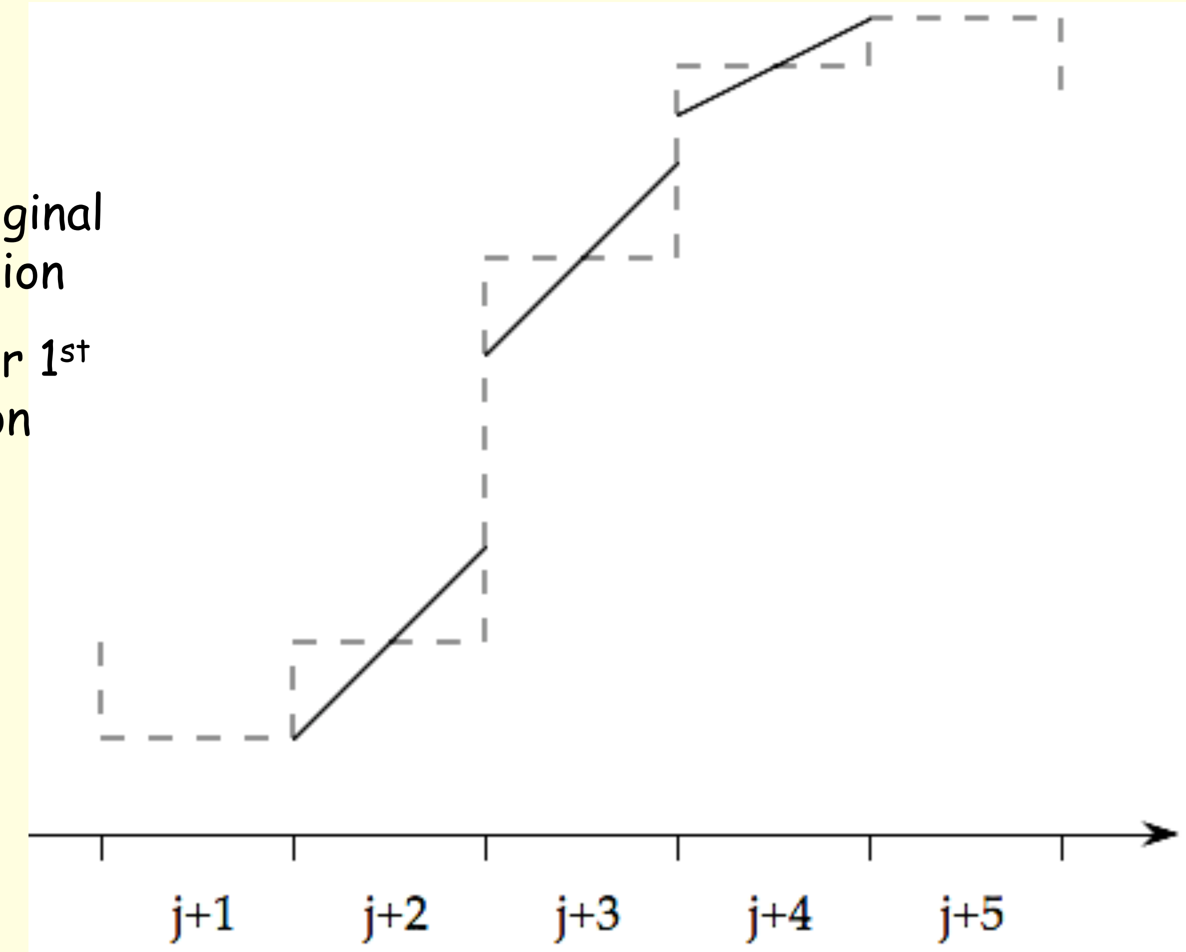


Figure 1. An example of the Eta iterative slope adjustment algorithm. The initial distribution is illustrated by the dashed line, with slopes in all five zones shown equal to zero. Slopes resulting from the first iteration are shown by the solid lines. See text for additional detail.

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!

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

References for Part I (if missing, check the CPTEC etaweb references site):

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

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Mesinger, F., 1974: An economical explicit scheme which inherently prevents the false two-grid-interval wave in the forecast fields. Proc. Symp. "Difference and Spectral Methods for Atmosphere and Ocean Dynamics Problems", Academy of Sciences, Novosibirsk, 17-22 September 1973; Part II, 18-34.

Mesinger, F., and A. Arakawa, 1976: Numerical Methods used in Atmospheric Models. WMO, GARP Publ. Ser. 17, Vol. I, 64 pp. [Available from World Meteorological Organization, Case Postale No. 5, CH-1211 Geneva 20, Switzerland.]

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).

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

Why eta coordinate (motivation) ?

What is the sigma PGF problem?

In hydrostatic systems:

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

The way we calculate things, in models,

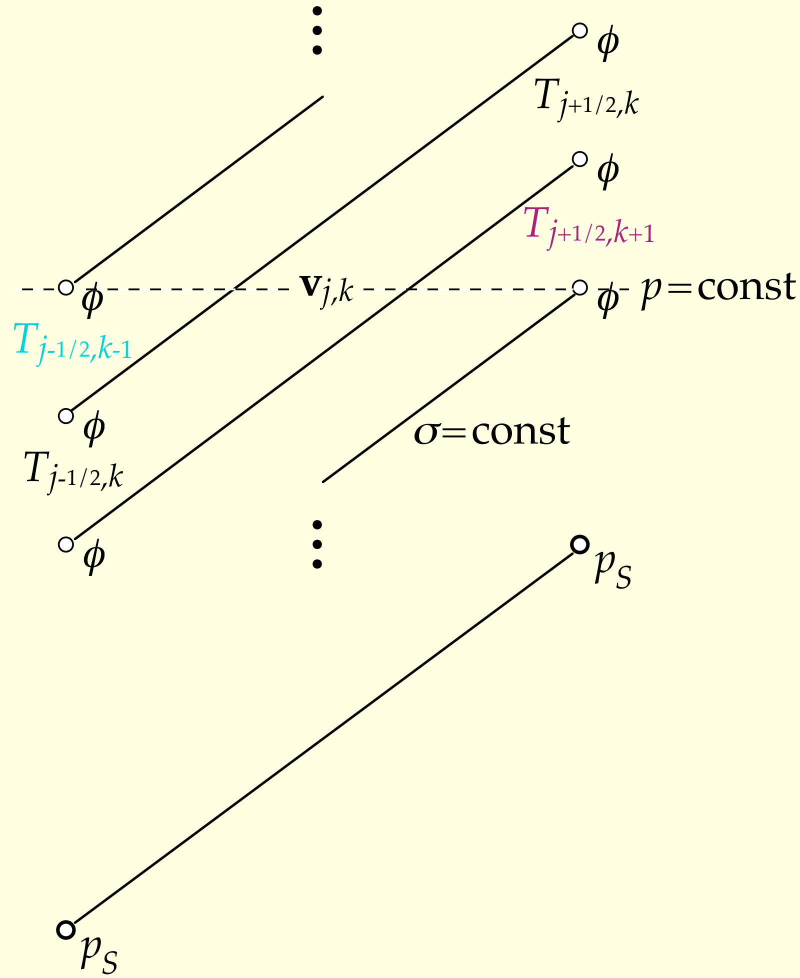
$$\phi = \phi_S - R_d \int_{p_S}^{p} T_v d \ln p$$

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*.

The problem aggravates with resolution ! (If the steepness does)

Mesinger 1982,

TABLE 1.

Errors of the pressure gradient force analogs obtained using the Corby et al. and the Burridge-Haseler schemes, for the "no inversion case" and the "inversion case"; see text for details. Values are given in increments of geopotential ($m^2 s^{-2}$), between two neighboring grid points, along the direction of the increasing terrain elevations. (Note that some of the numbers in the last two lines are slightly different from those published in the referred paper; this is a result of the removal of an error that Mesinger has found in his program for calculation of the Burridge-Haseler scheme values. The numbers published previously actually represented errors of a scheme which, within the geopotential gradient term, used geopotentials of the $\sigma = 0.9$ surface rather than values defined by (4.22).)

$\Delta\sigma =$	1/5	1/15	1/25	···	$\lim_{\Delta\sigma \to 0}$
Corby et al. scheme "no inversion case"	151.2	−48.7	29.0	···	0
Corby et al. scheme "inversion case"	−159.6	−159.6	−159.6	···	−159.6
Burridge-Haseler scheme "no inversion case"	0	0	0	···	0
Burridge-Haseler scheme "inversion case"	0	−142.1	−153.3	···	−159.6

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:

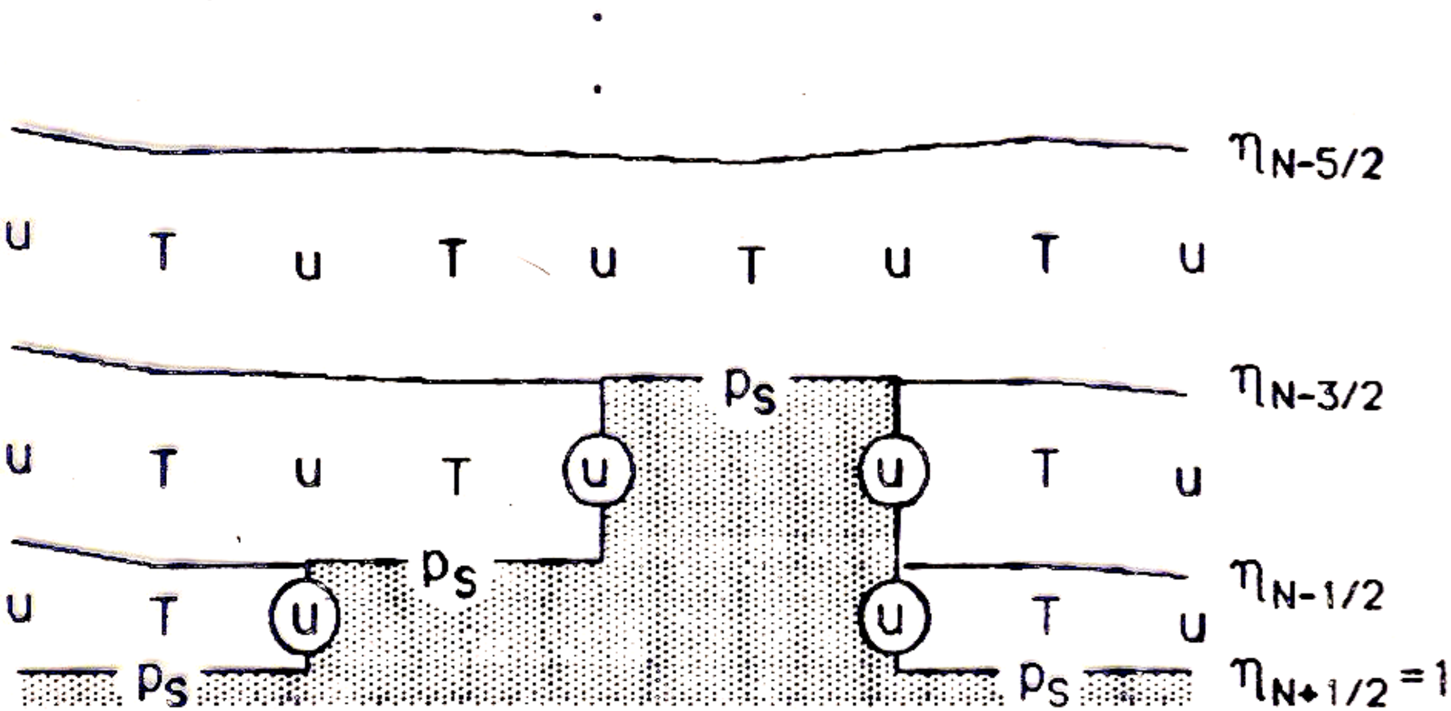


FIG. 1. Schematic representation of a vertical cross section in the eta coordinate using step-like representation of mountains. Symbols u, T and p_s represent the u component of velocity, temperature and surface pressure, respectively. N is the maximum number of the eta layers. The step-mountains are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

In early tests eta/ sigma,

and in those somewhat later in NCEP's

full-physics "Eta Model", Eta did extremely well:

Sigma Eta

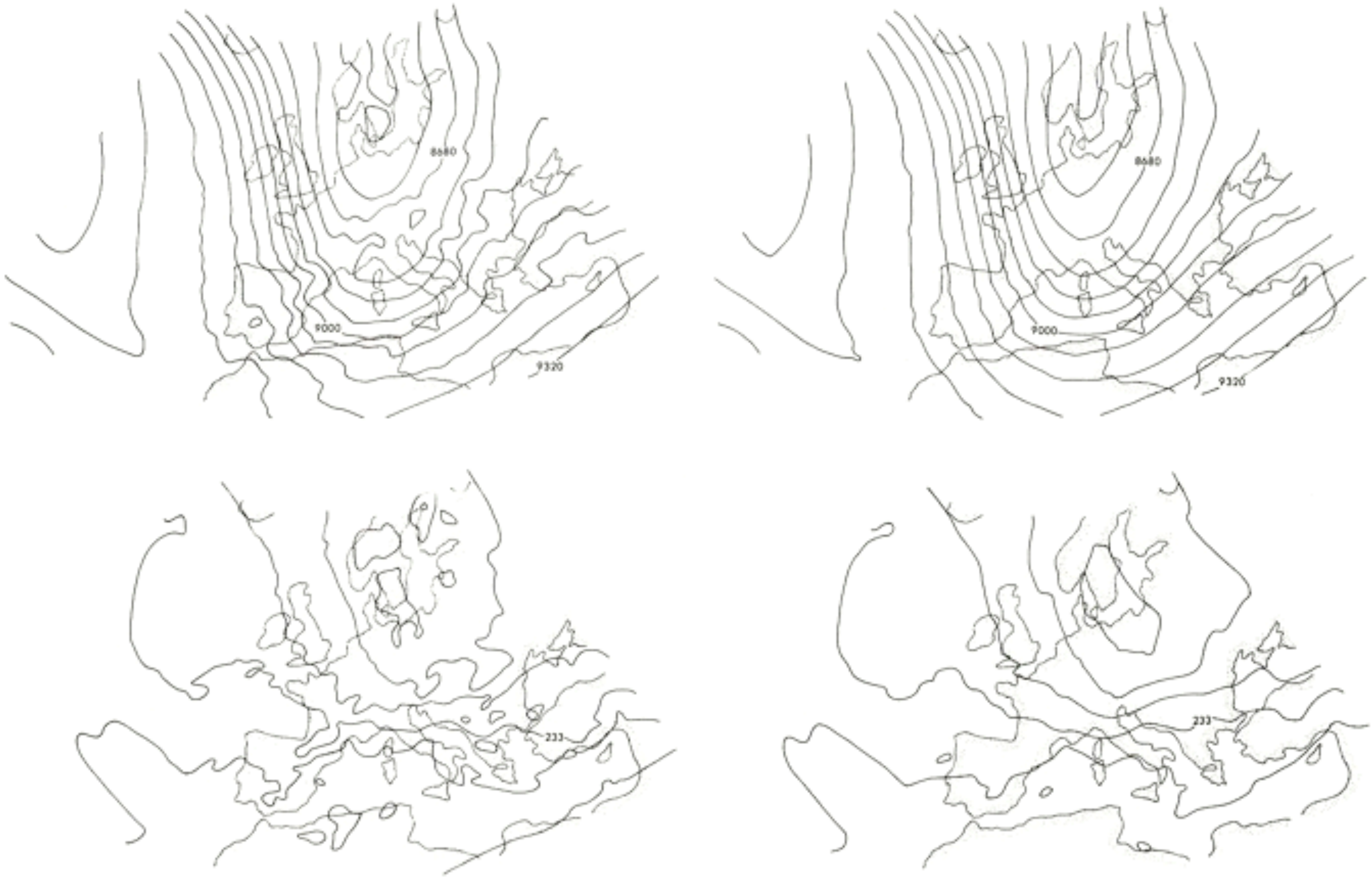


FIG. 6. 300 mb geopotential heights (upper panels) and temperatures (lower panels) obtained in 48 h simulations using the sigma system (left-hand panels) and the eta system (right-hand panels). Contour interval is 80 m for geopotential height and 2.5 K for temperature.

André Robert
Memorial Volume:

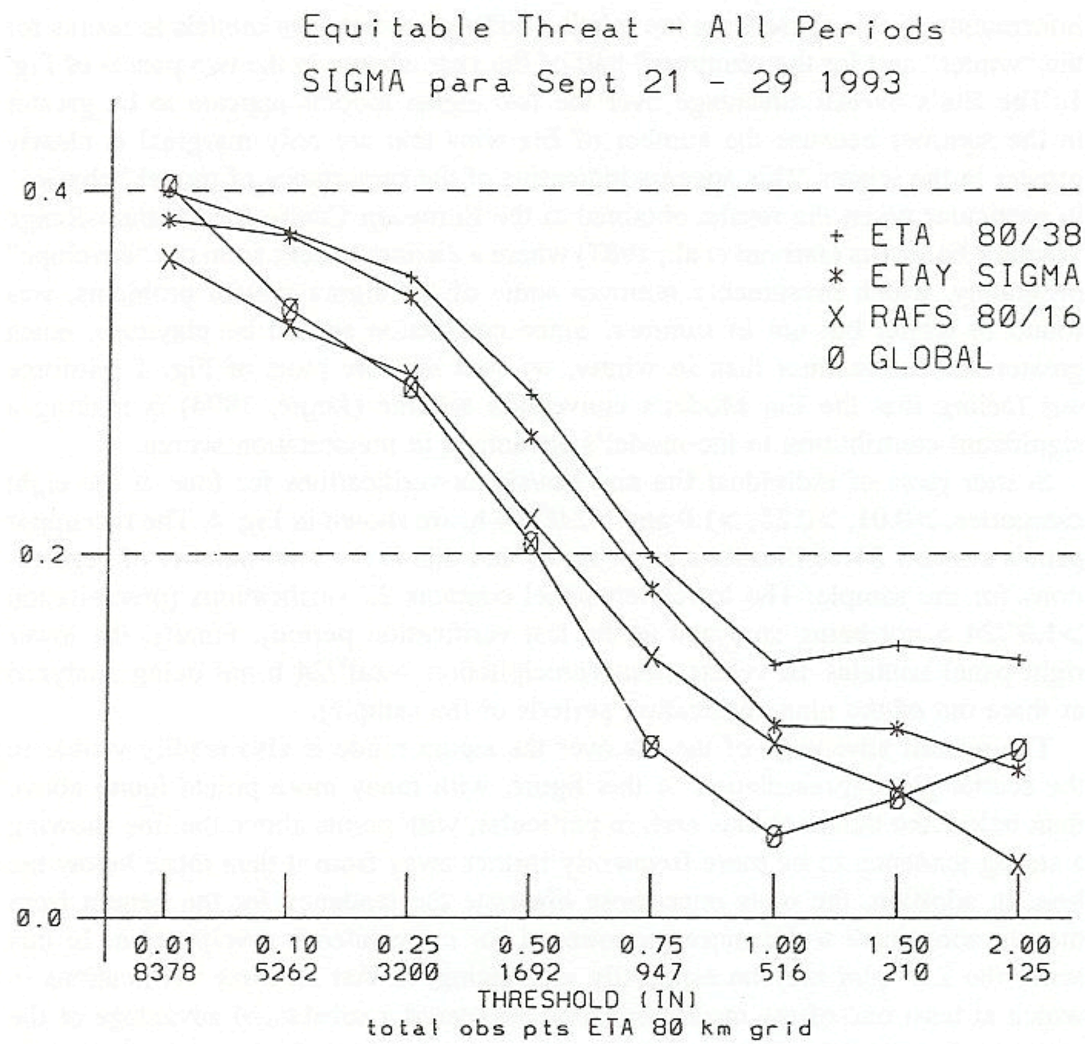
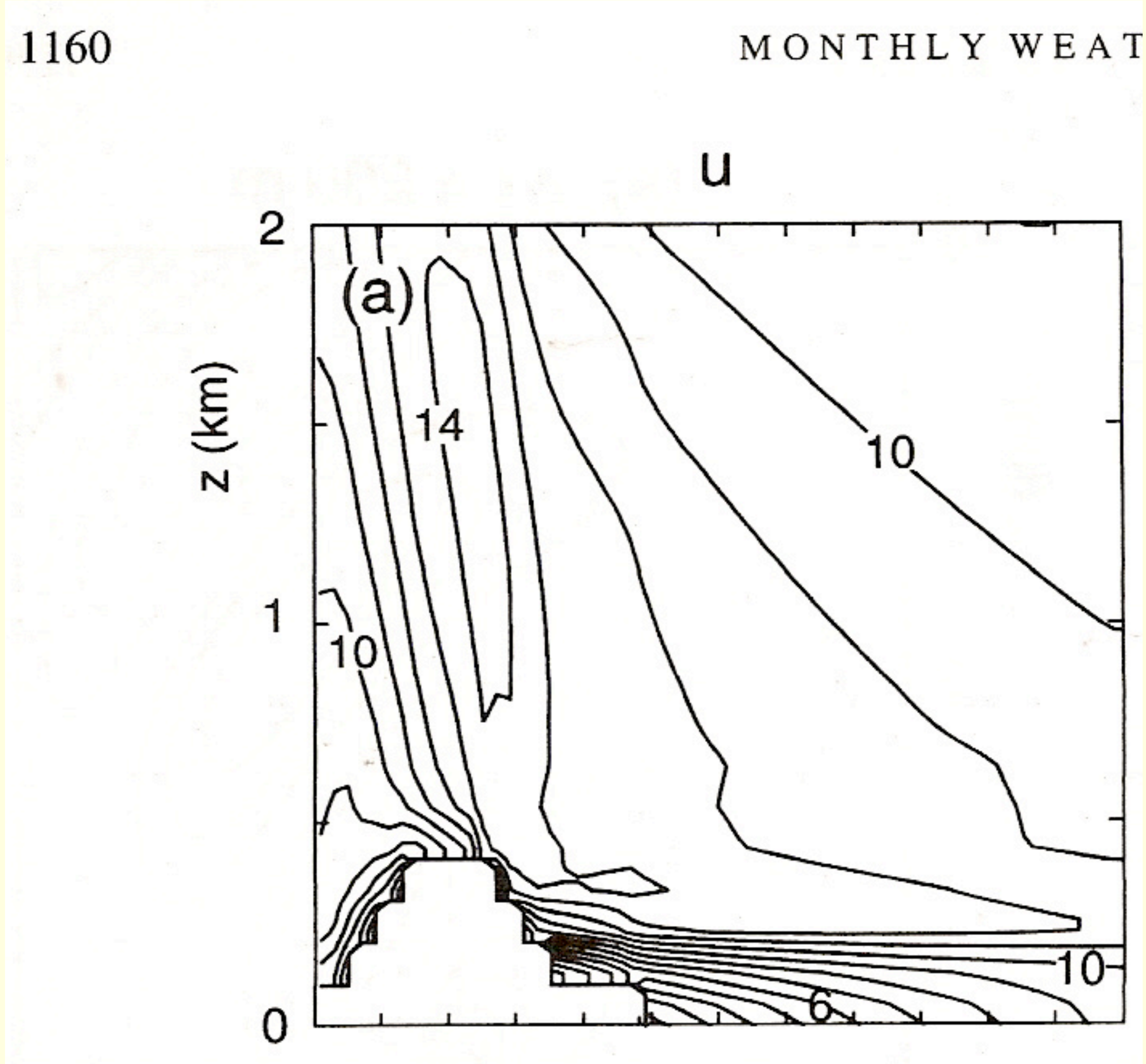


Fig. 3 Equitable precipitation threat scores for two versions of the Eta Model: Eta 80 km/38 layers ("ETA"), and the same version of the Eta Model but run using sigma coordinate ("ETAY"), and for the NGM (RAFS), and the Avn/MRF ("global") Model; for a sample of 16 forecasts verifying 1200 UTC 21 September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

Quite a few more !

However,

a 10-km Eta in 1997 did a poor job on a case of the so-called Wasatch downslope windstorm, while a sigma system MM5 did well; also: Gallus, Klemp (MWR, 2000)



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

("Witch of Agnesi" mountain)

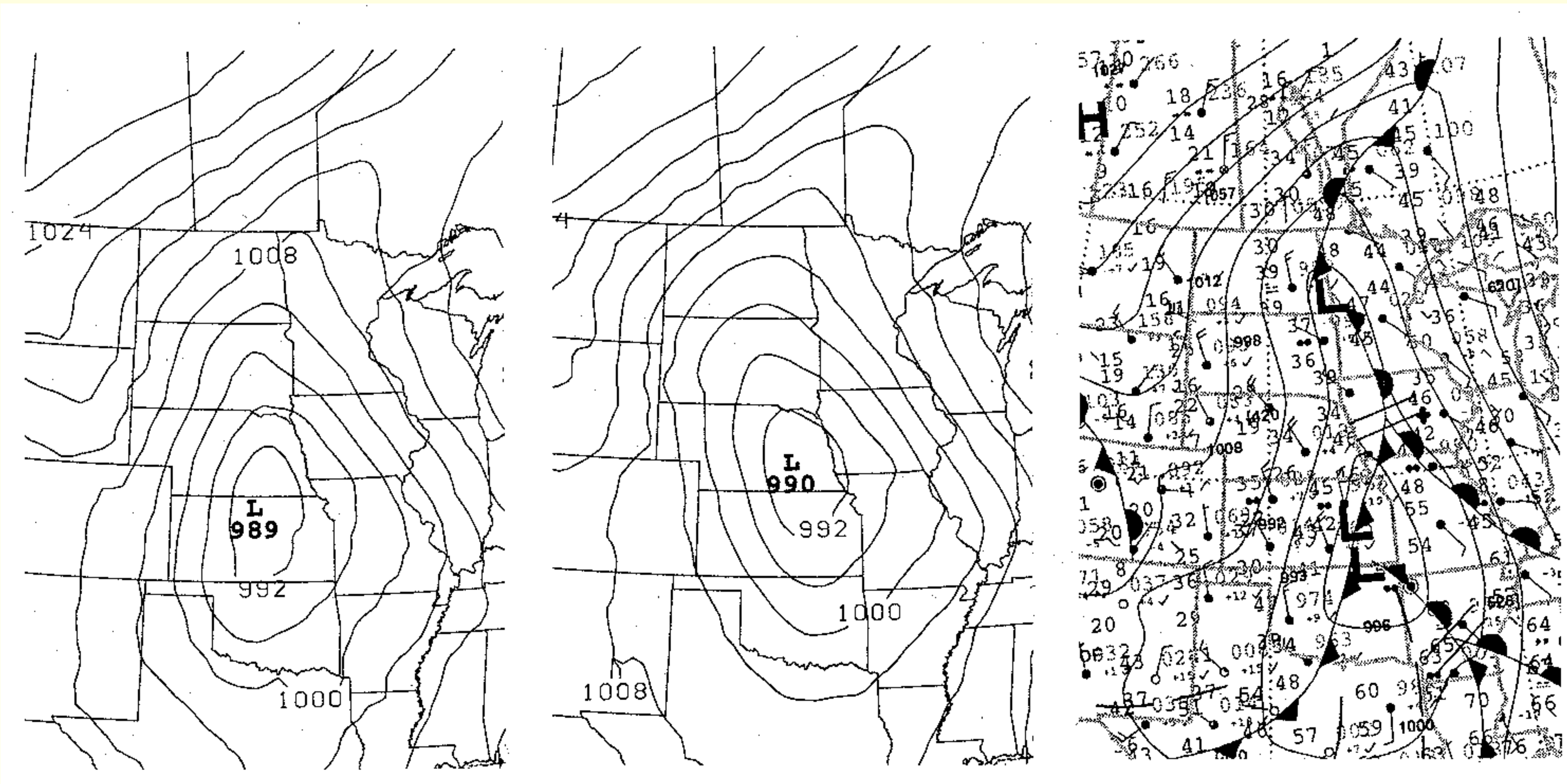
Eta: bad press for quite some time:

"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 ??

One “**eta favorable**” experiment at the time though, done in 2001:
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

Even so: the downslope windstorm problem;

also:

Claims made (Colle et al. 1999) claiming that sigma system MM5 is better than Eta in placing precip over topography;

Thus, when NCEP's "Nonhydrostatic Mesoscale Model" (NMM) derived from the Eta, was implemented on "hi-res windows" in 2002, switched from eta to sigma

NOAA-wide announcement:

"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".

Thus, when NCEP's "Nonhydrostatic Mesoscale Model" (NMM) derived from the Eta, was implemented on "hi-res windows" in 2002, switched from eta to sigma

NOAA-wide announcement:

"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".

Also: This was just a step toward development of an NCEP version of the "Weather Research and Forecasting" ("WRF") model - and continued precipitation results favoring eta had not enough power to convince management to return to the eta

The downslope windstorm problem:

1) What counts is not so much small mountains, but much more large mountains (e.g., Rockies, Andes !!) Many eta/sigma experiments suggest that it is in simulating the impact of large mountains that the benefit from the eta is at its most conspicuous;

2) The problem of the eta in getting the flow all the way down on the lee side of the mountain can be understood and addressed.

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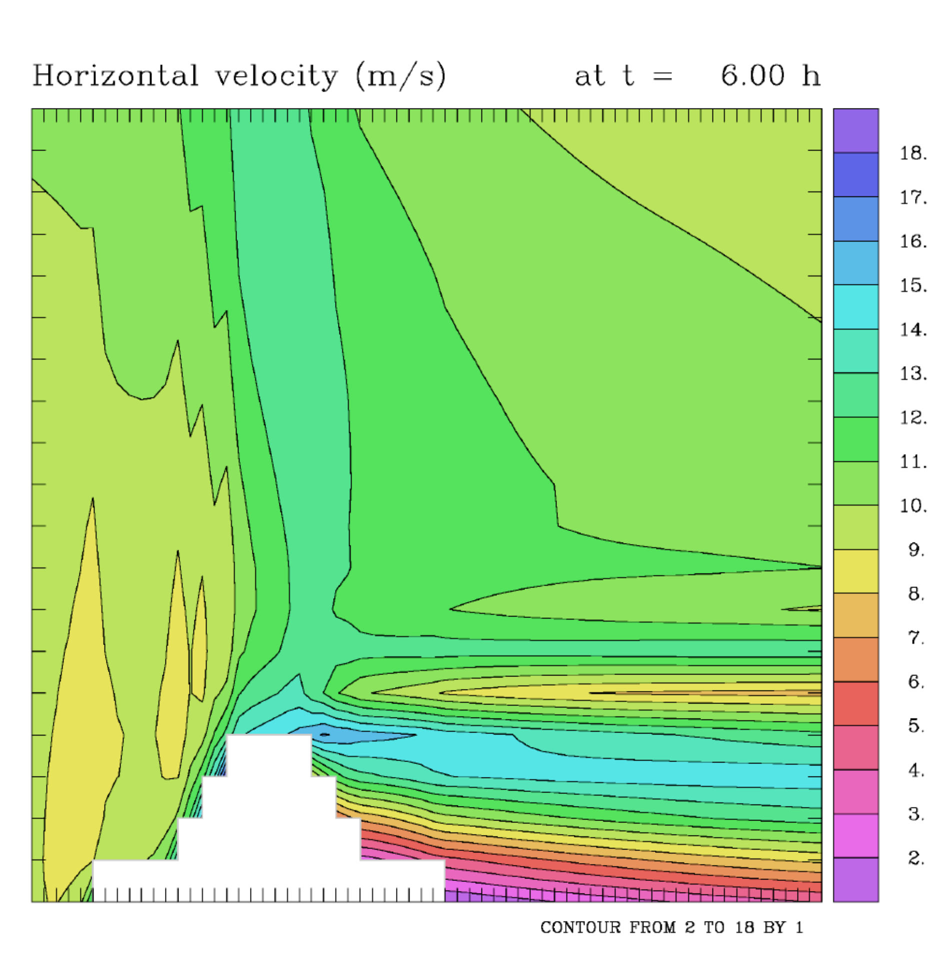
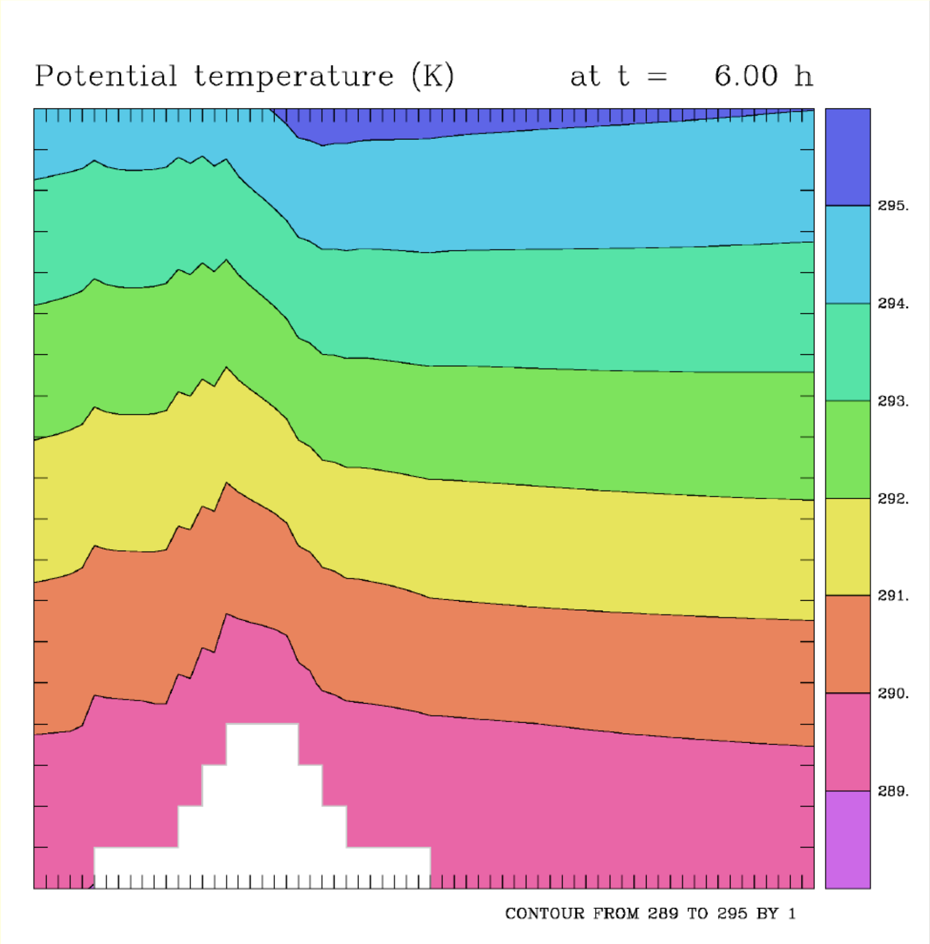
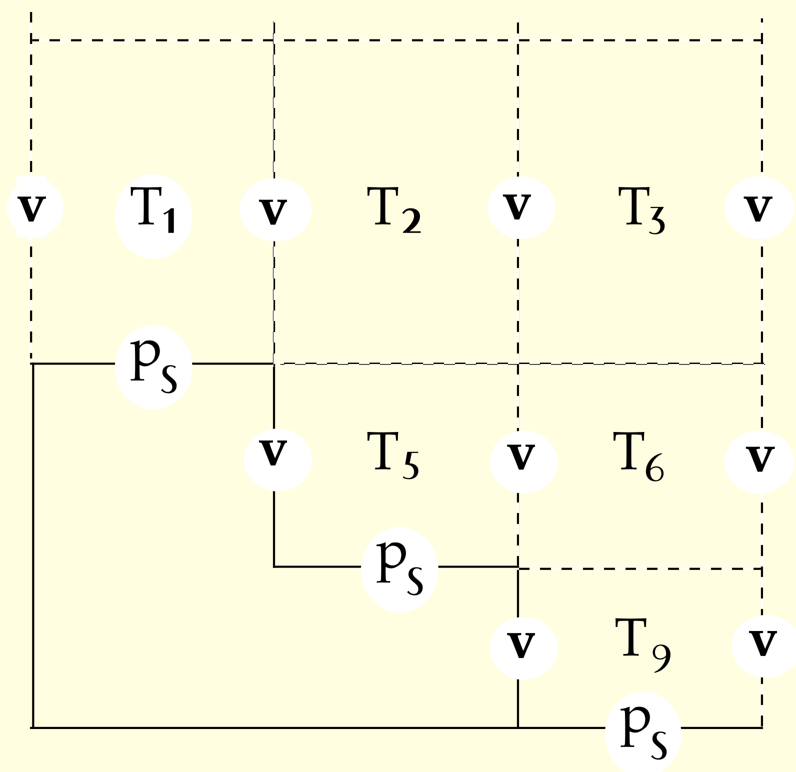
2) The problem of the eta in getting the flow all the way down on the lee side of the mountain can be understood and addressed.

Addressing the downslope windstorm problem: Flow separation on the lee side (à la Gallus and Klemp 2000):





Suggested explanation



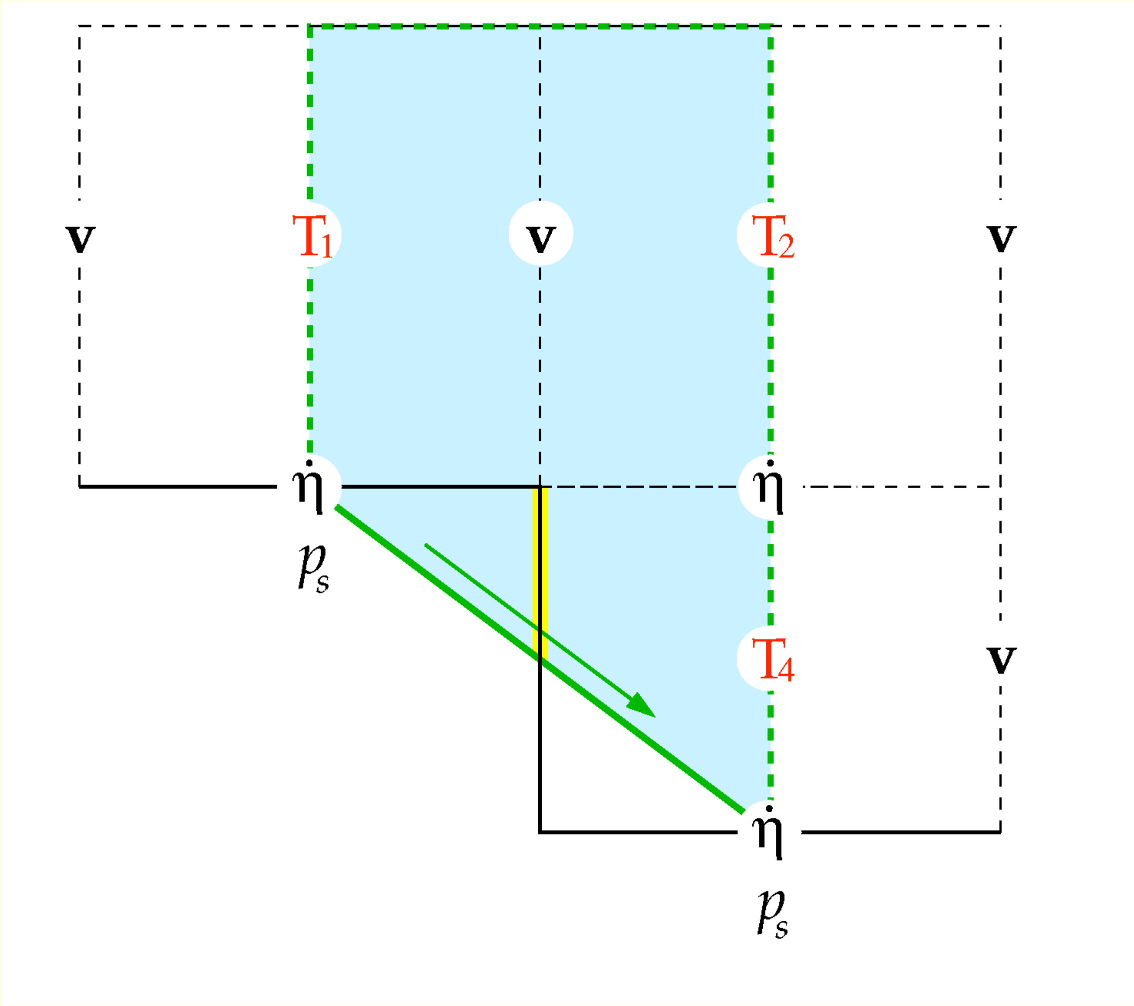
Flow attempting to move from box 1 to 5 is forced to enter box 2 first.

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.

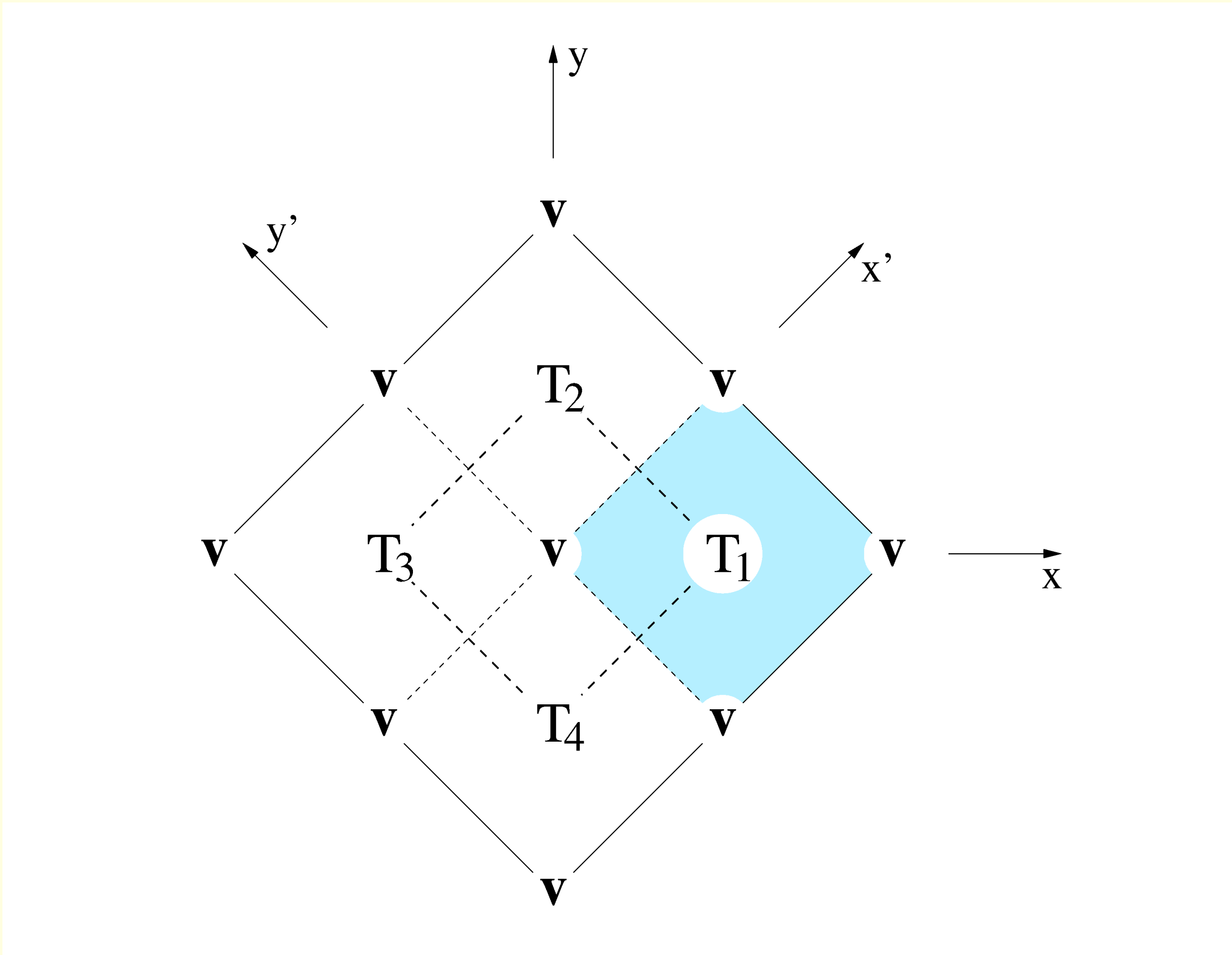
The sloping steps, vertical grid

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

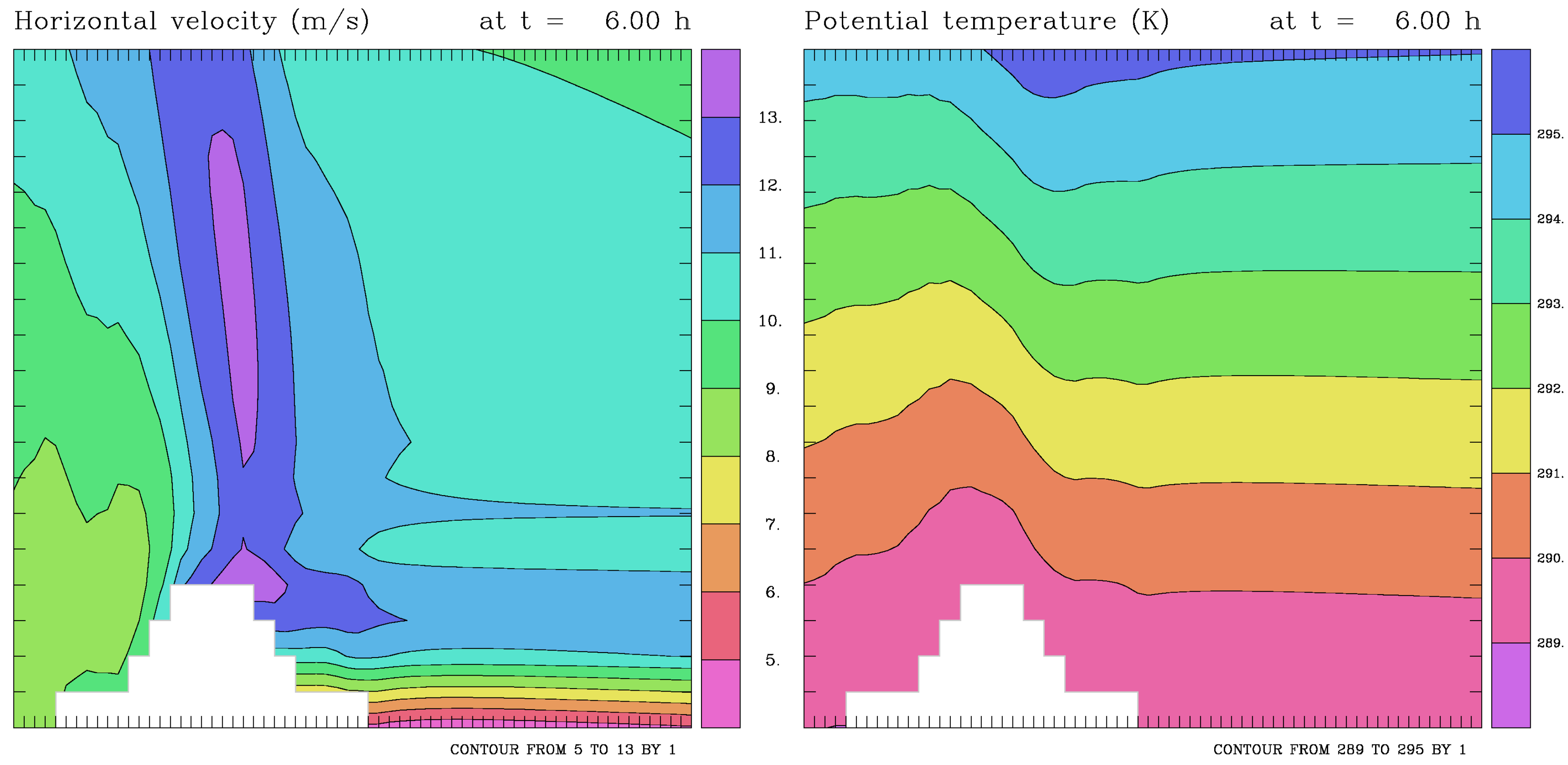
Example #2: topographies of boxes 1 and 2 are the same, and higher than those of 3, and 4; "Slope 2"

Topography descends from the centers of T1 and T2 down by one layer thickness, linearly, to the centers of T3 and T4

Etc.: Slopes 3, 4, …, 8

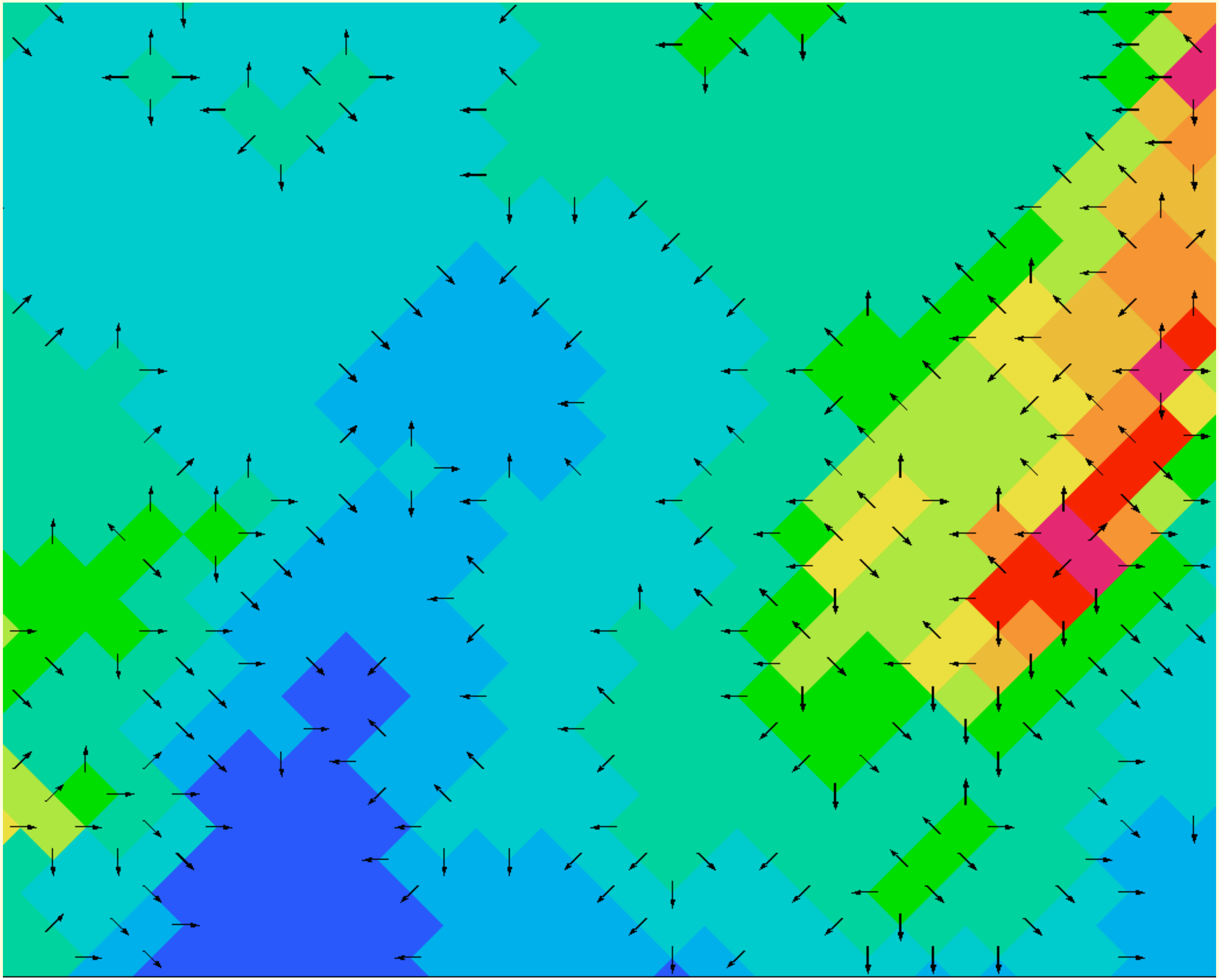
If two opposite, or if three topography boxes are the highest of the four: No slope

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" as in Gallus and Klemp ~ removed. Zig-zag features in isentropes at the upslope side removed.

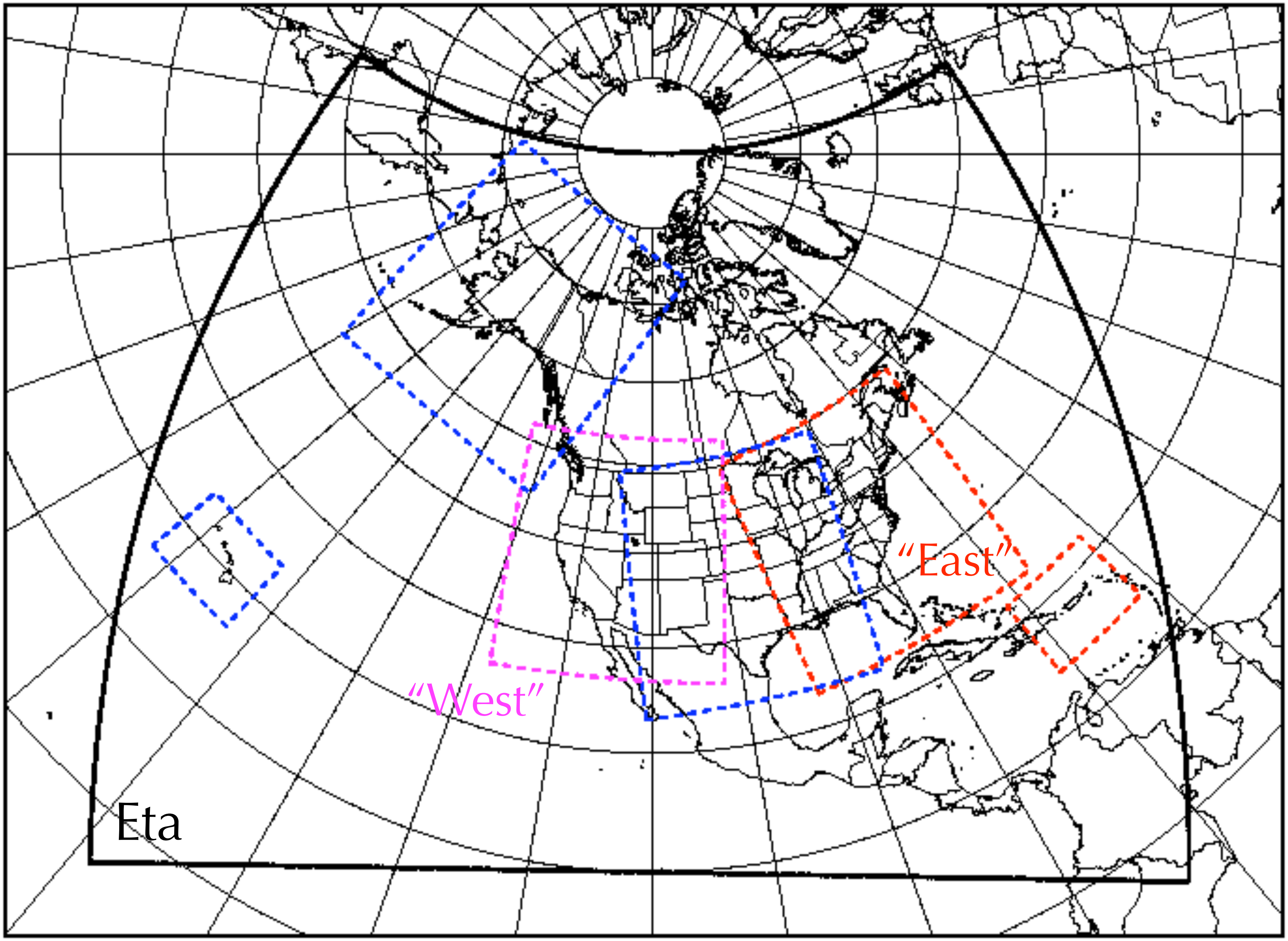
Example of slopes with an actual model topography:



Precipitation: continuously eta-favorable results

Now three-model precipitation scores were available, on NMM ConUS domains ("East" ,..., "West"), available Sep. 2002 to 2005

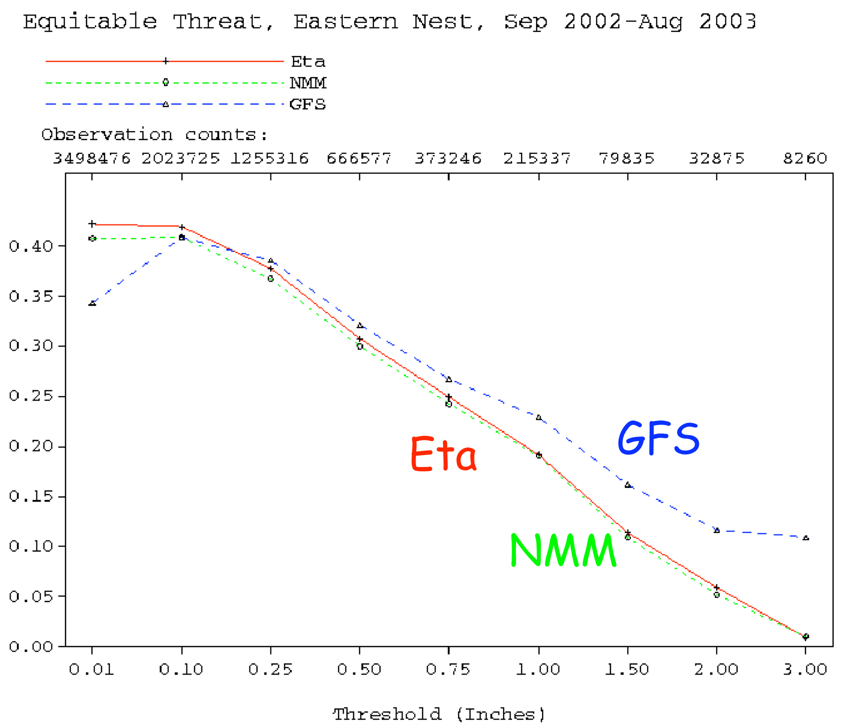
- Operational Eta: 12 km, driven by 6 h old GFS forecasts (a considerable handicap compared to GFS of the same initial time);
- NMM: 8 km, sigma, driven by the Eta;
- GFS (Global Forecasting System) as of the end of Oct. 2002 T254 (55 km) resolution, sigma

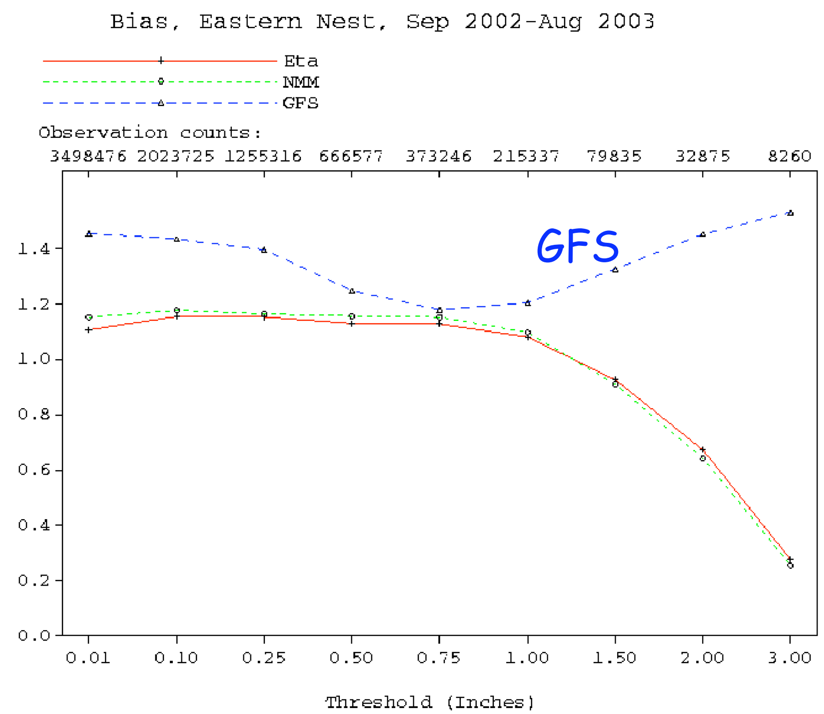


"East"
"West"
Eta

The first 12 months of three model scores:

East





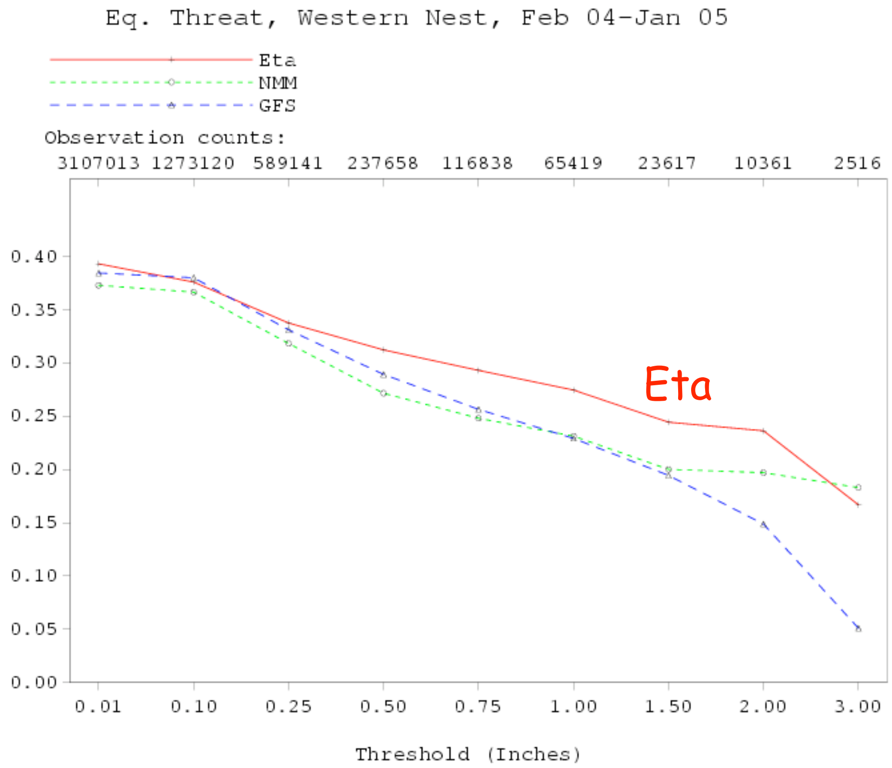
ETS (Equitable Threat Score) Bias

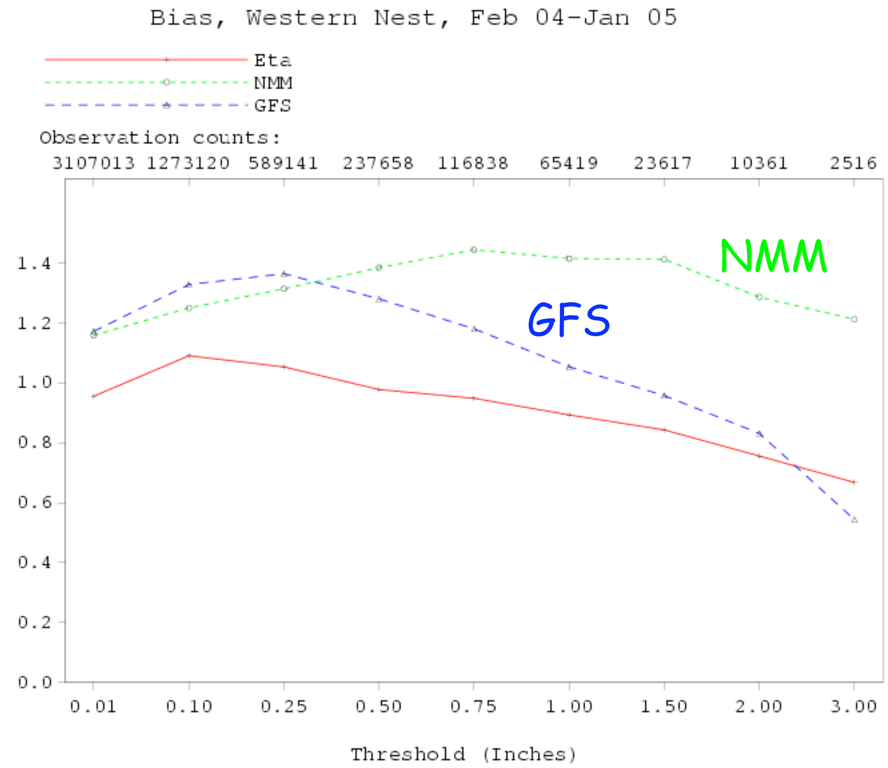
Is the GFS loosing (winning) because of its bias difference?

"The last 12 months": Feb. 2004 - Jan. 2005

(includes high impact California precip,
winter 2004-2005)

The last 12 months, now West



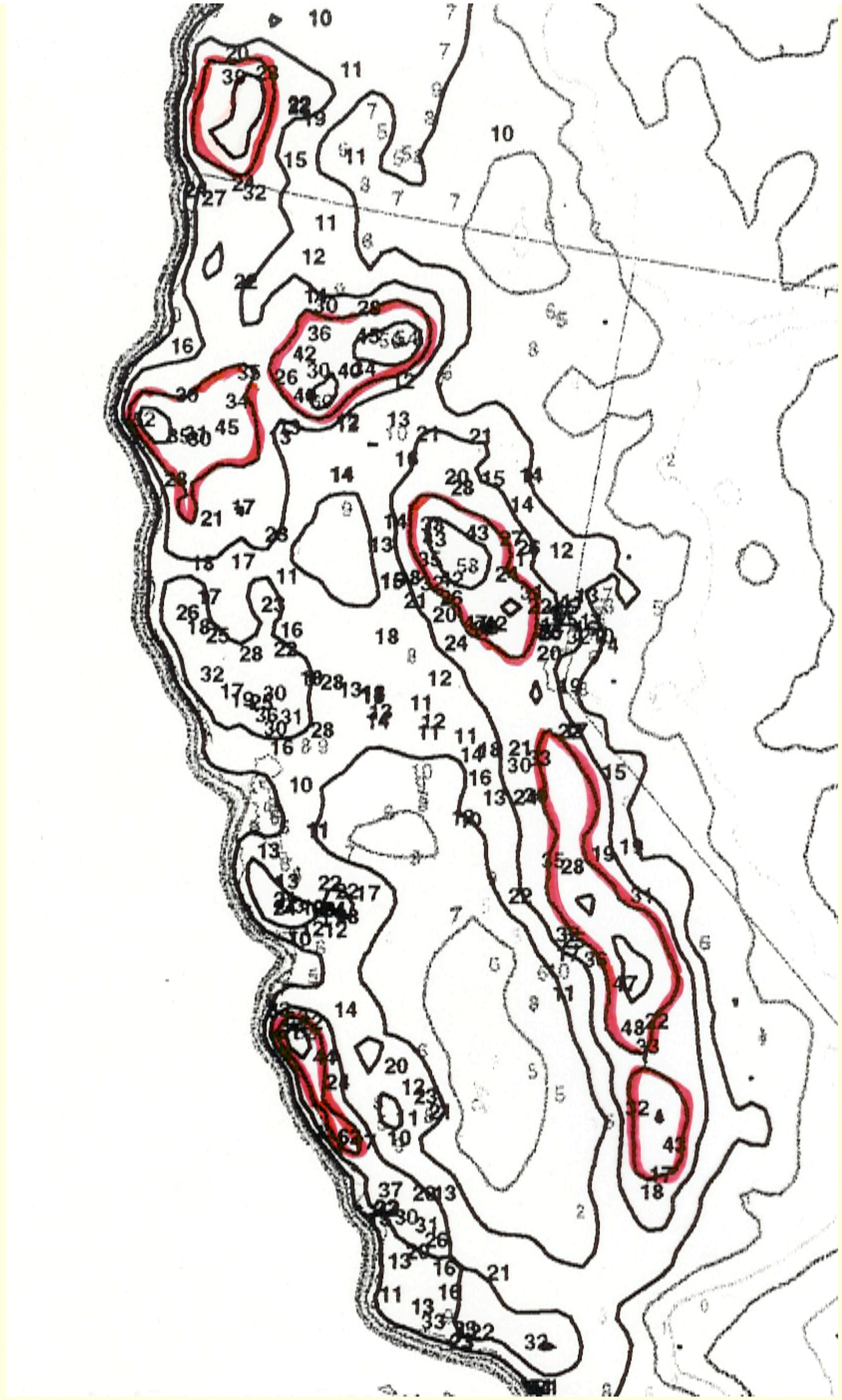


Is the green model loosing to red because of a bias penalty?

An example of precip at one of these events:

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

An extraordinary challenge to do well in QPF sense !



There is a problem however with using the ETS:

A model can have a higher ETS because of its erroneously high bias !

The problem addressed first in a conference paper:

J12.6

17th Prob. Stat. Atmos. Sci.; 20th WAF/16th NWP (Seattle AMS, Jan. '04)

BIAS NORMALIZED PRECIPITATION SCORES

Fedor Mesinger[1] and Keith Brill[2]

[1]NCEP/EMC and UCAR, Camp Springs, MD

[2]NCEP/HPC, Camp Springs, MD

and more recently - much more successfully(!) - in

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

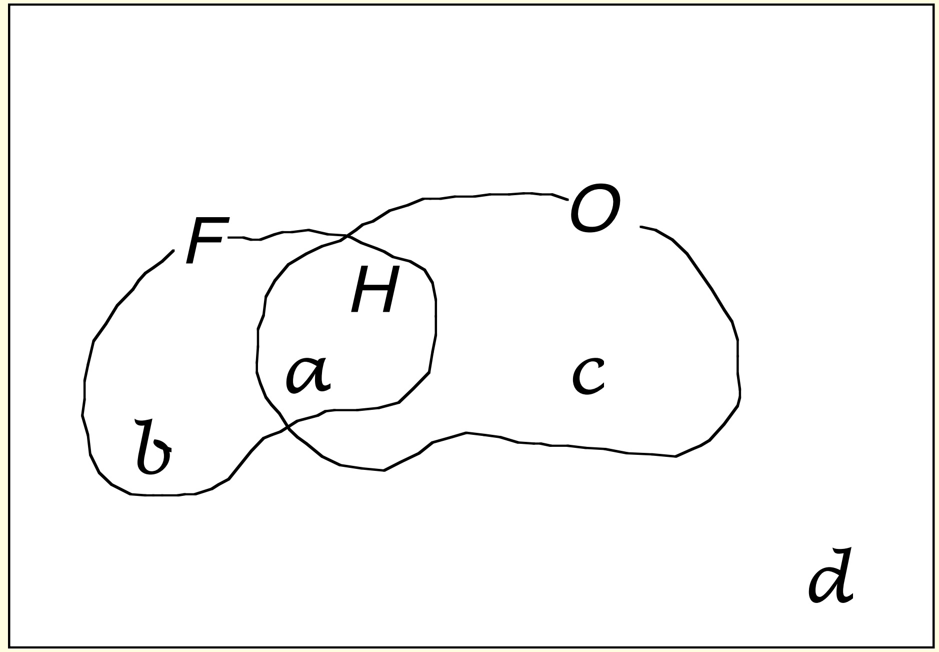
Objective:

obtain ETS adjusted to unit bias,

to show the model's accuracy in placing precipitation

"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:

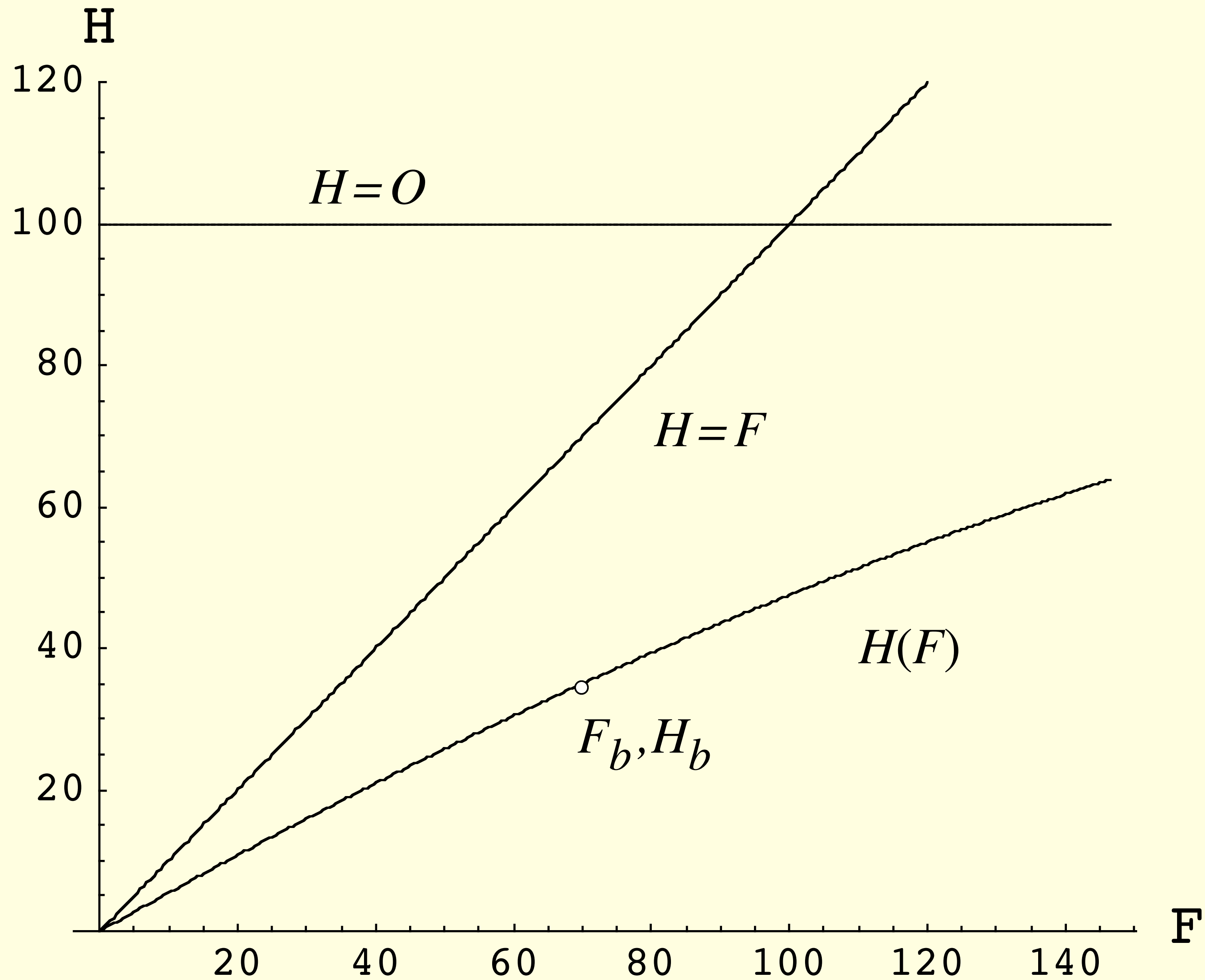
$$\frac{dH}{dA} = b(O - H) \qquad b = const$$

Differential equation, can be solved

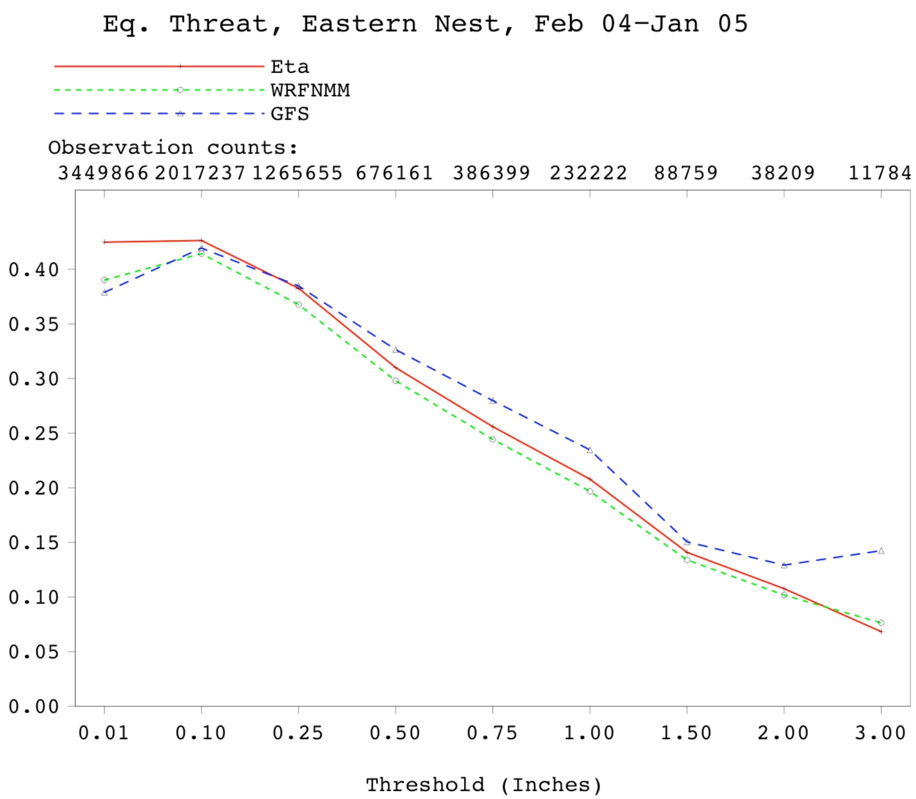
(Mathematica, or MATLAB)

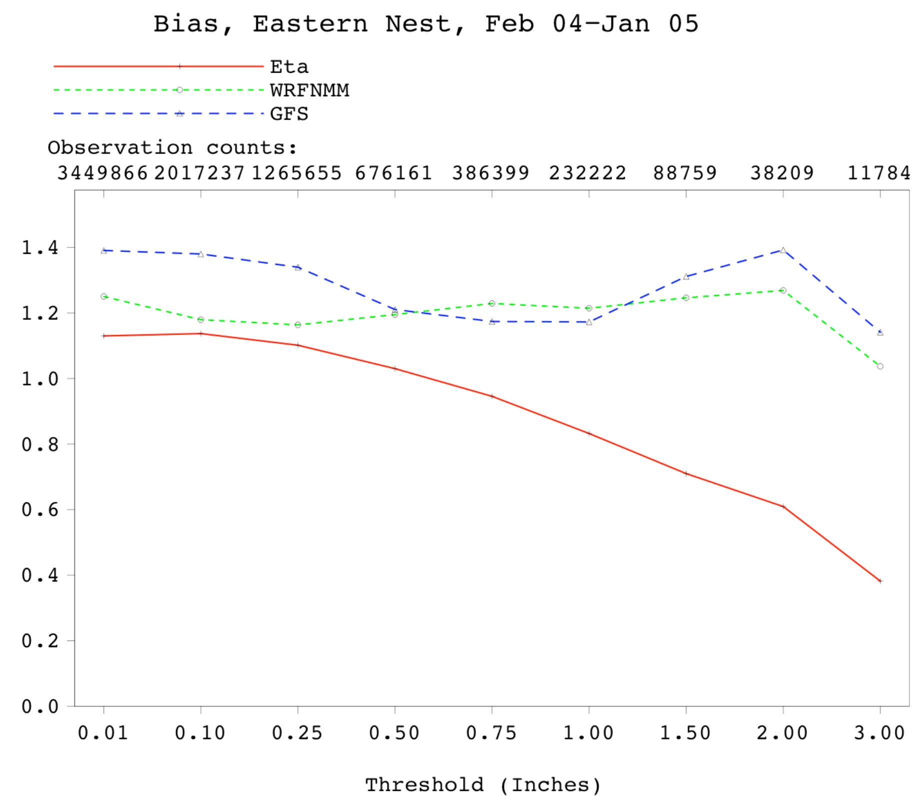
H(*F*) obtained that now satisfies an additional requirement of d*H*/d*F* never > 1

dHdA method

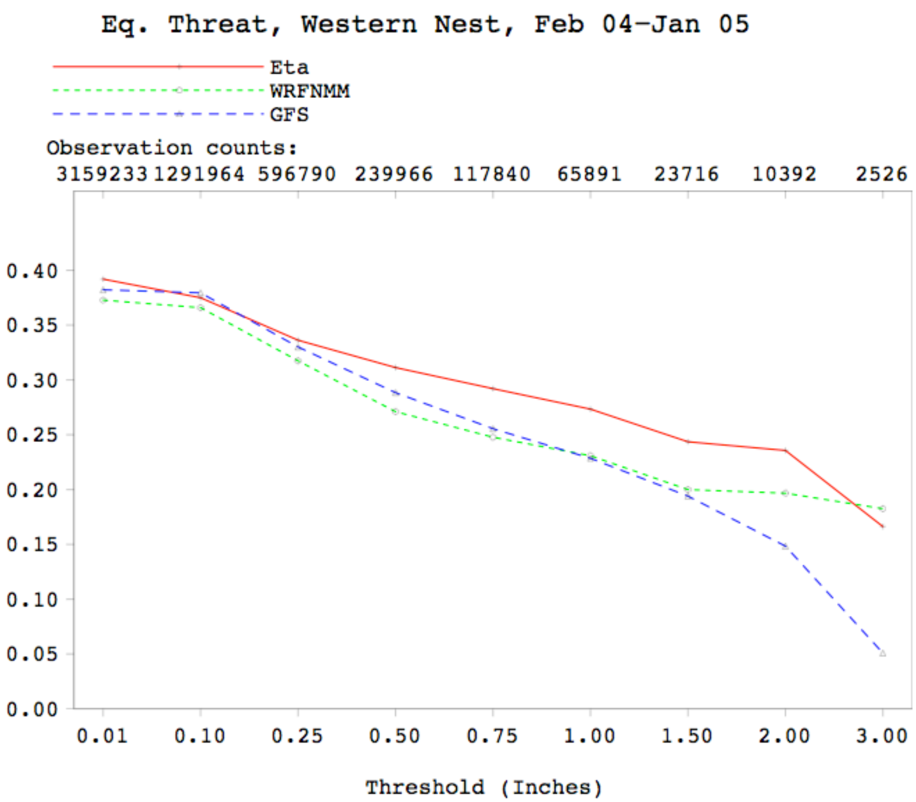


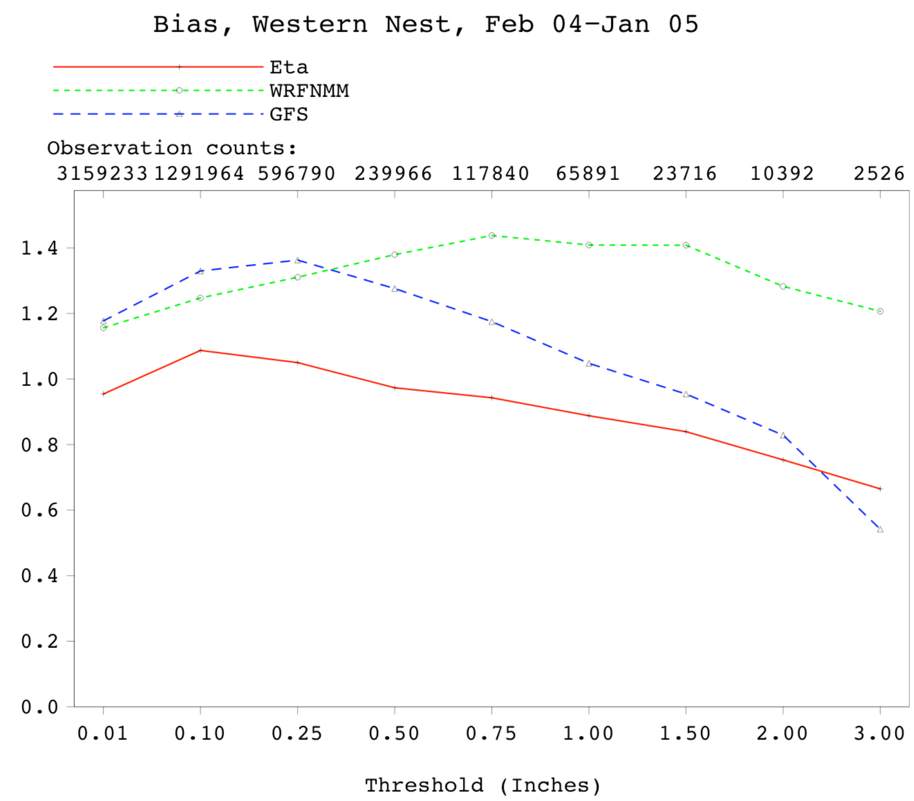
ETS, bias, East



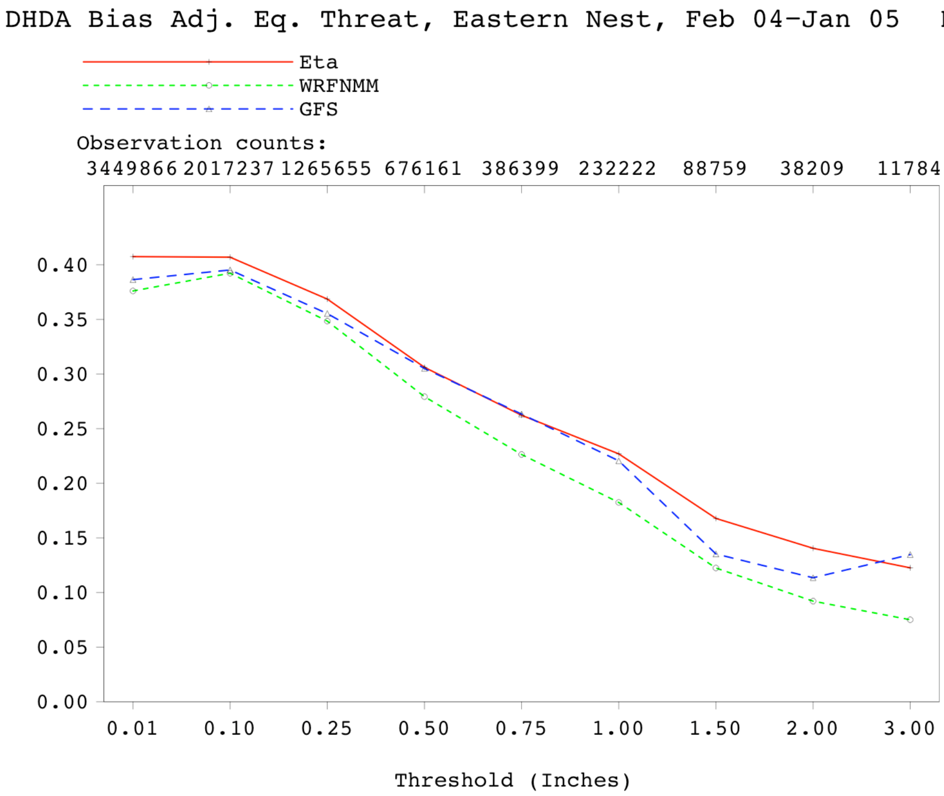


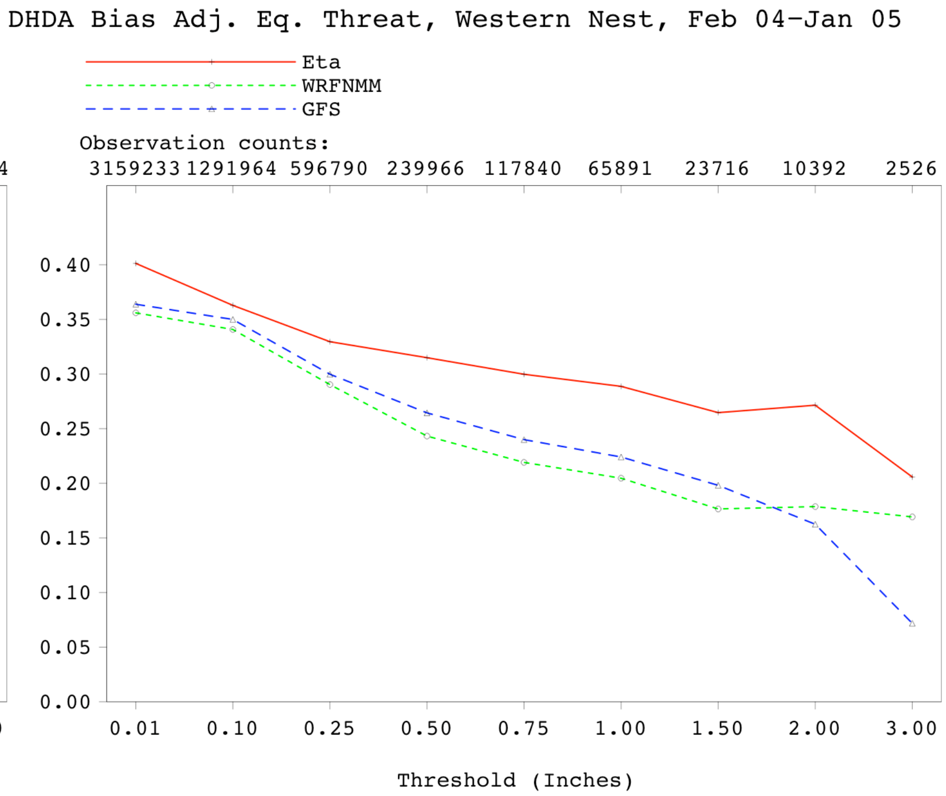
ETS, bias, West





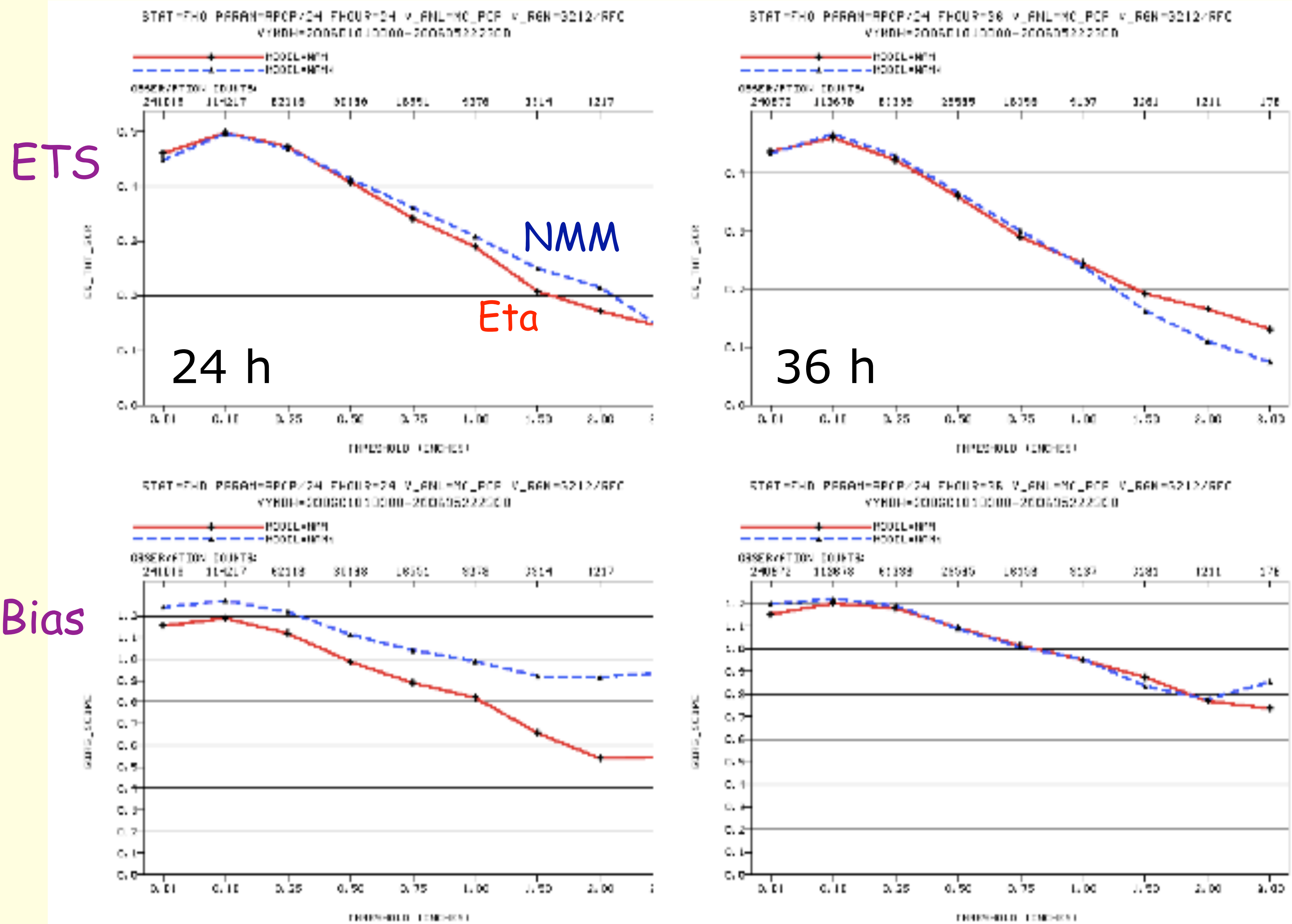
ETS corrected for bias, East, West

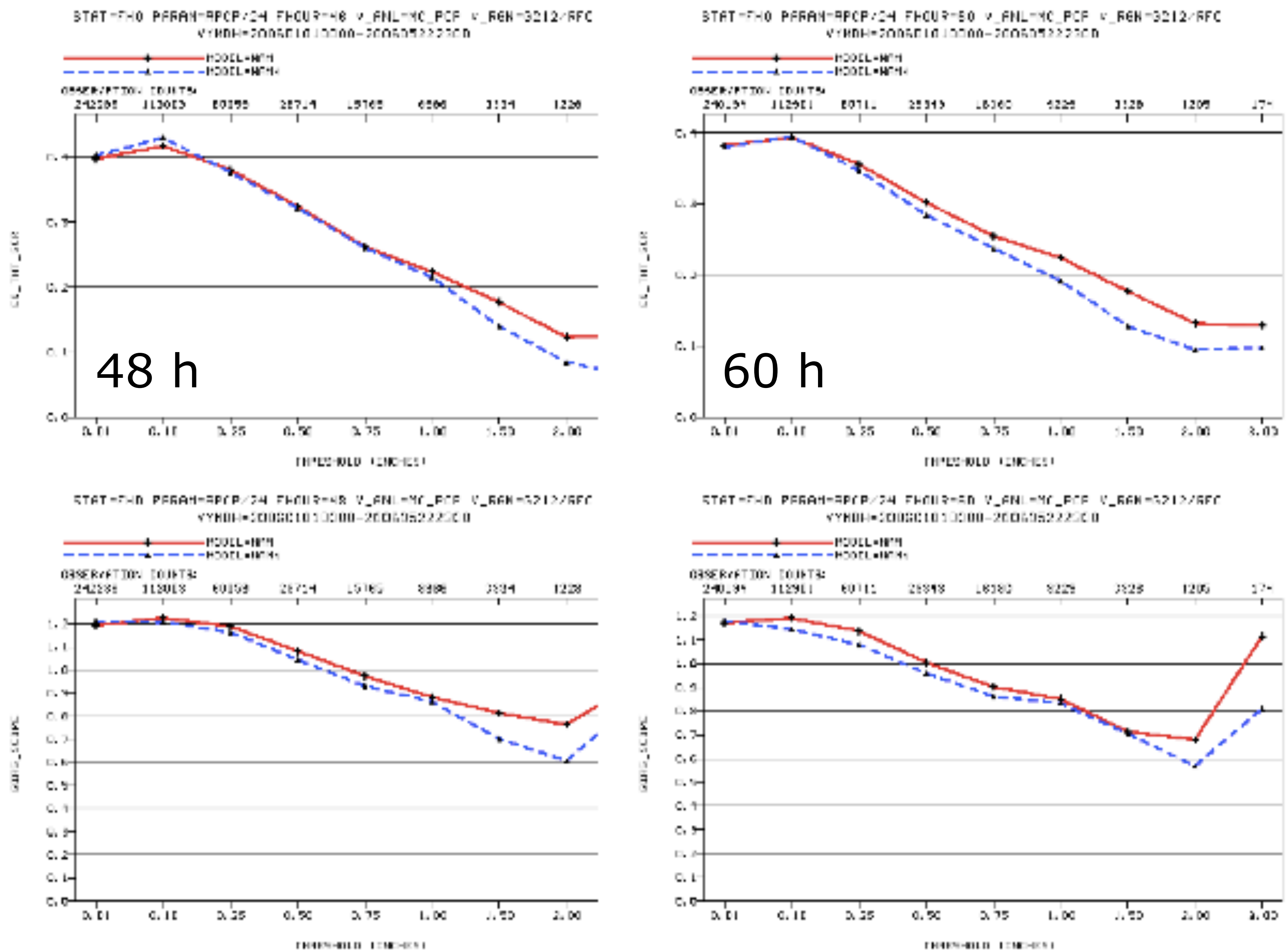


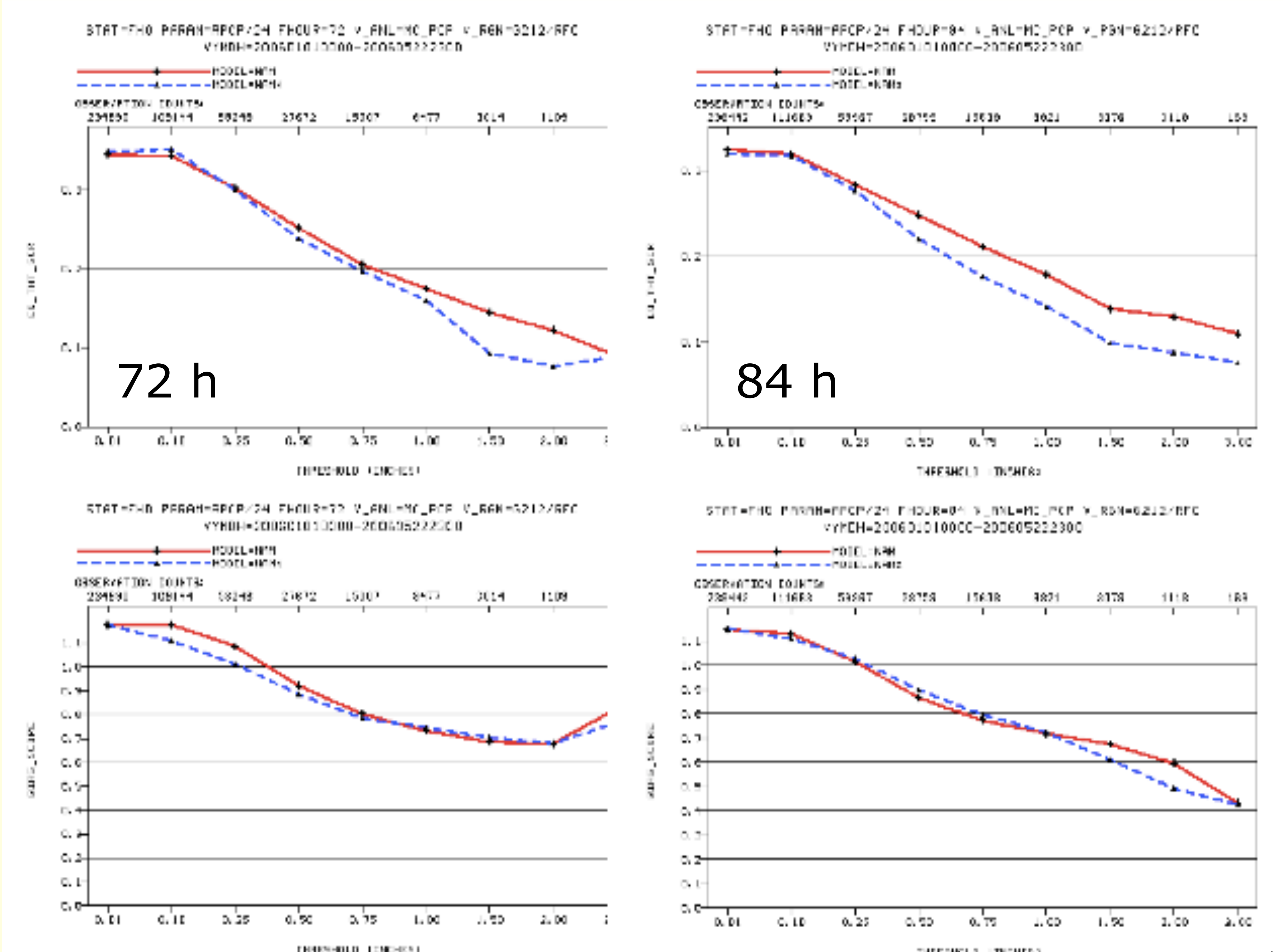


More recent results – comparison of Eta against the WRF-NMM, but with WRF-NMM using a new data assimilation system (from DiMego 2006)

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)

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 (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 ?

References for Part II (for the missing ones, check the CPTEC etaweb references site):

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., 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.