Eta Model Dynamics

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with contributions and assistance from many — from CPTEC, NCEP, and University of Belgrade.

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CPTEC Eta Workshop V – WorkEta V

Saõ José dos Campos, SP, 3-8 April 2016

Part I

Introduction, discretization schemes used

- Approach, lateral boundary conditions
- Gravity-wave coupling/ time differencing;
- Horizontal advection:
- Energy transformations;
- Finite volume vertical advection of v, T;
- Nonhydrostatic effects

Part II:

2.1) Pressure-gradient force, eta coordinate, various tests of the impact;

2.2) More recent developments:

- "sloping steps," change of slantwise advection to finite volume,
- revisiting Gallus Klemp problem following a horizontal diffusion upgrade

2.3) Tests of overall performance in ensembles driven by ECMWF 32-day ensembles

"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;

"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;
- . . .

Computational mode ?

Difference solution that does not tend to the physical solution when Δt -> 0

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

The term used increasingly today: "mimetic" properties

Akio Arakawa:

(1998, Symposium:

General Circulation Model Development: Past, Present and Future)

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

Lateral boundary conditions (LBCs) are needed

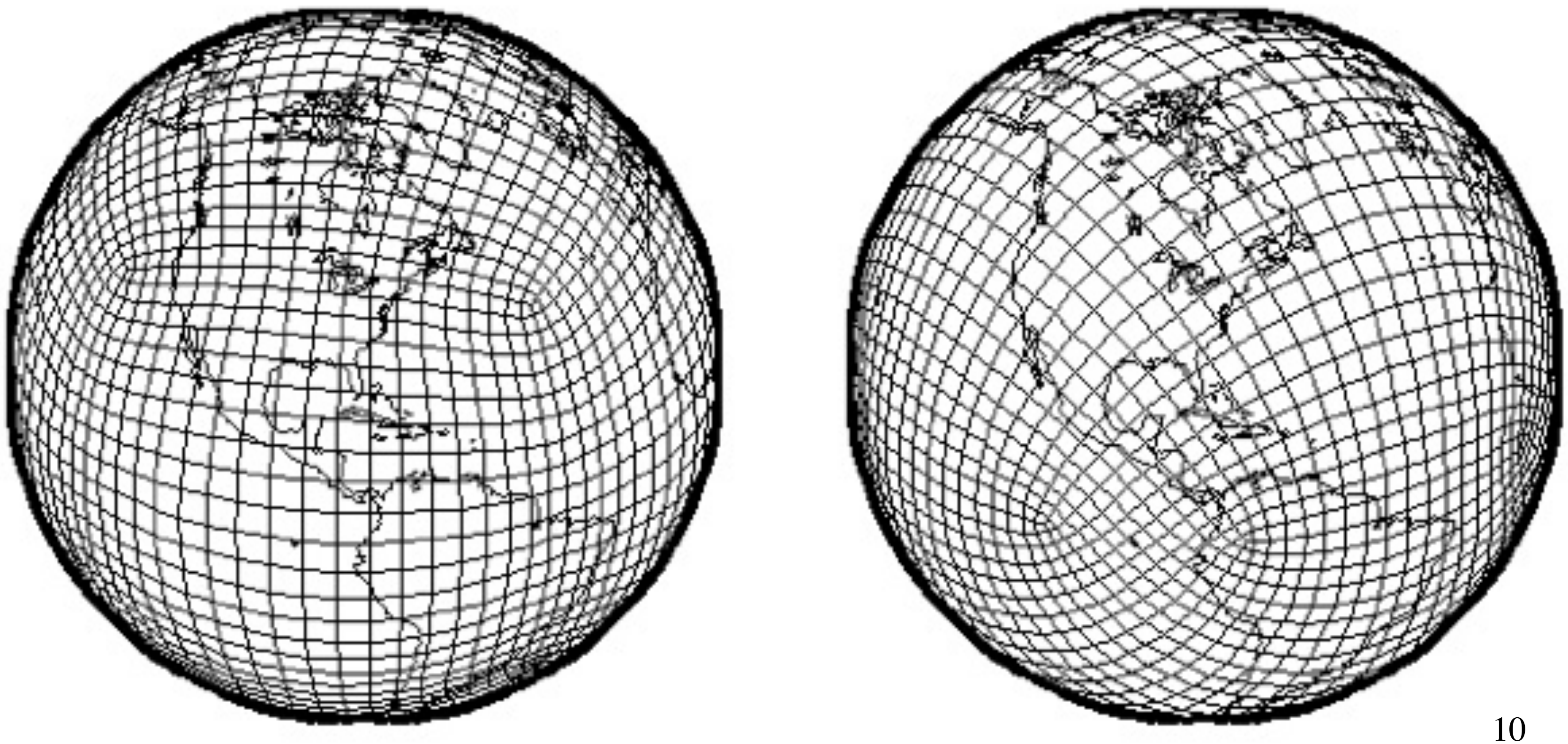
The Eta: Driver model u,v,T prescribed at the single outermost row of inflow grid points; at the outflow grid points same except that tangential velocity is extrapolated from inside the model domain

Mesinger and Veljovic (Meteor. Atm. Phys. 2012): comparison of the Eta scheme against the "relaxation scheme" used in perhaps all other limited area models

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.

Dragan Latinović upgrading by adding nonhydrosatic option



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;

- Finite-volume vertical advection of dynamic variables (**v**, T)

- Nonhydrostatic option;

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

- Gravity wave (gravity-inertia wave) scheme

Linearized shallow-water equations:

The forward-backward scheme:

(Richtmyer ?)

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

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

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

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

No computational mode

Coriolis terms: trapezoidal scheme

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

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

Unconditionally neutral

(Fischer, MWR, 1965)

Neutral with time steps twice those of the leapfrog scheme !!

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.

Arakawa and Winninghoff, end of the sixties:

geostrophic ajustm. :

"the green book"

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

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

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

Arakawa, dynamics:
- geostrophic adjustment
- simulation of slow, quasi-geostrophic motions

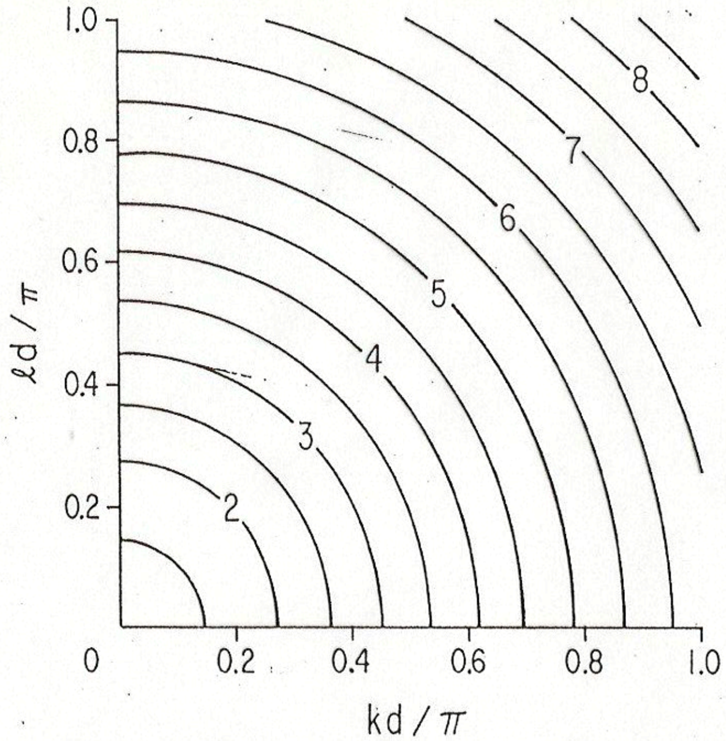


FIG. 9. Contours of the (nondimensional) frequency as a function of the (nondimensional) horizontal wave numbers for the differential shallow water equation for $\lambda/d = 2$, presented for comparison with Fig. 8.

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

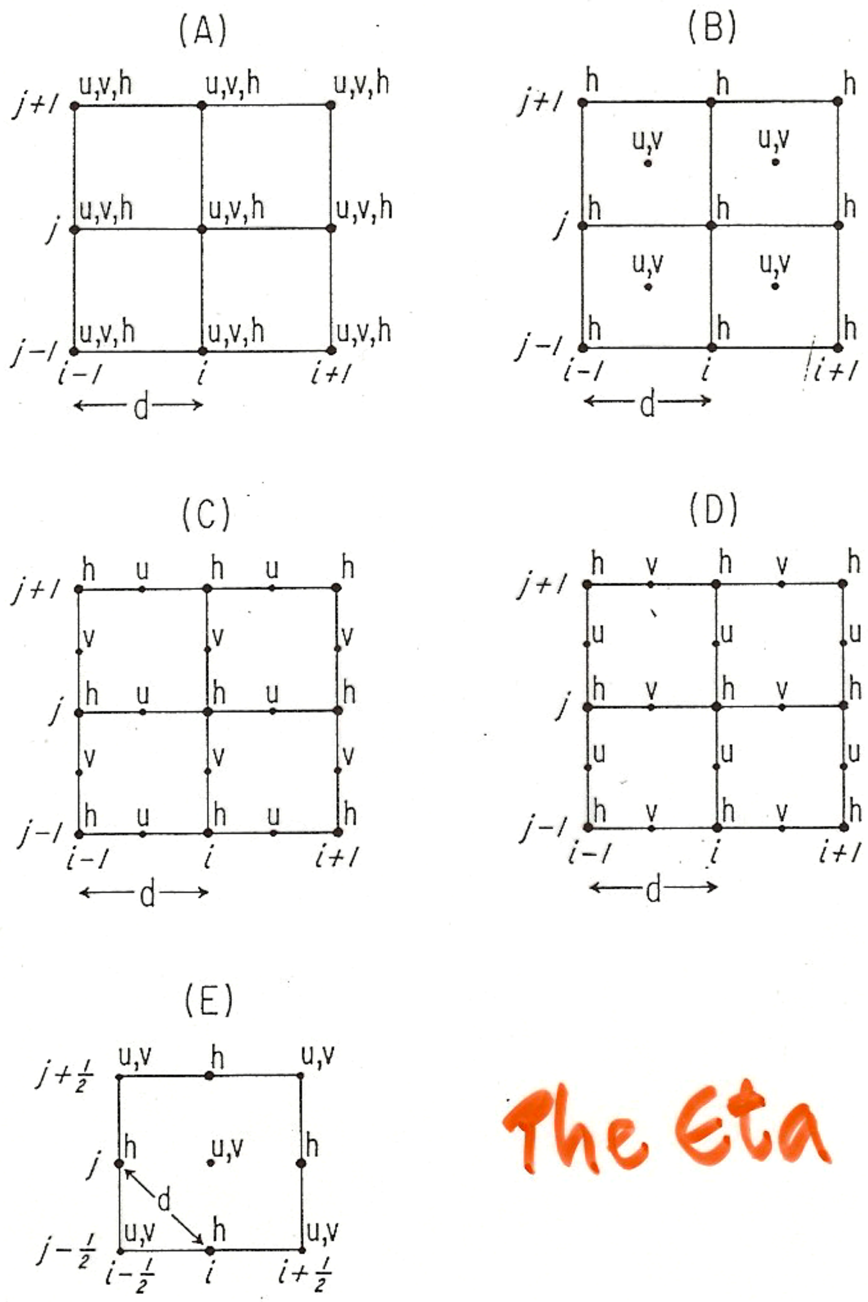
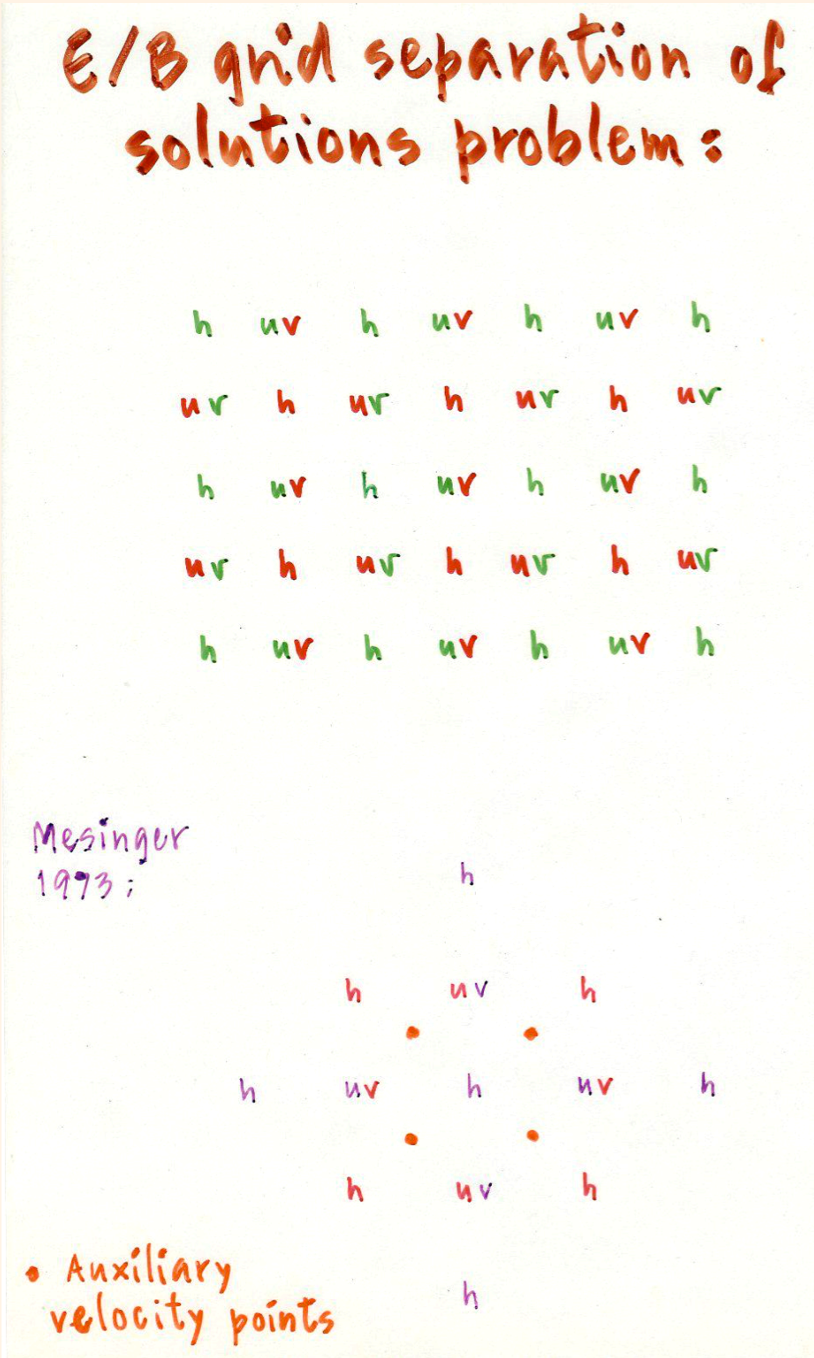


FIG. 3. Spatial distributions of the dependent variables on a square grid.

Note:

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



(Two C-subgrids)

Mesinger (1973): To calculate change of h in the center, use half of the velocities in the x direction (purple), and half of those at the auxiliary points (orange)

Obtain these at the middle or end of the time step by averaging the two nearest at the beginning of the time step, and adding the acceleration contribution

“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

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

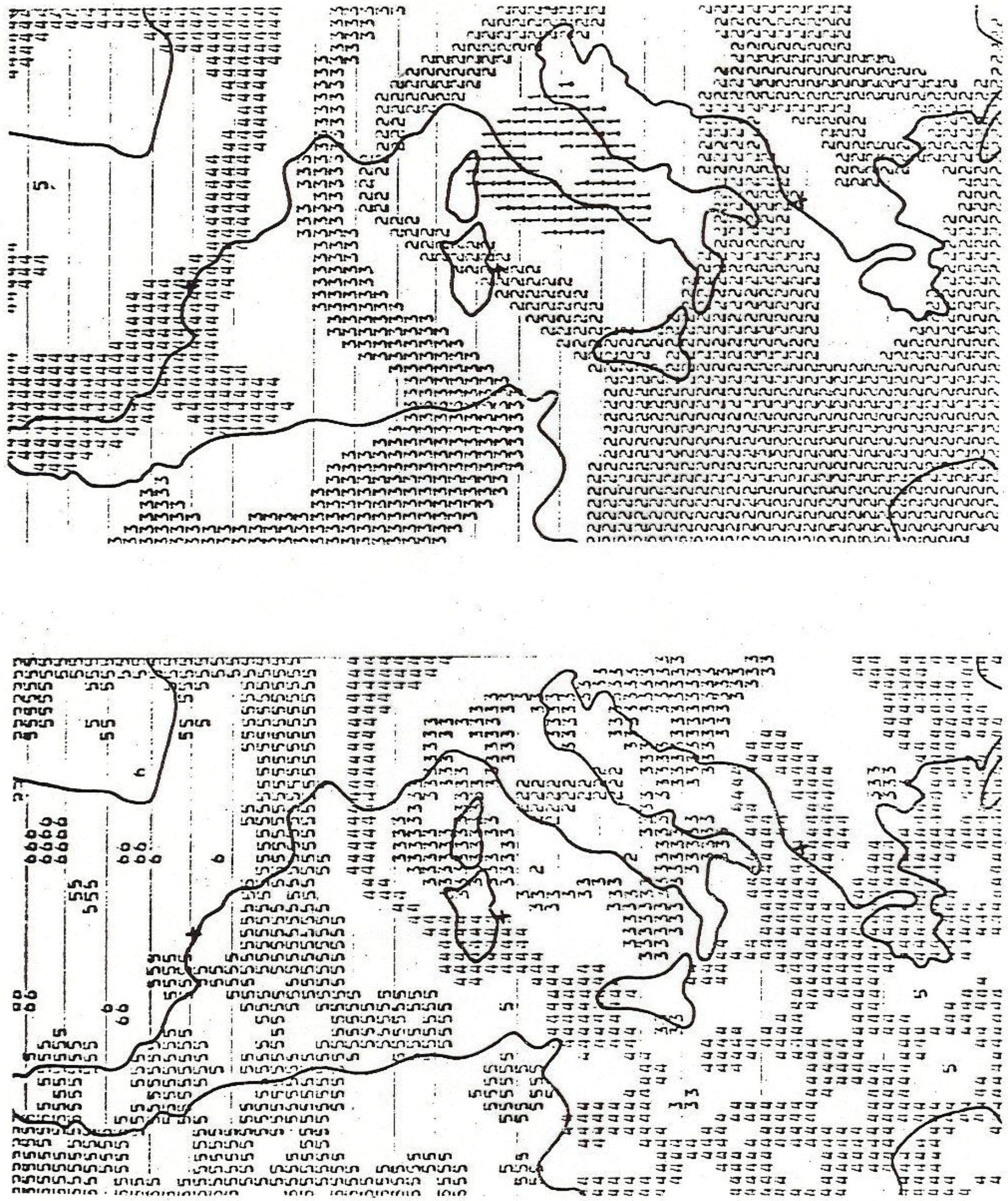
continuity eq. forward, vs momentum eq. forward

No visible difference ! (Why?)

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 / GEF)

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;

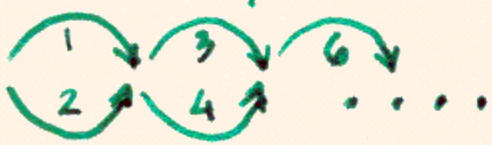
. . . . .

Time differencing: split explicit

A variety of time steps:

time →

Cont. eq.



"forward-backward" sch.

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

→ 5

. . .

Horiz. adv. (~ Heun)

→

. . .

Some physics (incl. convection)

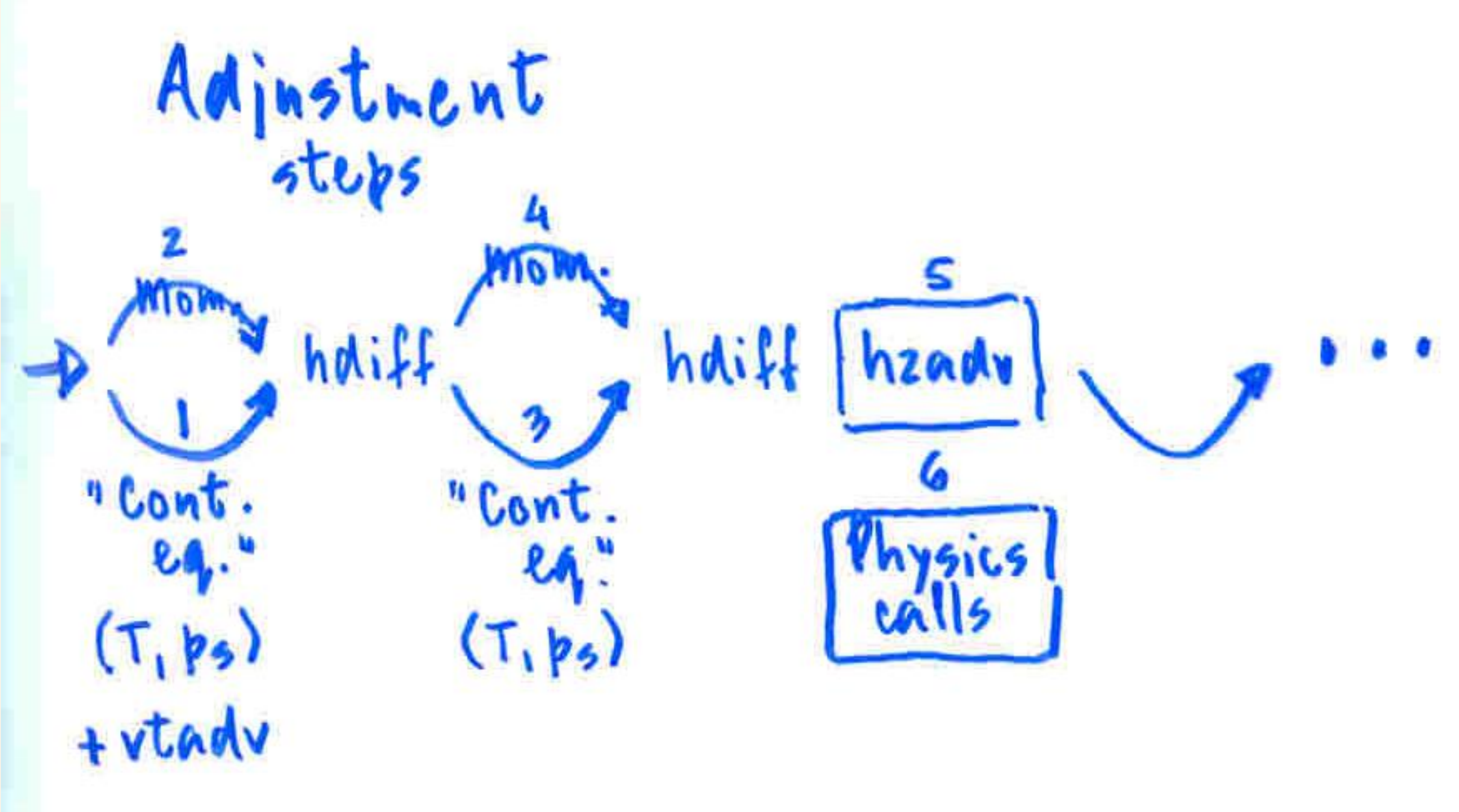
→

More physics

:

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 ("wα") 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.

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

- Horizontal advection

For two-dimensional and nondivergent flow:

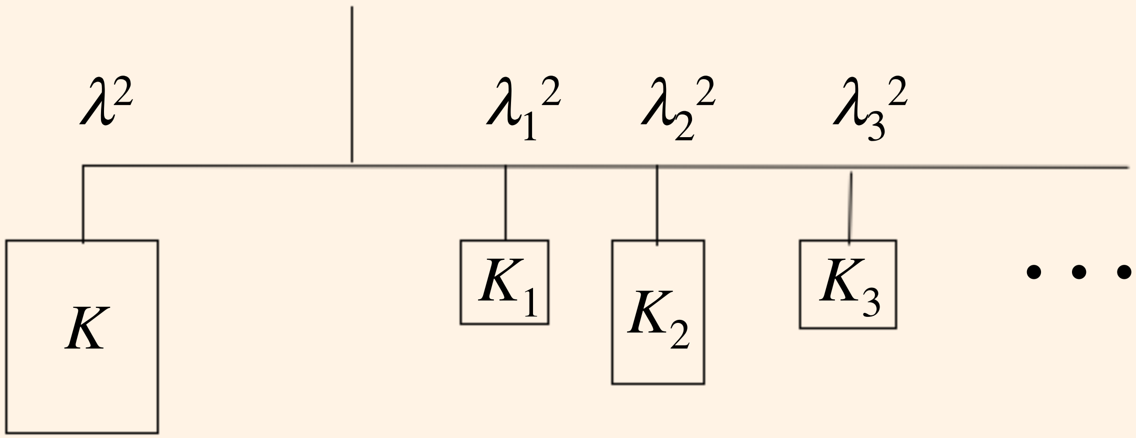
One obtains*, average "enstrophy"=

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

The famous Arakawa horizontal advection scheme:

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 !!!

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

Primitive equations ?

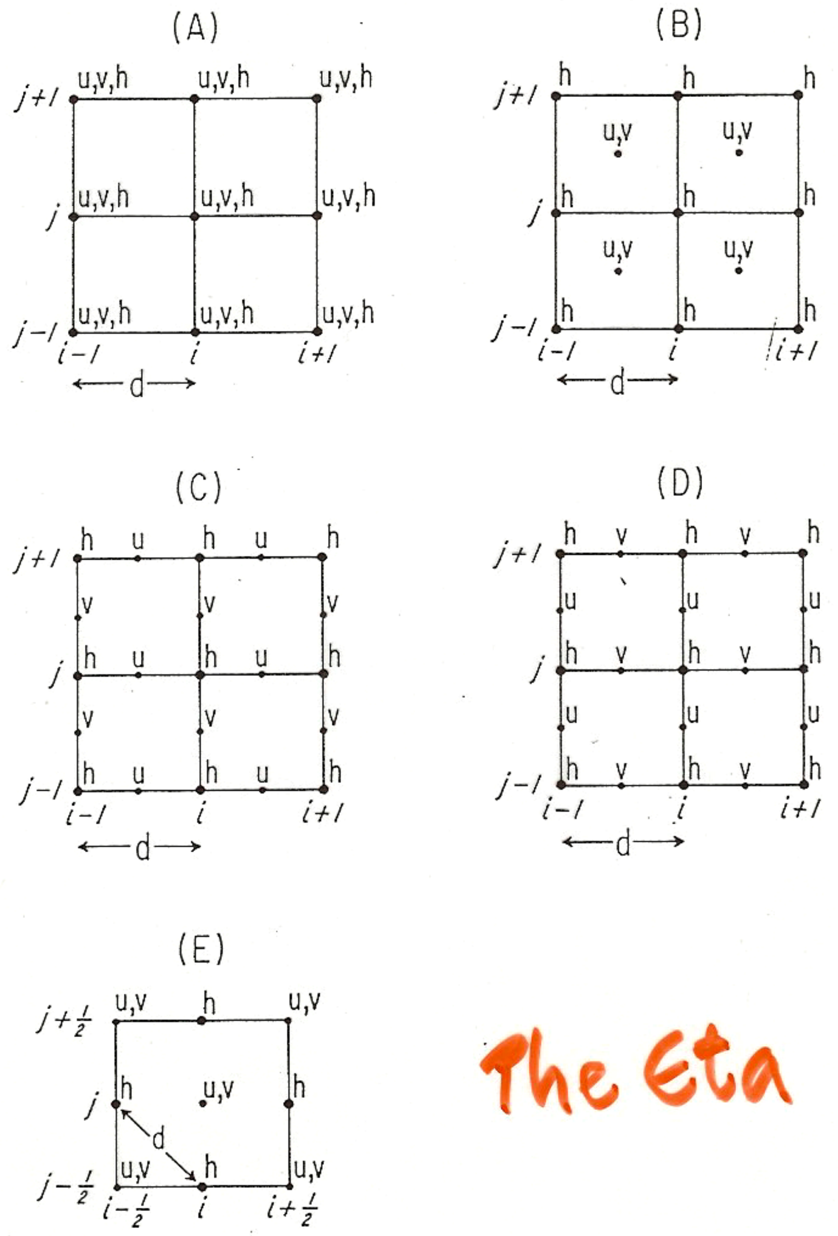


FIG. 3. Spatial distributions of the dependent variables on a square grid.

From ECMWF Seminar 1983:

The horizontal advection scheme:

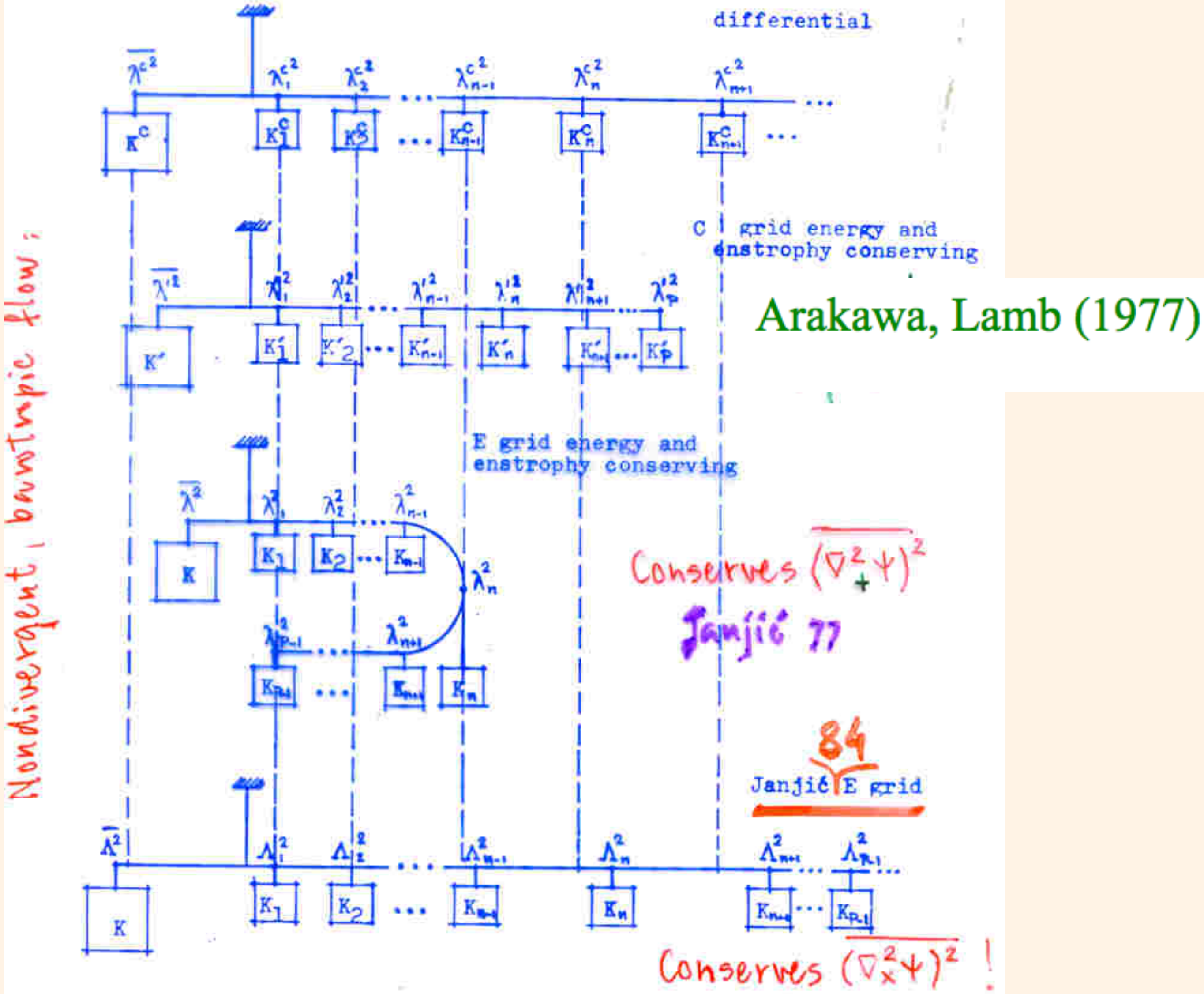


Fig. 3.12. Mechanical analogies of the constraints imposed on the non-linear energy cascade in the continuous case, in the case of the C-grid energy and enstrophy conserving scheme, in the case of the E-grid energy and enstrophy conserving scheme, and in the case of the scheme due to Janjić (1984).

(ECMWF Seminar '83)

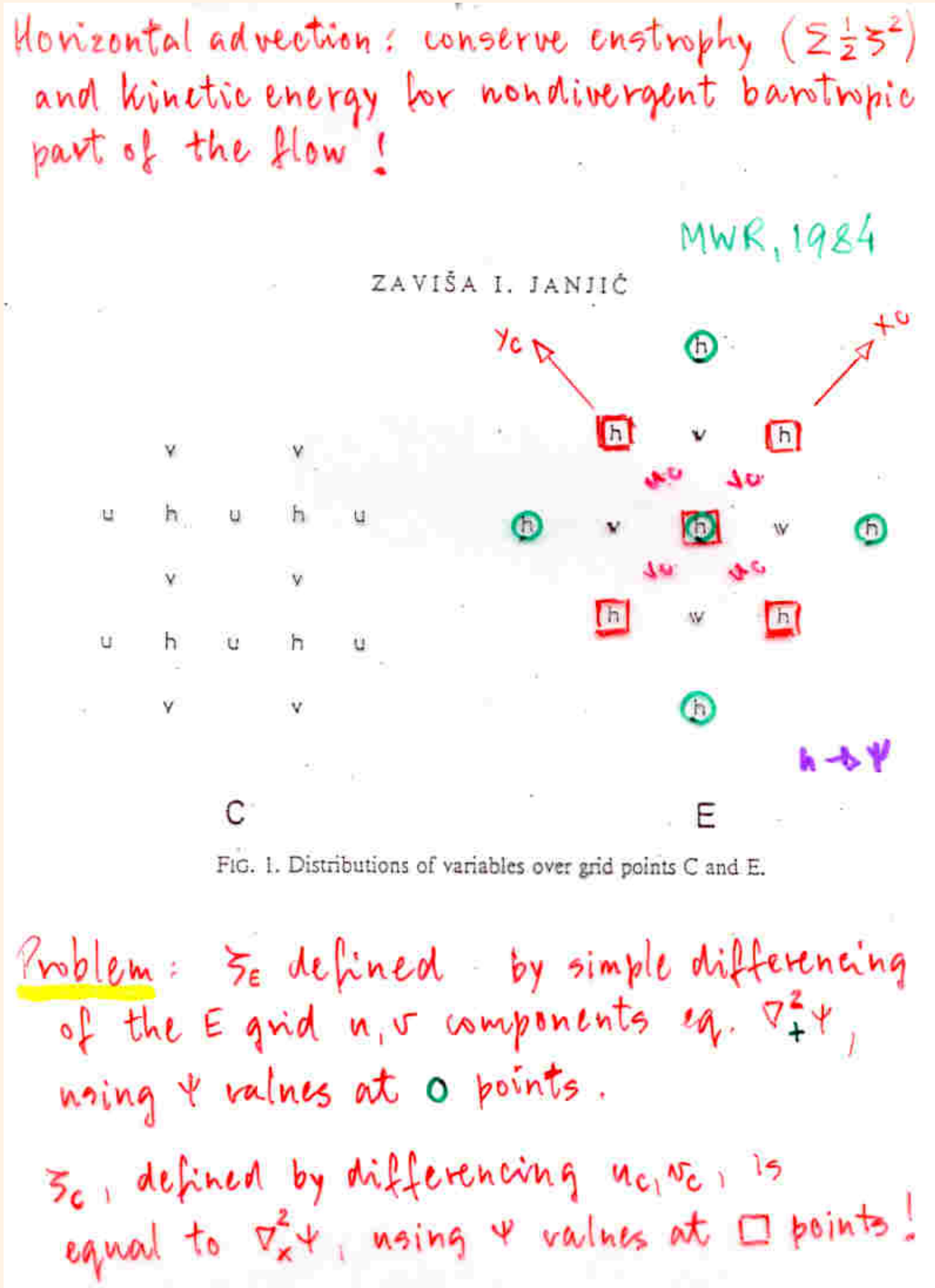


FIG. 1. Distributions of variables over grid points C and E.

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

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

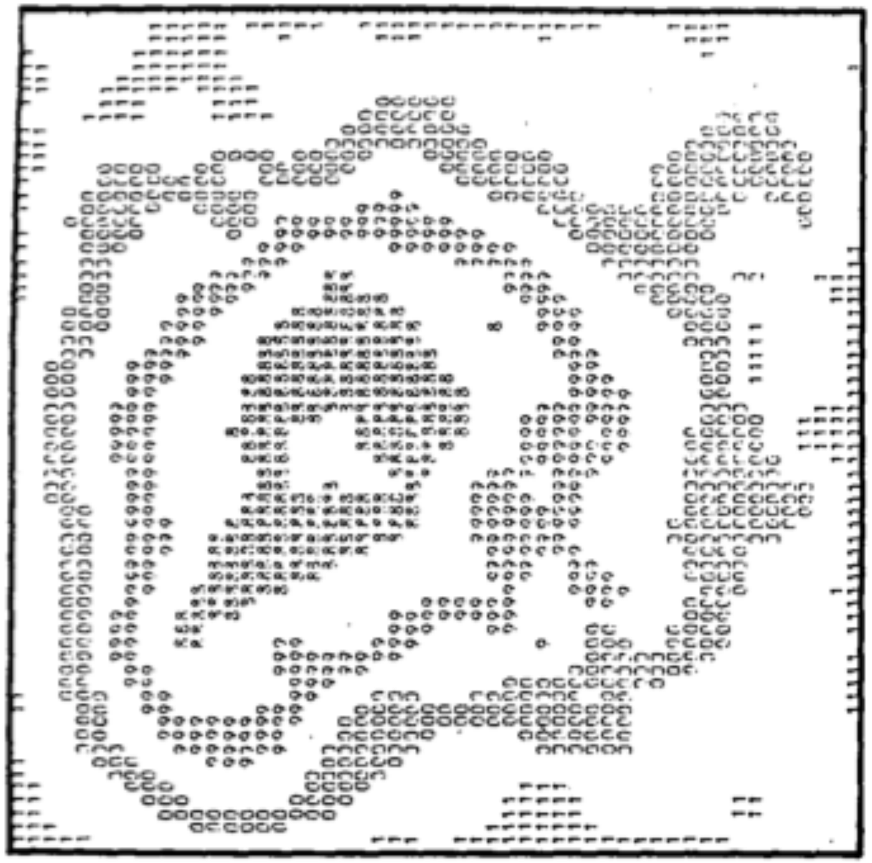


FIG. 13. Height field after 10 000 time steps in the control experiment. The shading interval is 160 m.

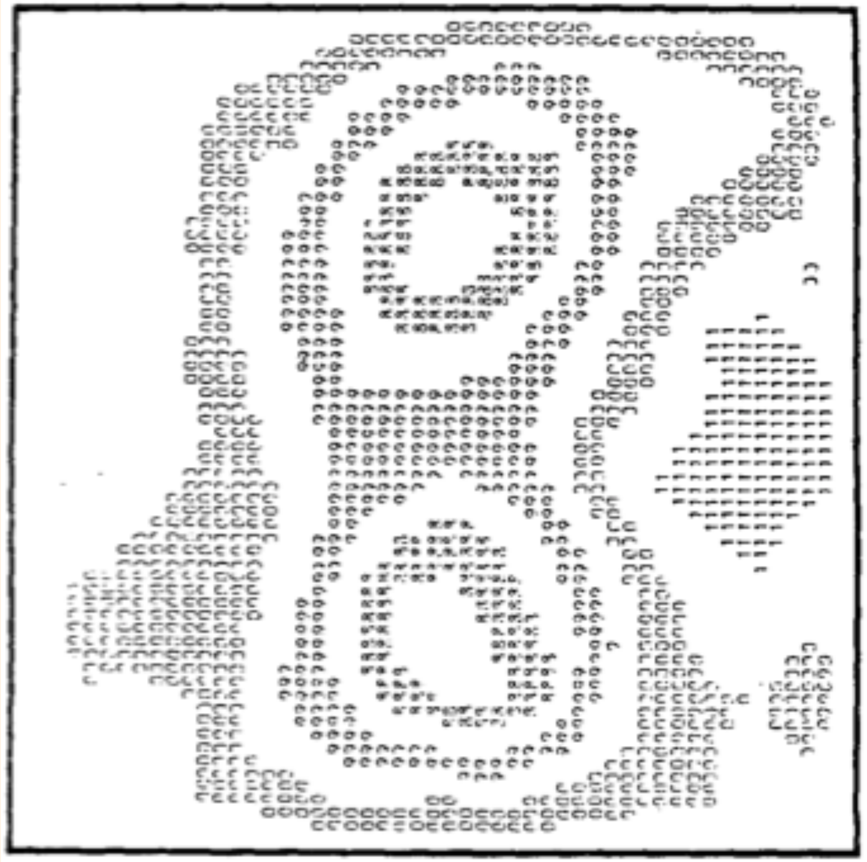


FIG. 12. Height field after 10 000 time steps in the main experiment. The shading interval is 160 m.

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 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)

Vertical (and "slantwise") 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 though:

false advection occurs from below ground !

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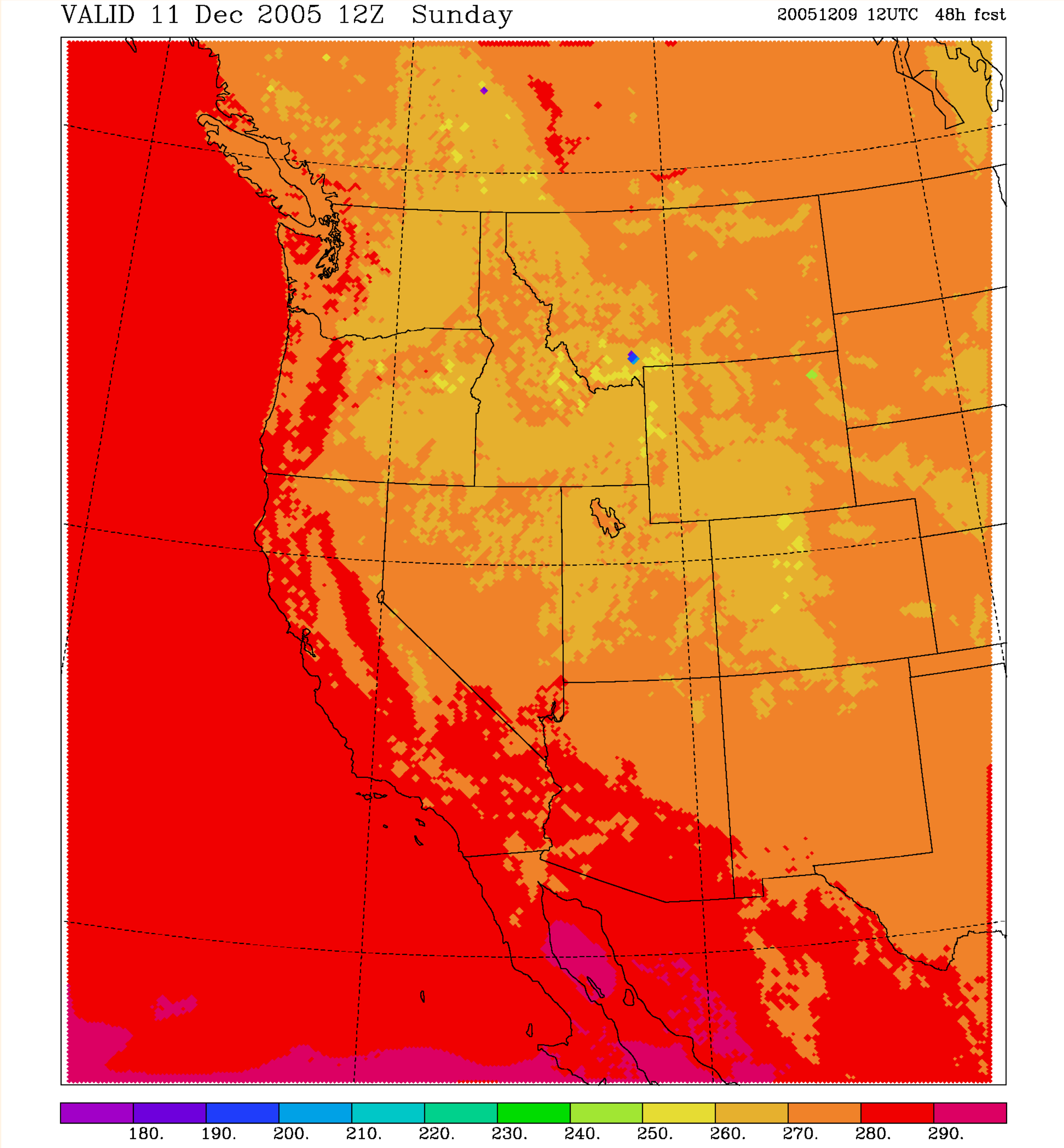
How was this discovered ?

Lowest layer temperature, 48 h fcst



8 km, 60 lyr resolution

Lorenz-Arakawa finite-difference vertical advection replaced by a piecewise-linear scheme (used only for moisture until that time)

Mesinger and Jovic (2002):

Dashed: original distribution

Solid: after 1st iteration

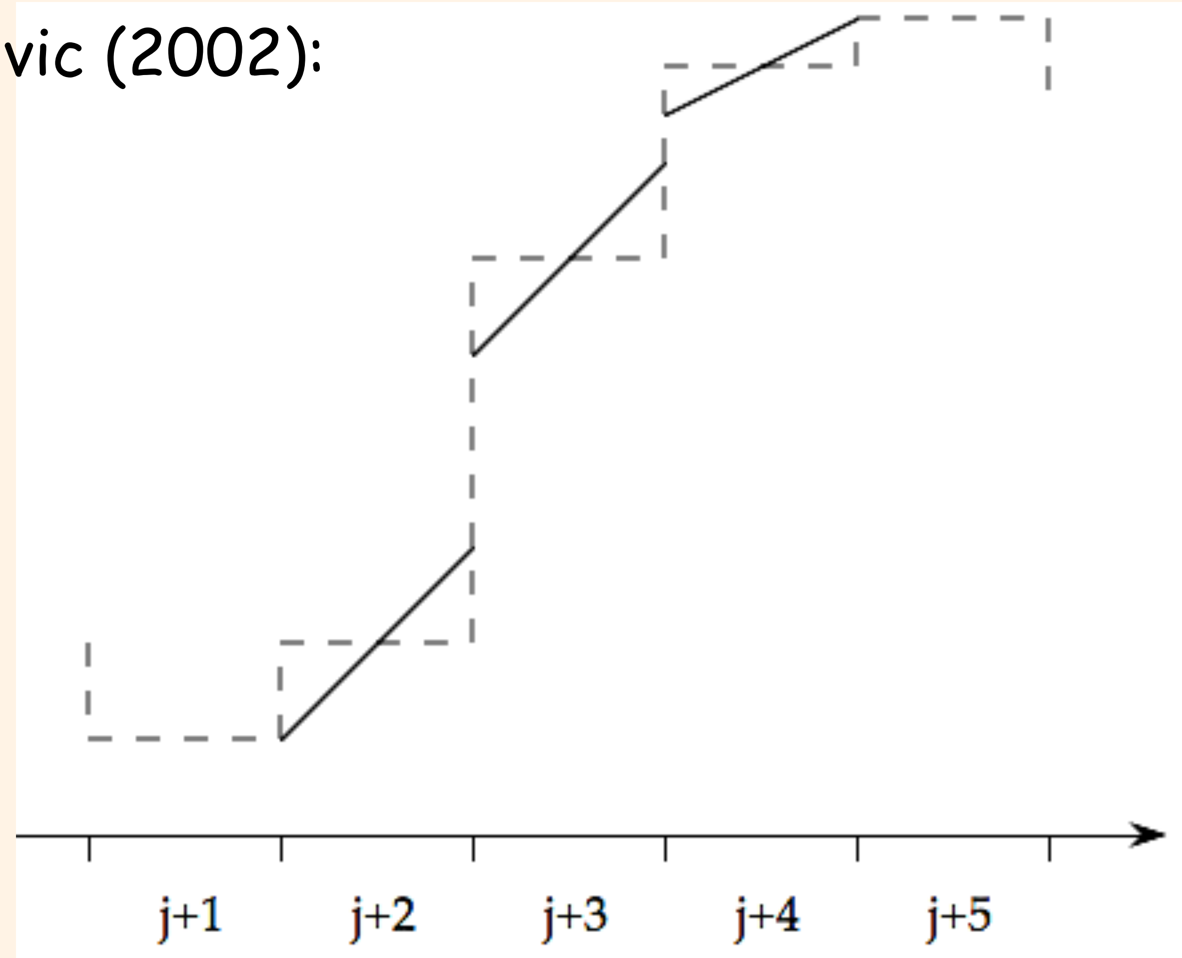


Figure 1. An example of the Eta iterative slope adjustment algorithm. The initial distribution is illustrated by the dashed line, with slopes in all five zones shown equal to zero. Slopes resulting from the first iteration are shown by the solid lines. See text for additional detail.

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:

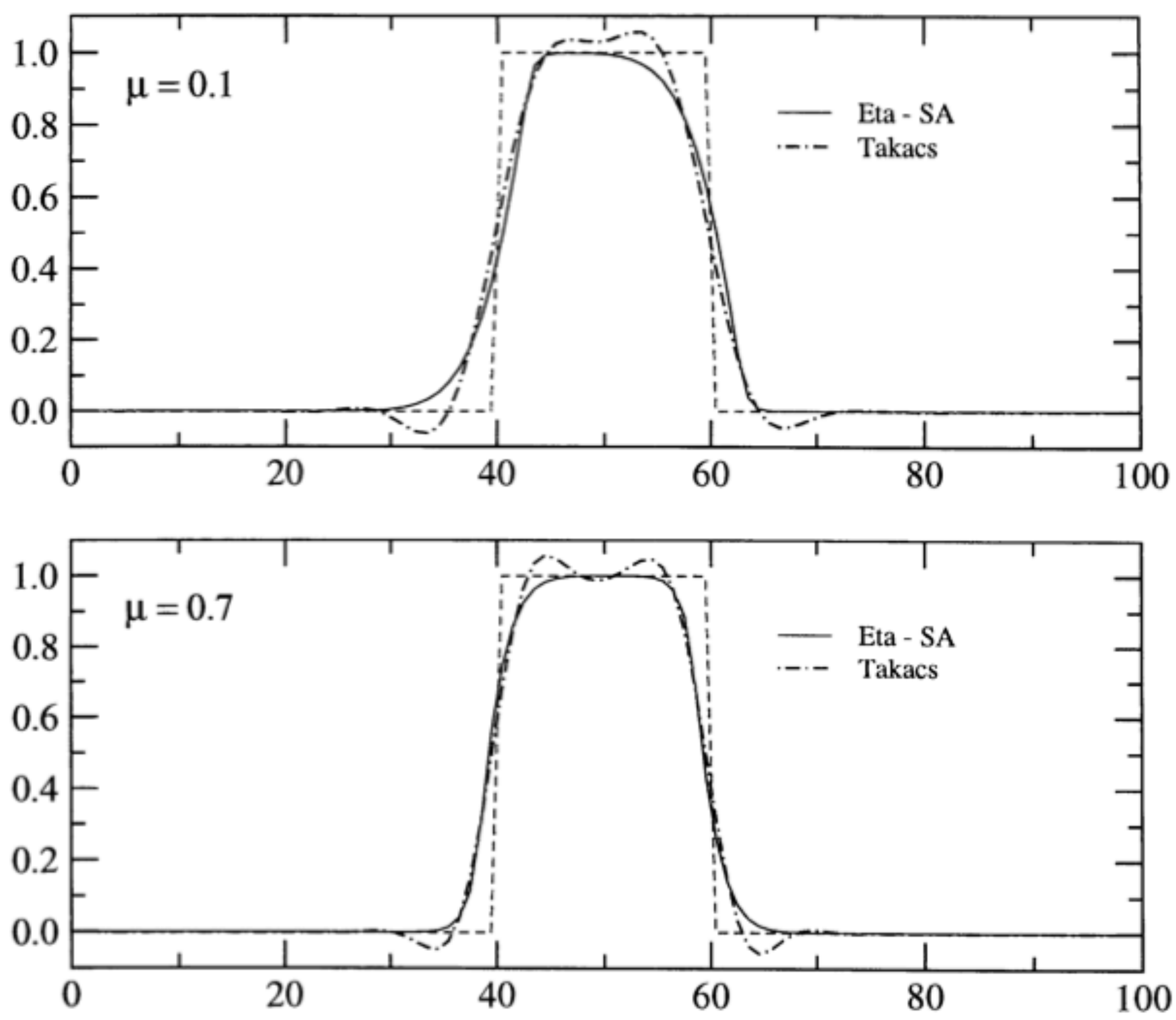


Figure 9. Same as Fig. 2, except for the Eta slope-adjustment scheme results (SA, solid line) compared against those using the Takacs (1985) third-order "minimized dissipation and dispersion errors" scheme (dot-dashed line). See text for definitions of schemes.

Nonhydrostatic option (a switch available),

Janjic et al. 2001:

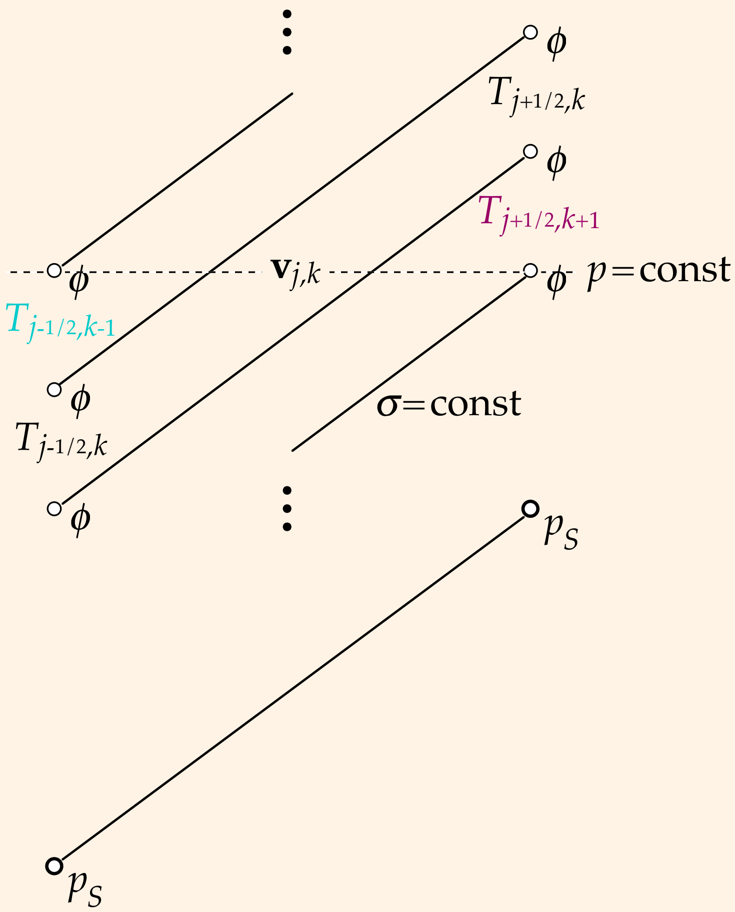
$$\left(\frac{\partial w}{\partial t}\right)^{\tau+1/2} \rightarrow \frac{w^{\tau+1} - w^{\tau}}{\Delta t}$$

Concluding dynamics remark: since piecewise-linear advection of dynamic variables replaces the only remaining purely finite-difference scheme, and since with the eta coordinate vertical sides of grid cells in a layer are very nearly of the same area, multiplication of fluxes by areas of cell sides not needed. Thus, Eta is very nearly a finite-volume model. Recall that many Eta dynamical core features are not achieved in standard finite-volume models; thus, "finite volume+".

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

Why?

Terrain-following coordinates: pressure gradient force



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 “eta” coordinate:

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

Setting $\eta_S = 0$ this becomes sigma: switch in the code !

"Step-topography" eta:

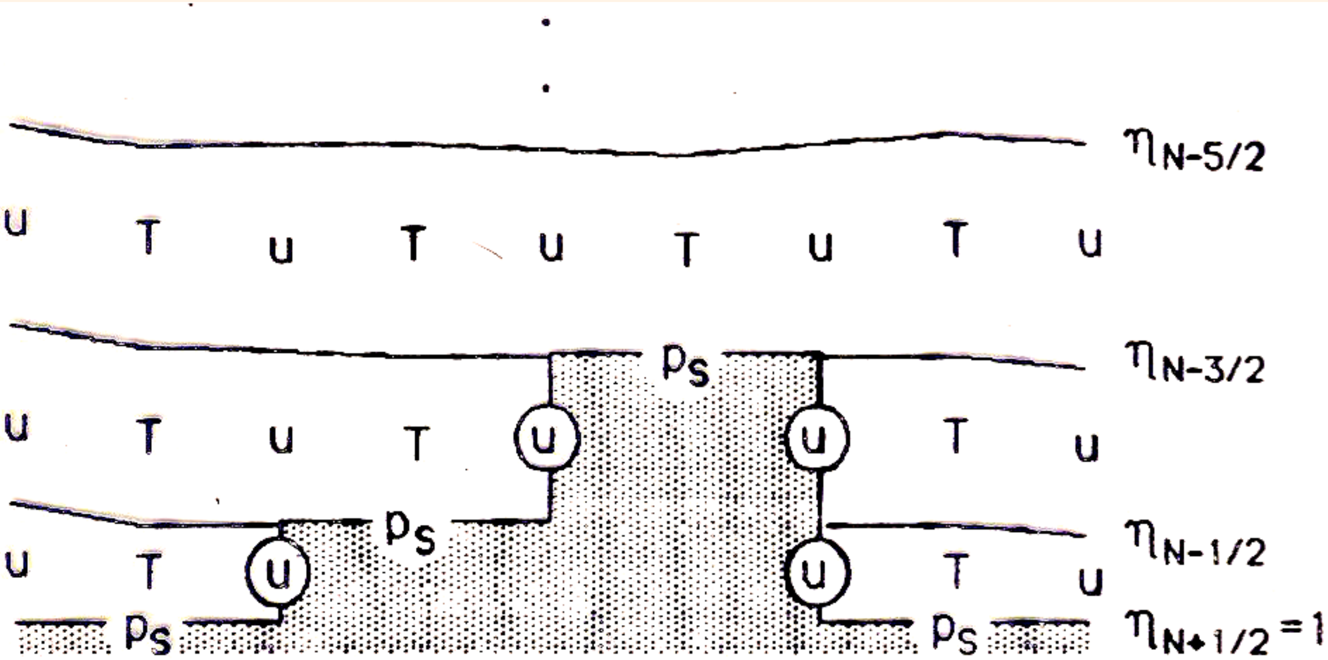


FIG. 1. Schematic representation of a vertical cross section in the eta coordinate using step-like representation of mountains. Symbols *u*, *T* and p_s represent the *u* component of velocity, temperature and surface pressure, respectively. *N* is the maximum number of the eta layers. The step-mountains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

Over the years, five documented tests eta vs sigma

#1 Sigma Eta

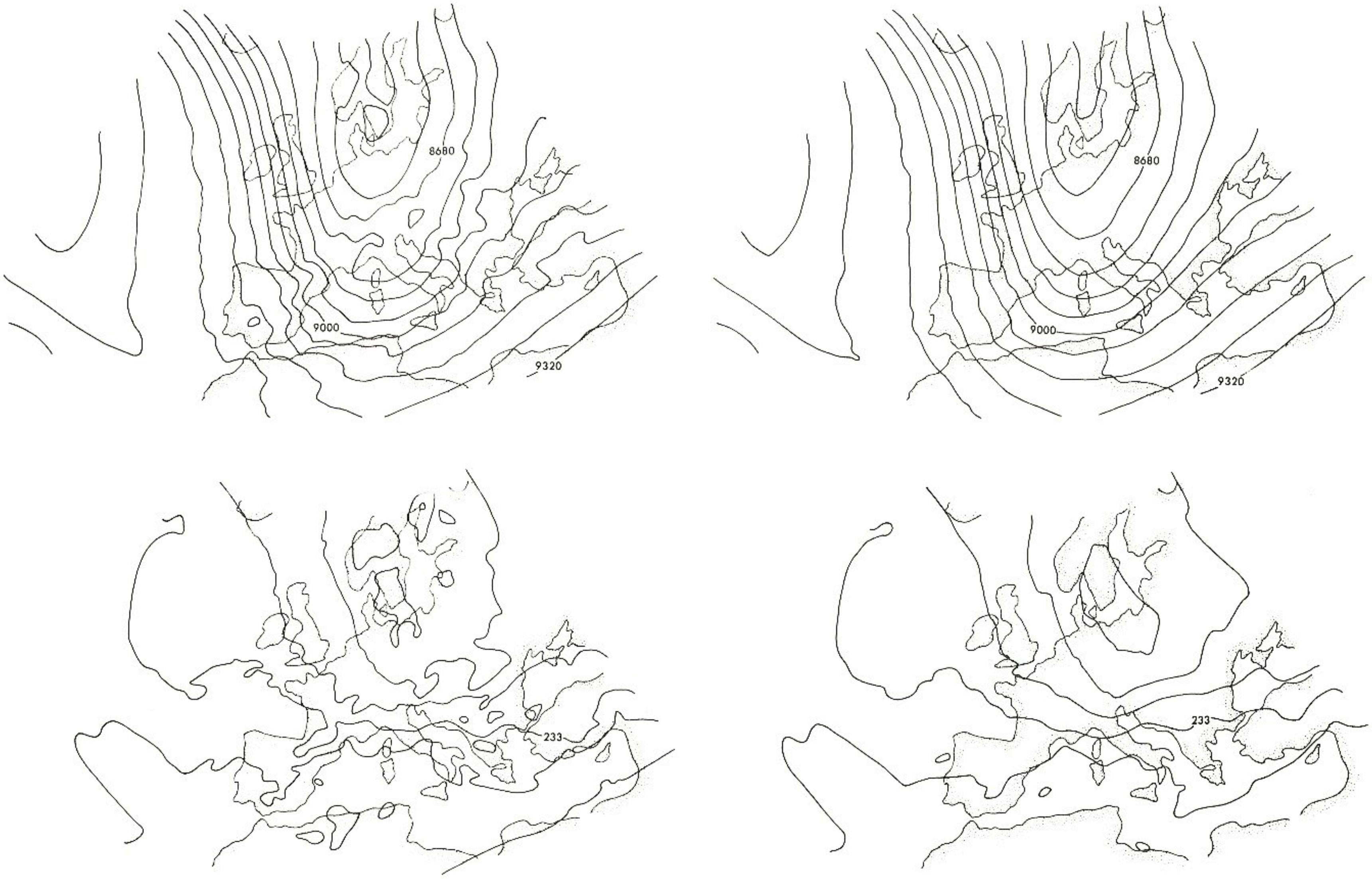


FIG. 6. 300 mb geopotential heights (upper panels) and temperatures (lower panels) obtained in 48 h simulations using the sigma system (left-hand panels) and the eta system (right-hand panels). Contour interval is 80 m for geopotential height and 2.5 K for temperature.

#2 to #5: Various accuracy tests; precipitation scores and better placement of storms in the lee of the Rockies standing out

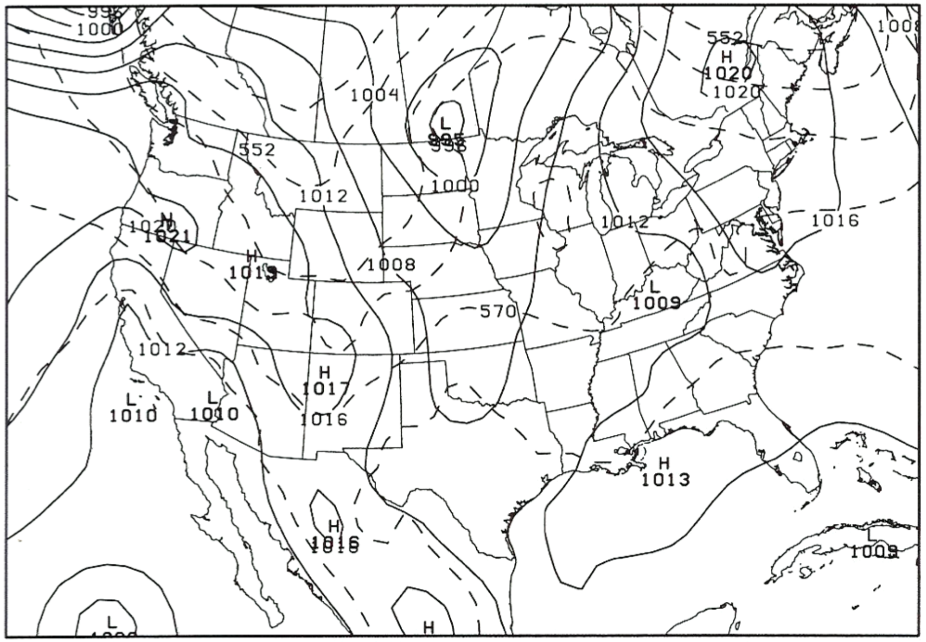
Summarized at WorkEta IV, and in a manuscript in review

The three low centers case

Valid at

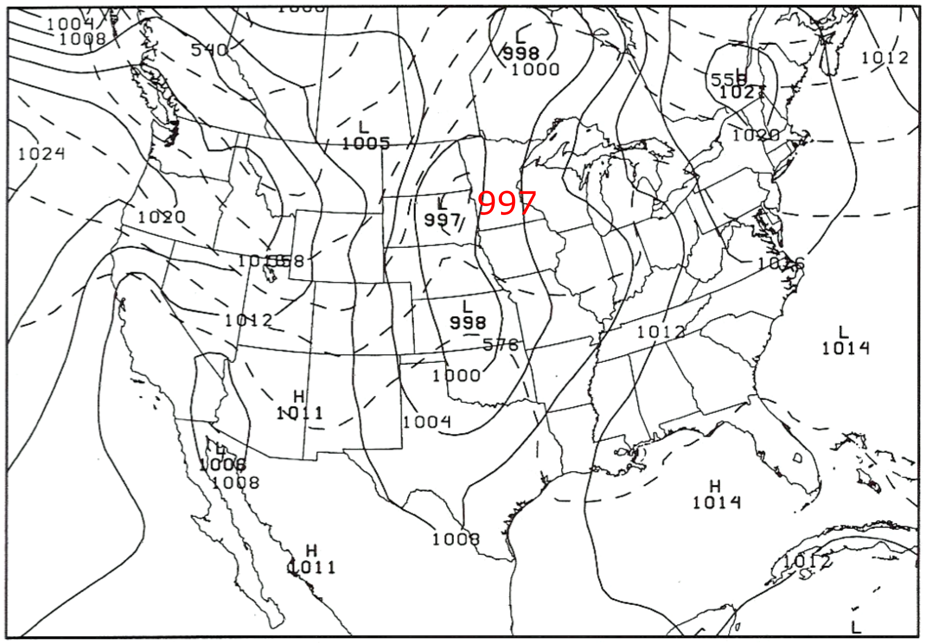
12z 18 September 2002

Avn



020918/1200V060 SFC MSLP & THCK -- AVN

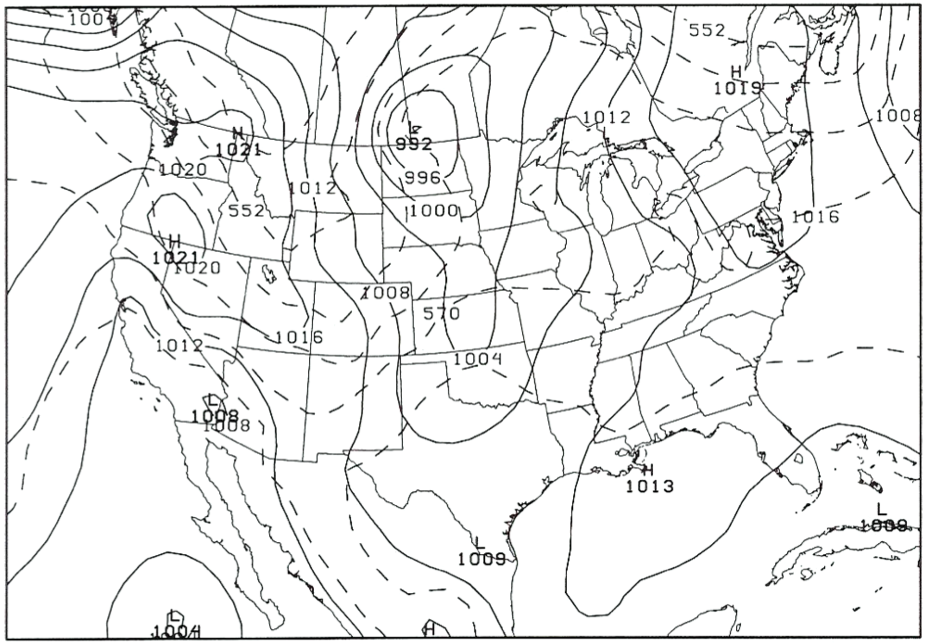
Eta



020918/1200V060 SFC MSLP & THCK -- ETA

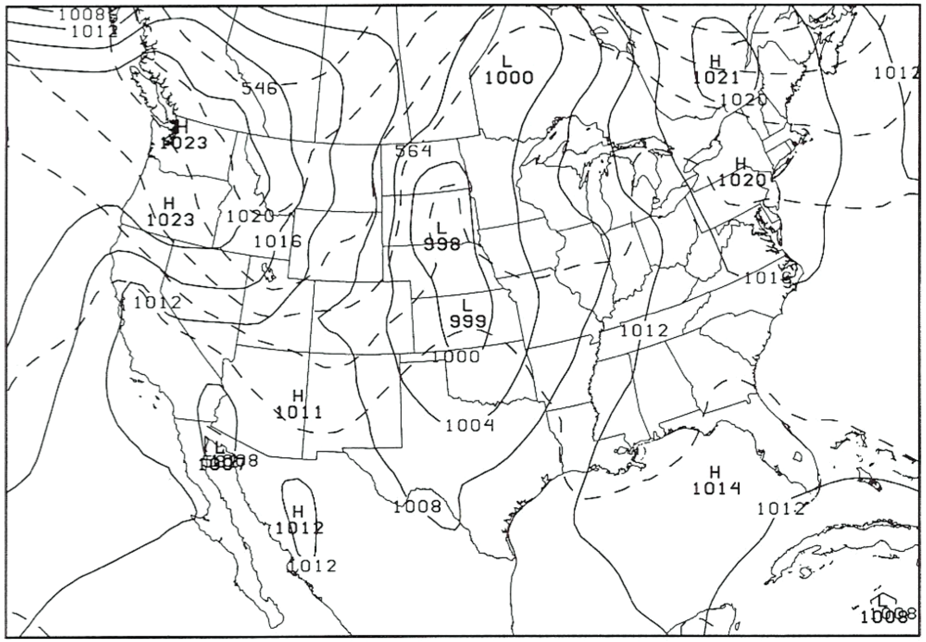
60 h fcsts

Avn



020918/1200V048 SFC MSLP & THCK -- AVN

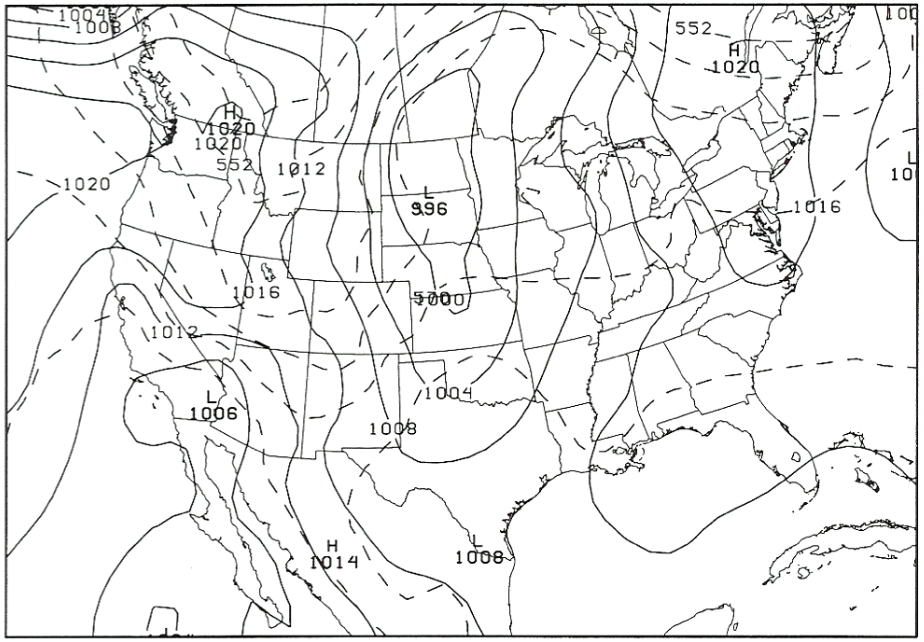
Eta



020918/1200V048 SFC MSLP & THCK -- ETA

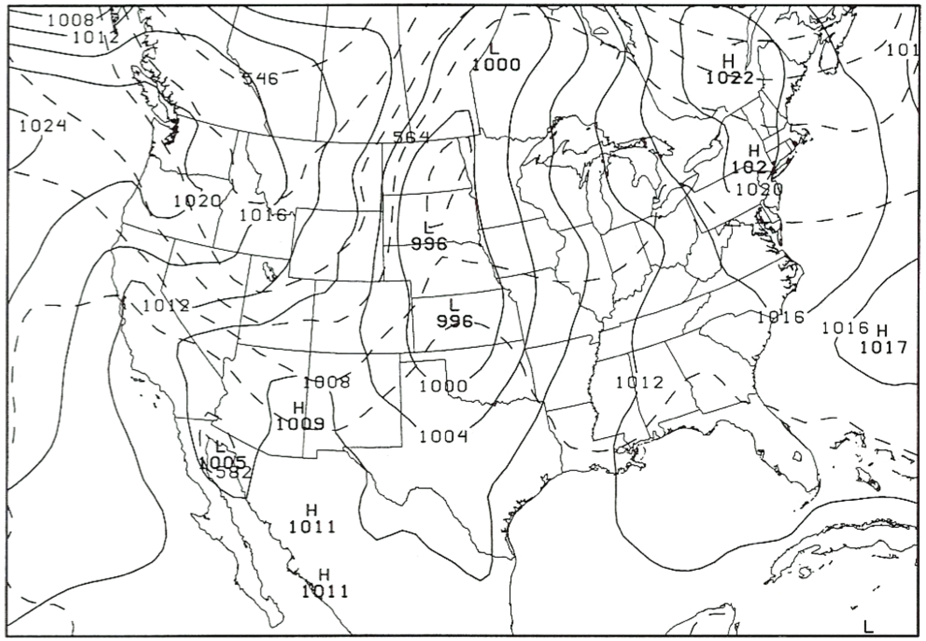
48 h fcsts

Avn



020918/1200V036 SFC MSLP & THCK -- AVN

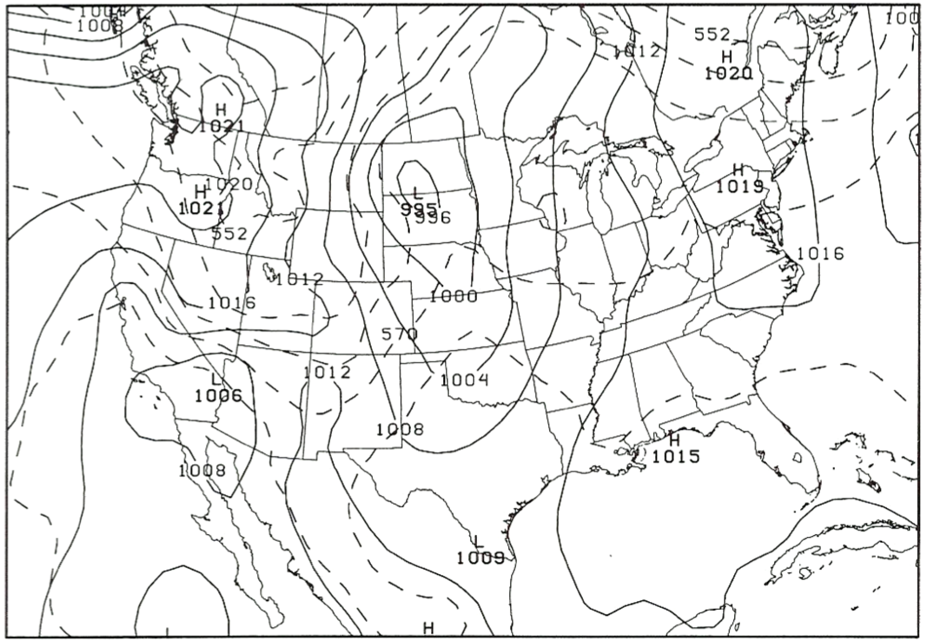
Eta



020918/1200V036 SFC MSLP & THCK -- ETA

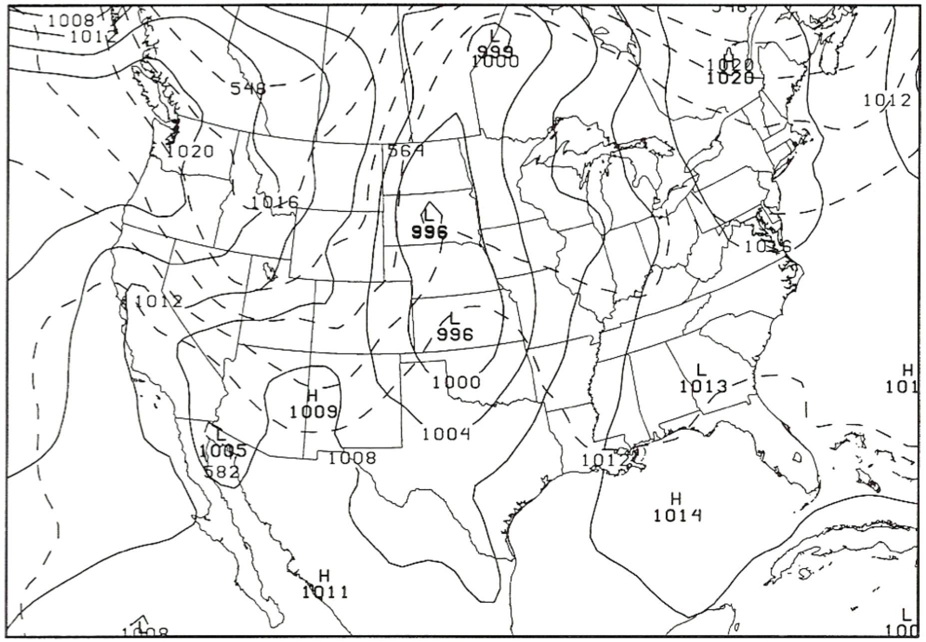
36 h fcsts

Avn



020918/1200V024 SFC MSLP & THCK -- AVN

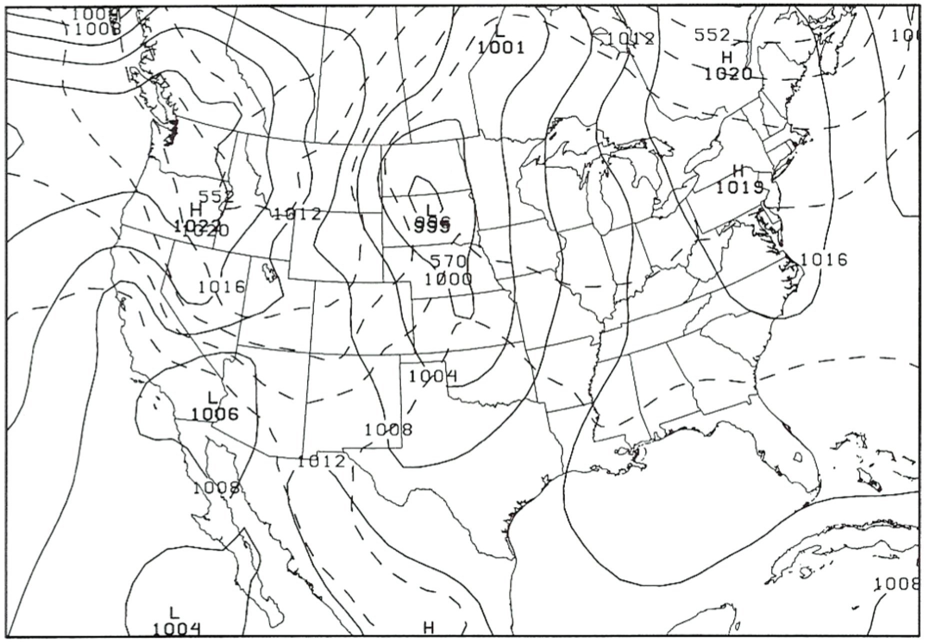
Eta



020918/1200V024 SFC MSLP & THCK -- ETA

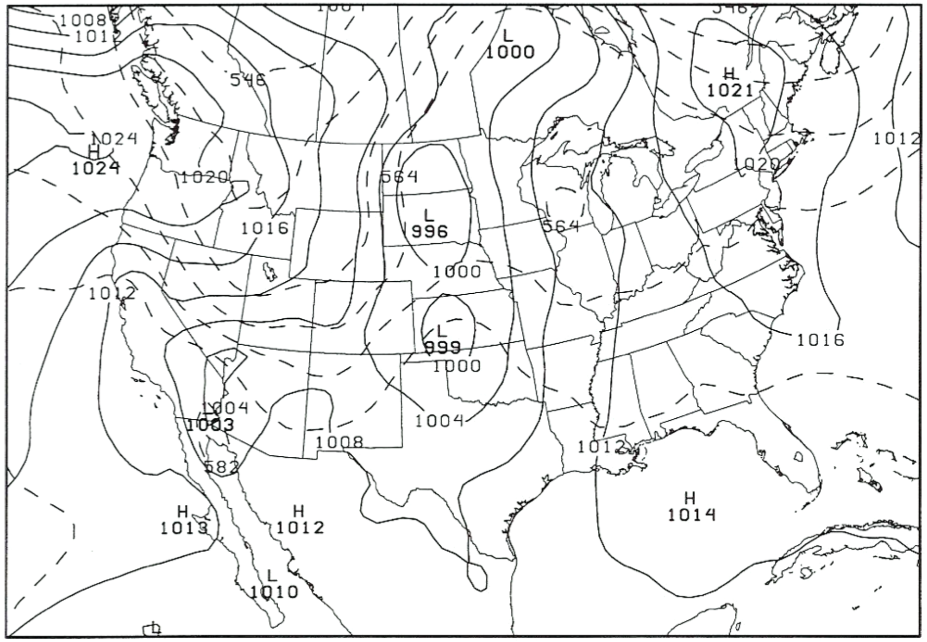
24 h fcsts

Avn



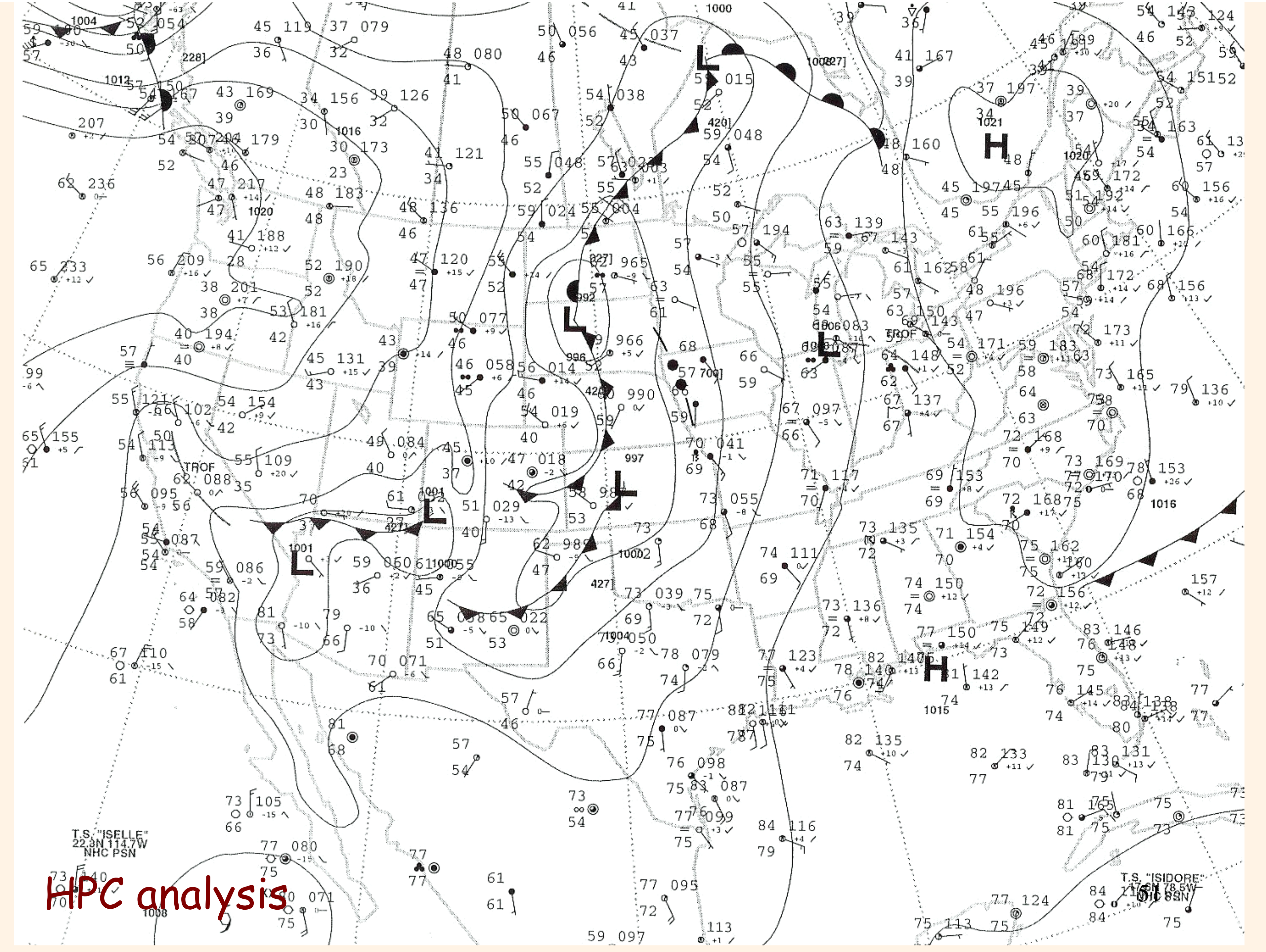
020918/1200V012 SFC MSLP & THCK -- AVN

Eta



020918/1200V012 SFC MSLP & THCK -- ETA

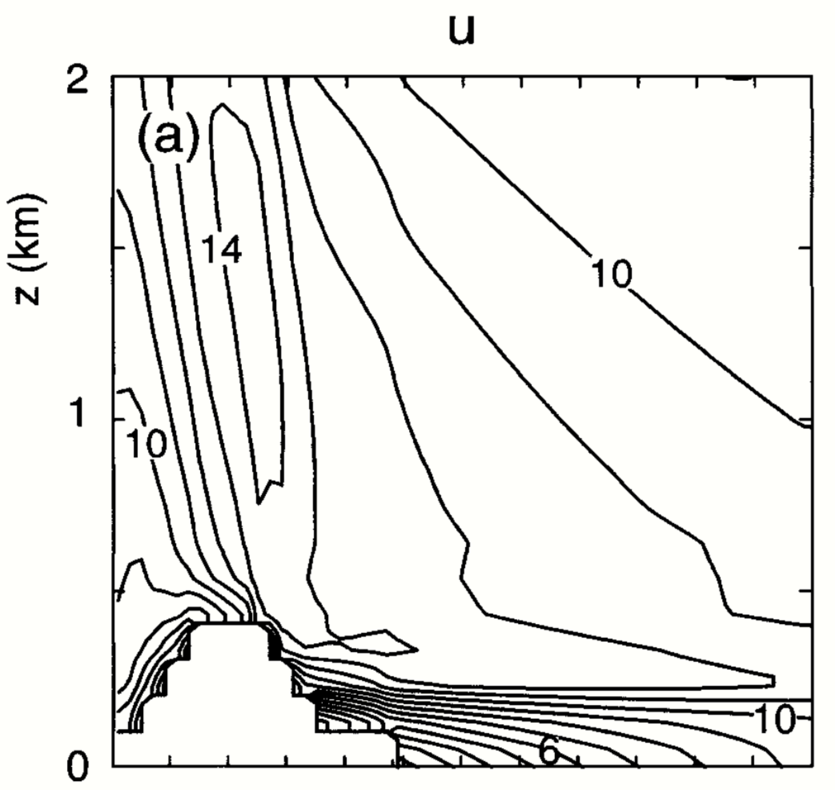
12 h fcsts

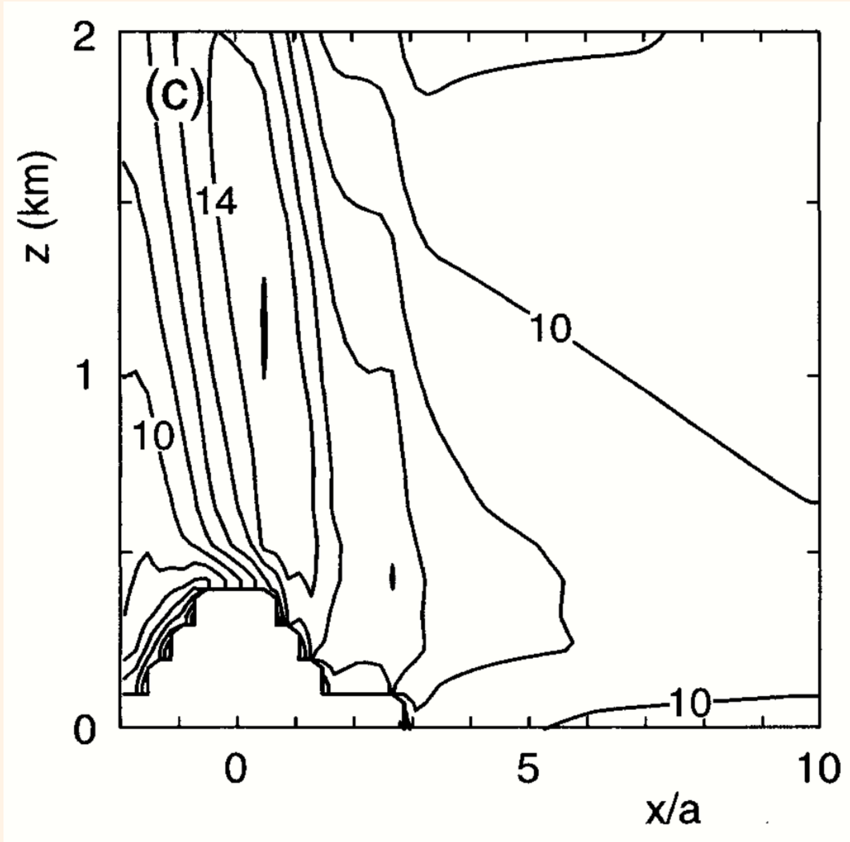


HPC analysis

However: "Eta Gallus-Klemp problem" (MWR 2000)

Bell-shaped ("Witch of Agnesi") mountain:





Gallus-Klemp (2000) Fig. 6:

Gallus-Rančić Eta code

Modified by G-K next to step corners

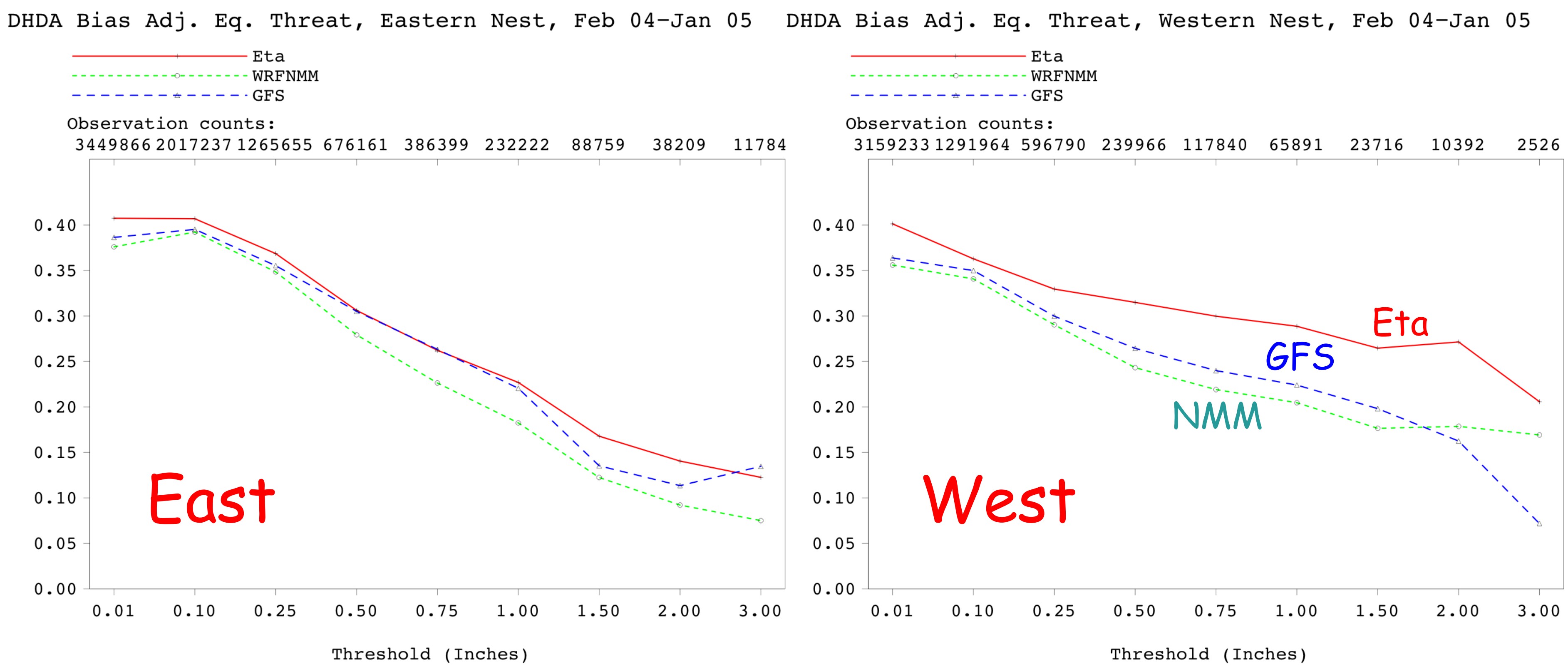
Also: poor Eta performance for a case of a downslope windstorm

Consequently: After summer of 2002 all NCEP mesoscale efforts toward the development of the NMM ("NMM-WRF" to be), sigma system;

Eta "frozen"

Last 12 months of the availability of three model scores, Feb 04-Jan 05:

ETS corrected for bias, "hi-res nests" over ConUS:

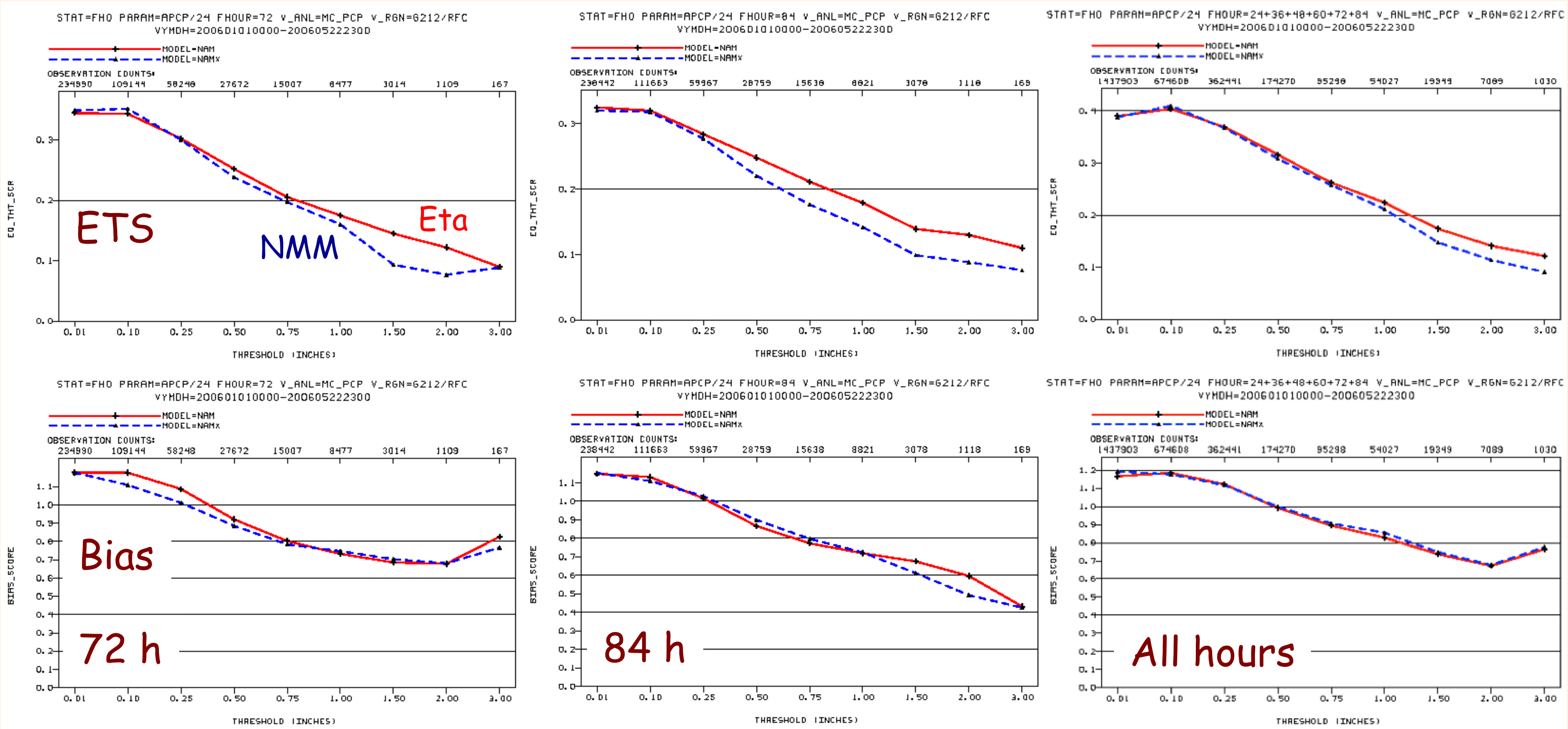


Eta 12-km, NMM 8-km; correction for bias: Mesinger (Adv. Geosci. 2008): In order to obtain score that verifies placement of precipitation !

Precipitation scores of the parallel NMM/GSI vs Eta/EDAS, 1 Jan-22 May 2006:

(ETS not corrected for bias)

(From DiMego 2006)



24-h precipitation Equitable Threat Scores (upper panels) and Bias Scores (lower panels) of the Eta model/EDAS (red) and NMM-WRF/GSI (blue), of the 1 January-22 May 2006 parallel, run at 12-km resolutions. 24-h precipitation thresholds are increasing from 0.01 to 3 in/24 hours along the abscissas of the plots. Verifications at 72 h (left), 84 h (middle), and combined 24, 36, 48, 60, 72 and 84 h (right). After DiMego (2006).

2.2) Eta developments subsequent to its NCEP "Workstation version":

Mesinger, F., S. C. Chou, J. Gomes, D. Jovic, P. Bastos, J. F. Bustamante, L. Lazic, A. A. Lyra, S. Morelli, I. Ristic, and K. Veljovic, 2012: An upgraded version of the Eta model. *Meteor. Atmos. Phys.*, **116**, 63-79.

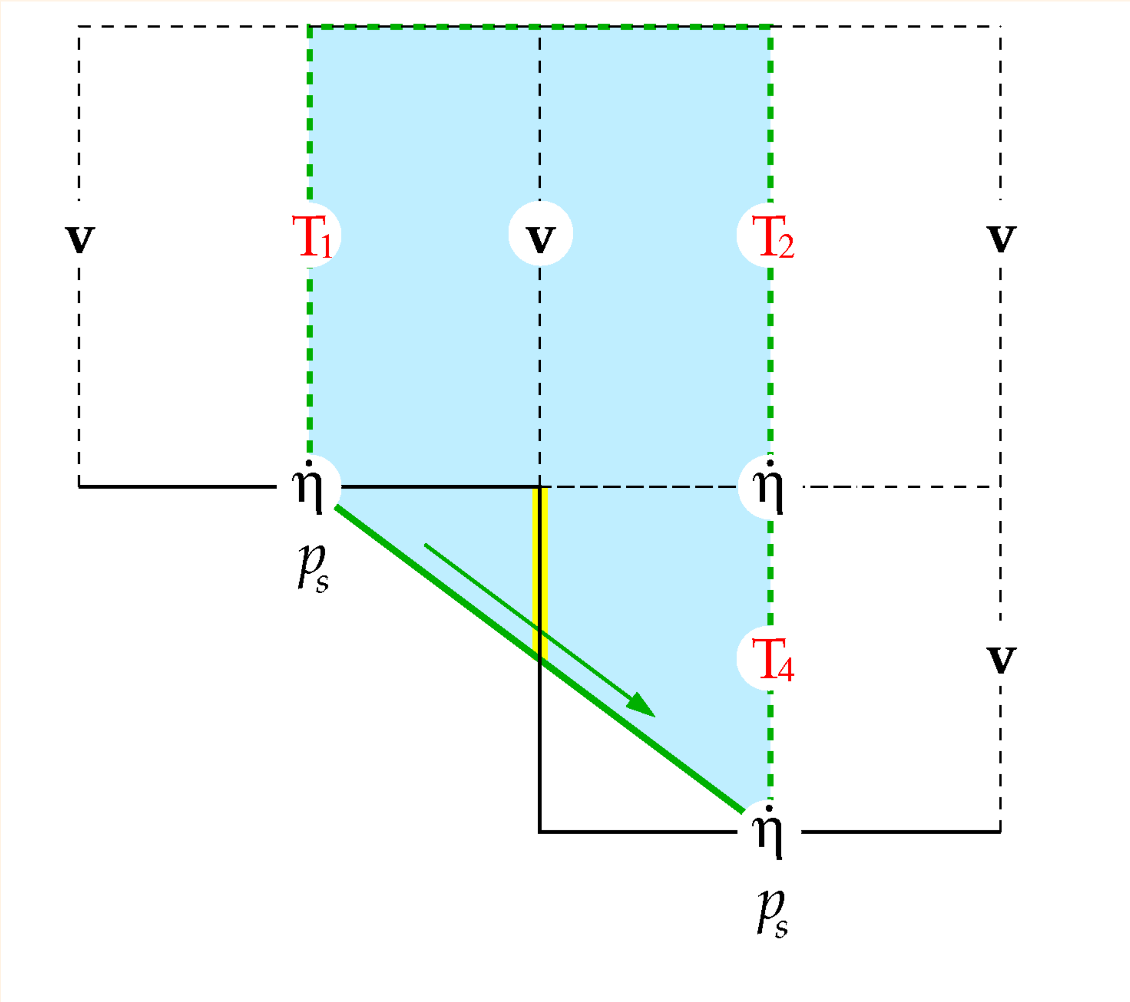
Major new feature: "sloping steps"

(Mesinger and Jovic, NCEP ON 439, 2002; change of "slantwise advection" to finite volume, 2012)

Revisit of the of the Gallus-Klemp problem following discovery of a horizontal diffusion oversight, and change to an unconditionally stable and monotonic scheme

The sloping steps disretization, vertical grid

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



Case used for a test:

A real data downslope windstorm test:

Zonda case of 11-12 July 2006

Acknowledgement:

. . .

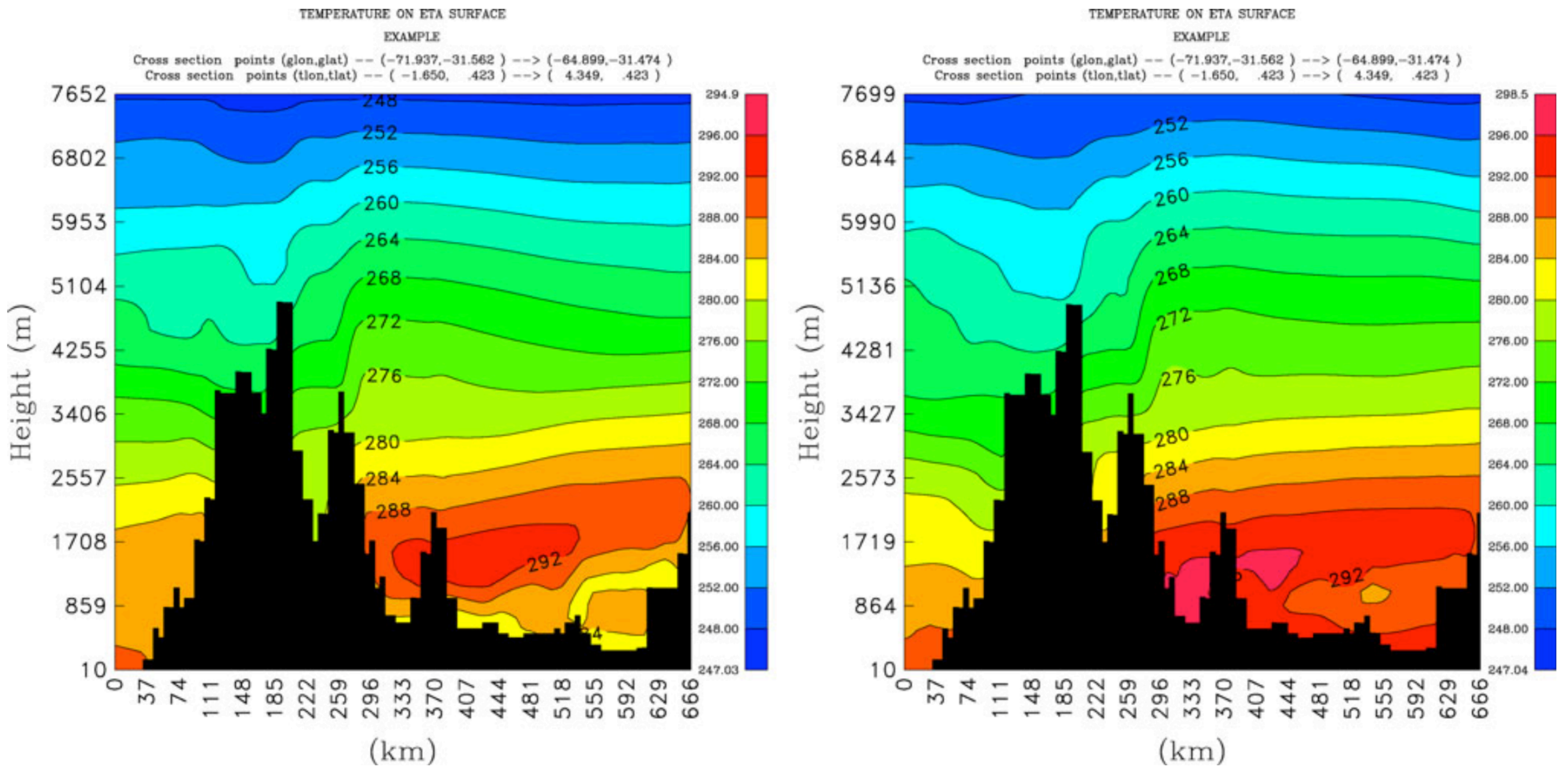
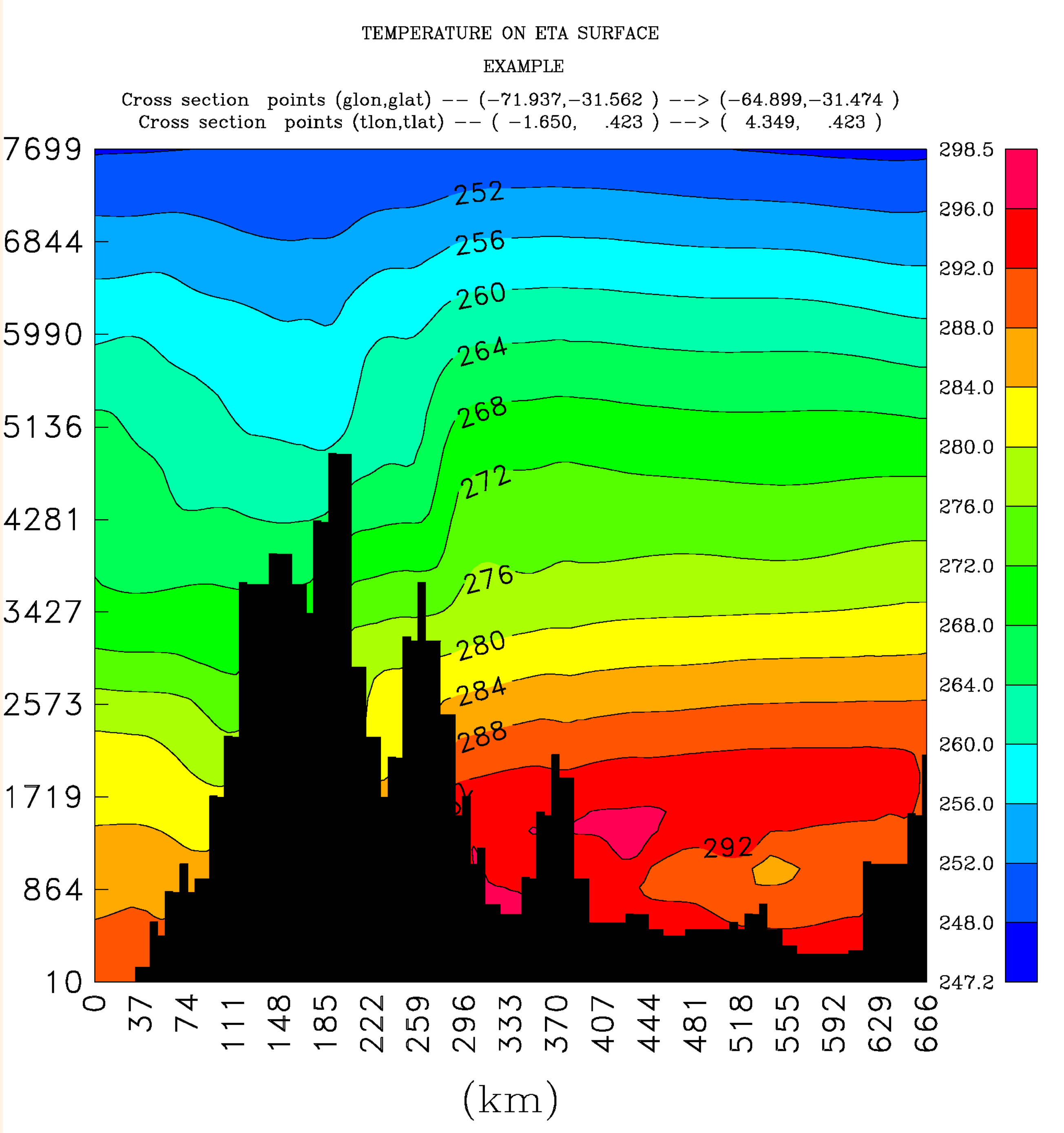


Fig. 8 Vertical cross sections of topography and temperature at 24 h after the initial time of the forecast, at 1200 UTC 10 July 2006, *left panel*, and at 33 h, *right panel*, respectively, across the Andes at about the place of their highest elevation. The code used is that of the upgraded Eta, with its nonhydrostatic option on



TEMPERATURE ON ETA SURFACE
EXAMPLE
Cross section points (glon,glat) -- (-71.937,-31.562) --> (-64.899,-31.474)
Cross section points (tlon,tlat) -- (-1.650, .423) --> (4.349, .423)
7699
6844
5990
5136
4281
3427
2573
1719
864
10
252
256
260
264
268
272
276
280
284
288
292
298.5
296.0
292.0
288.0
284.0
280.0
276.0
272.0
268.0
264.0
260.0
256.0
252.0
248.0
247.2
0 37 74 111 148 185 222 259 296 333 370 407 444 481 518 555 592 629 666
(km)

The Eta topography

NARR Q&A.   Summary:

Grid cell silhouette and mean topography values calculated;

Where Laplacian of the mean > 0, mean
Where Laplacian of the mean < 0, silhouette,
unless this closes major mountain passes;

No topography smoothing

Examples of treatment of topography in some other models / by other authors

Webster et al. QJ 2003:

SMOOTHING THE OROGRAPHY (3 and a ½ page section)

(a) Motivation

A fundamental limitation of any numerical model is that features close to the grid-scale are poorly resolved; at these scales truncation effects (numerical errors) will dominate the true solution. As emphasized by Lander and Hoskins (1997), it is therefore desirable that these scales should not be forced directly as otherwise the well-resolved scales may very soon be contaminated by the errors forced at, or close to, the grid-scale

Weller, Shahrokhi, MWR 2014:

ABSTRACT

Steep orography can cause noisy solutions and instability in models of the atmosphere. A new technique for modeling flow over orography is introduced ….

. . . .

NMM, DiMego 2006:

"Lightly smoothed, grid-cell mean everywhere"

Gallus-Klemp / Witch of Agnesi test

Failure of an experimental Eta to do well a Wasatch downslope windstorm, and Gallus, Klemp experiments (MWR 2000) led to a widespread opinion that the eta coordinate was "ill suited for high resolution prediction models"

From the 2012 paper:

An upgraded version of the Eta model

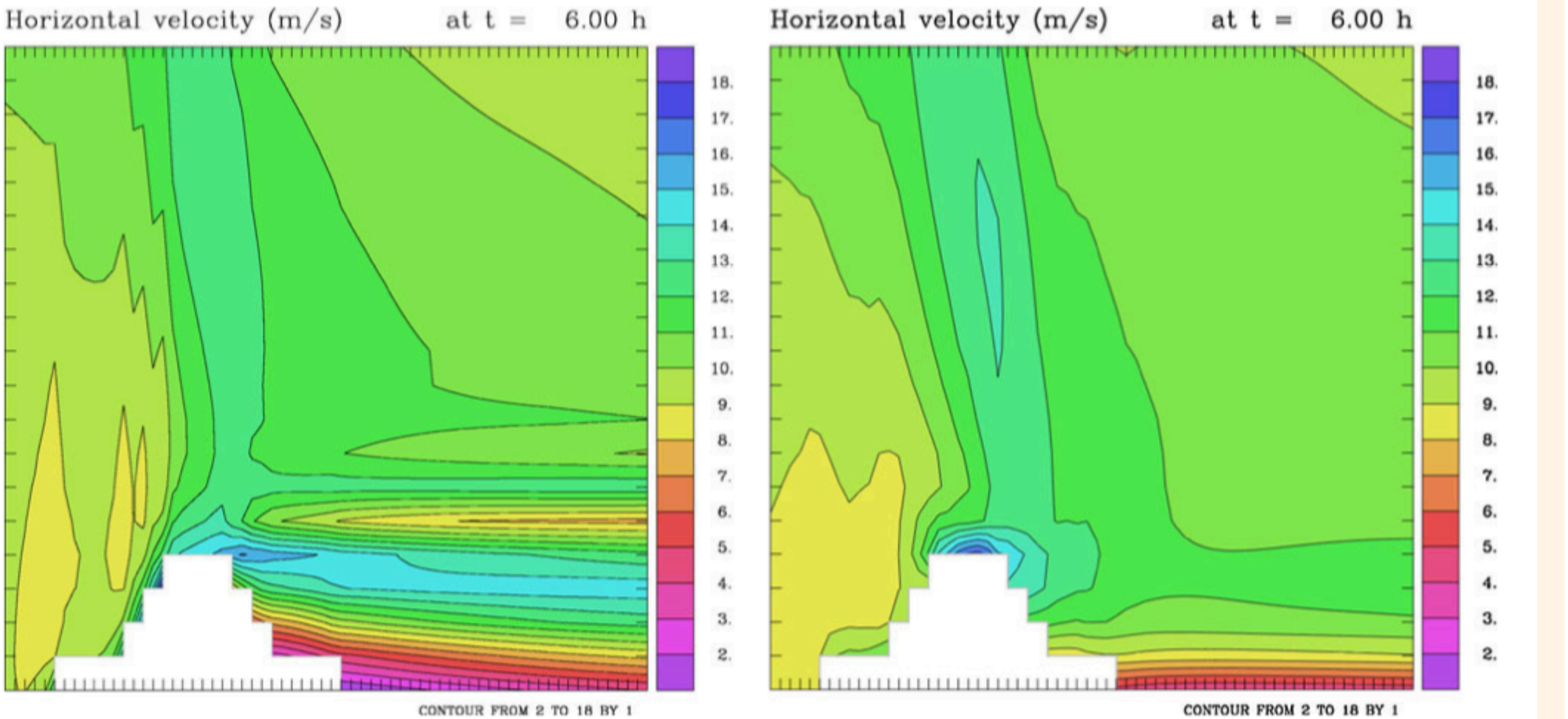
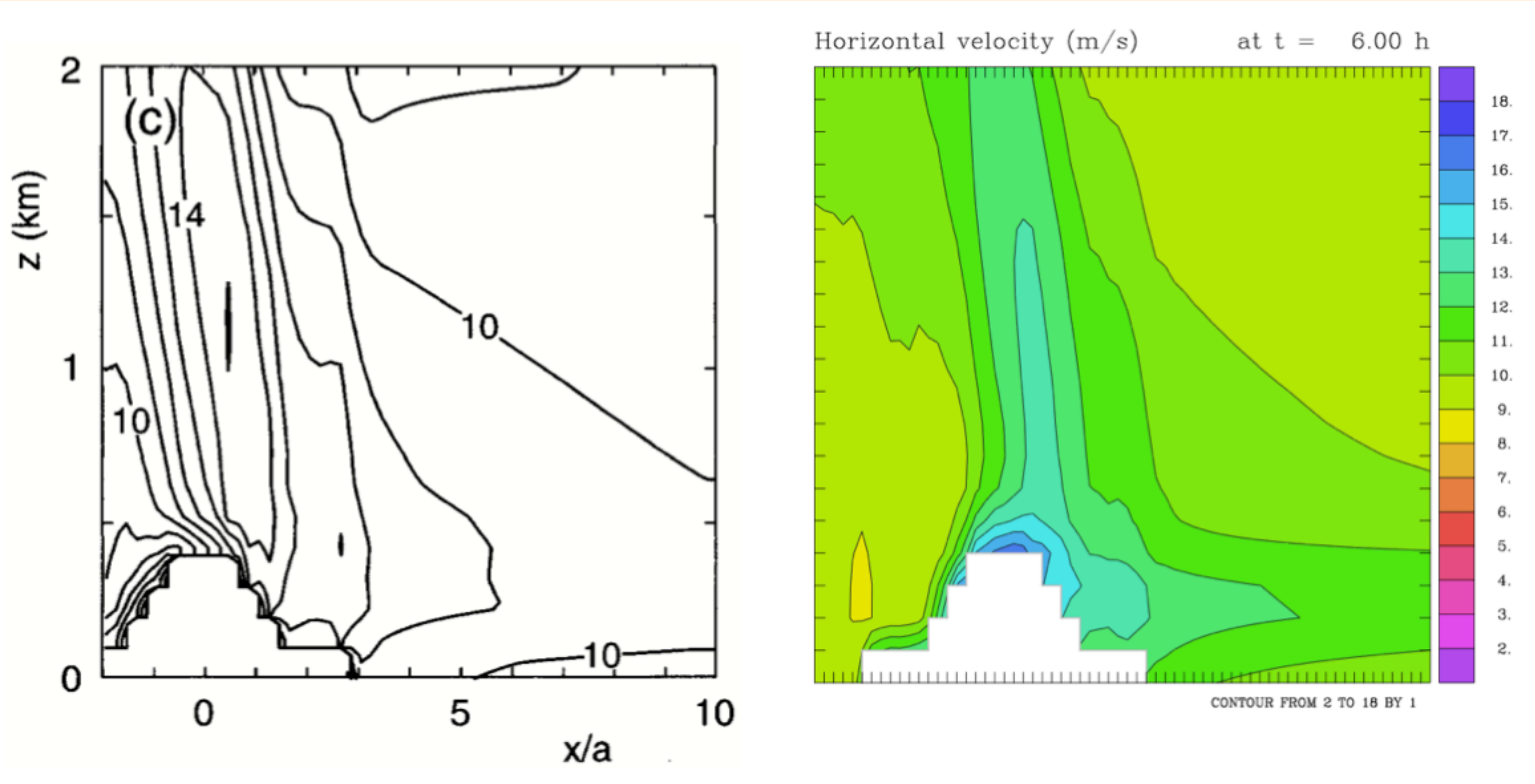


Fig. 3 Gallus–Klemp experiment, with parameters chosen so as to mimic the results shown in Gallus–Klemp (2000) Fig. 6. Control, *left panel*; code using sloping steps eta discretization, *right panel*

Recently, it was noted that the horizontal diffusion code was not made aware of the sloping steps discretization. Attending to this issue an unconditionally stable and monotonic Smagorinsky-like horizontal diffusion scheme was put in place.

Now:



Simulation of the Gallus-Klemp experiment with the Eta code allowing for velocities at slopes in the horizontal diffusion scheme, right hand plot. The plot (c) of Fig. 6 of Gallus and Klemp (2000), left hand plot.

2.3) Skill in 250 hPa winds vs. ECMWF in ensemble experiments

Veljovic et al. (M. Zeitschrift, 2010):

Eta 26 member ensemble driven by an ECMWF 32-day ensemble:

(Upgraded) Eta: ~31 km/45 layer, 12,000 x 7,580 km domain;

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

Verification against ECMWF analyses

Question asked:

Can a nested model improve on large scales ?

How do we look at "large scales" ?

Winds at 250 hPa:

position of the jet stream !

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Can a nested model improve on large scales ?

How do we look at "large scales" ?

Winds at 250 hPa:

position of the jet stream !

Picture credit: Sin Chan Chou

To stand a decent chance of improving on large scales of the driver global model, one needs to

- Run a domain greater than traditionally used in RCM work (domain is cheap; resolution is expensive !!);
- Use LBCs that do not ignore the basic mathematics of the problem (e.g., do NOT use Davies relaxation LBCs !! See Mesinger, Veljovic, Meteor. Atmos. Phys. 2013);
- Run experiments using forecast (GCM) LBCs (NOT reanalysis LBCs);
- Use an RCM with a dynamical core not inferior to that of the driver global model

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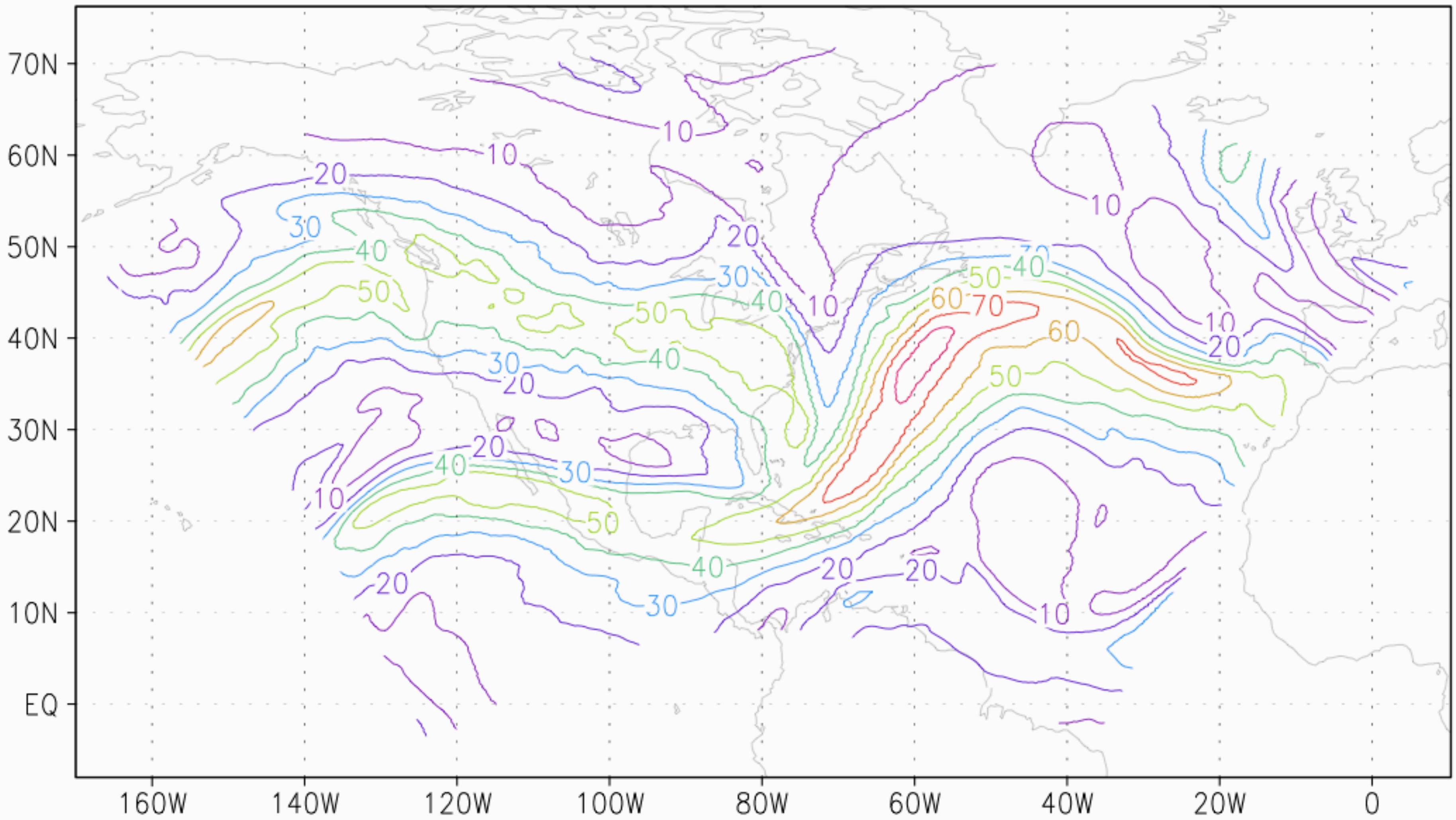
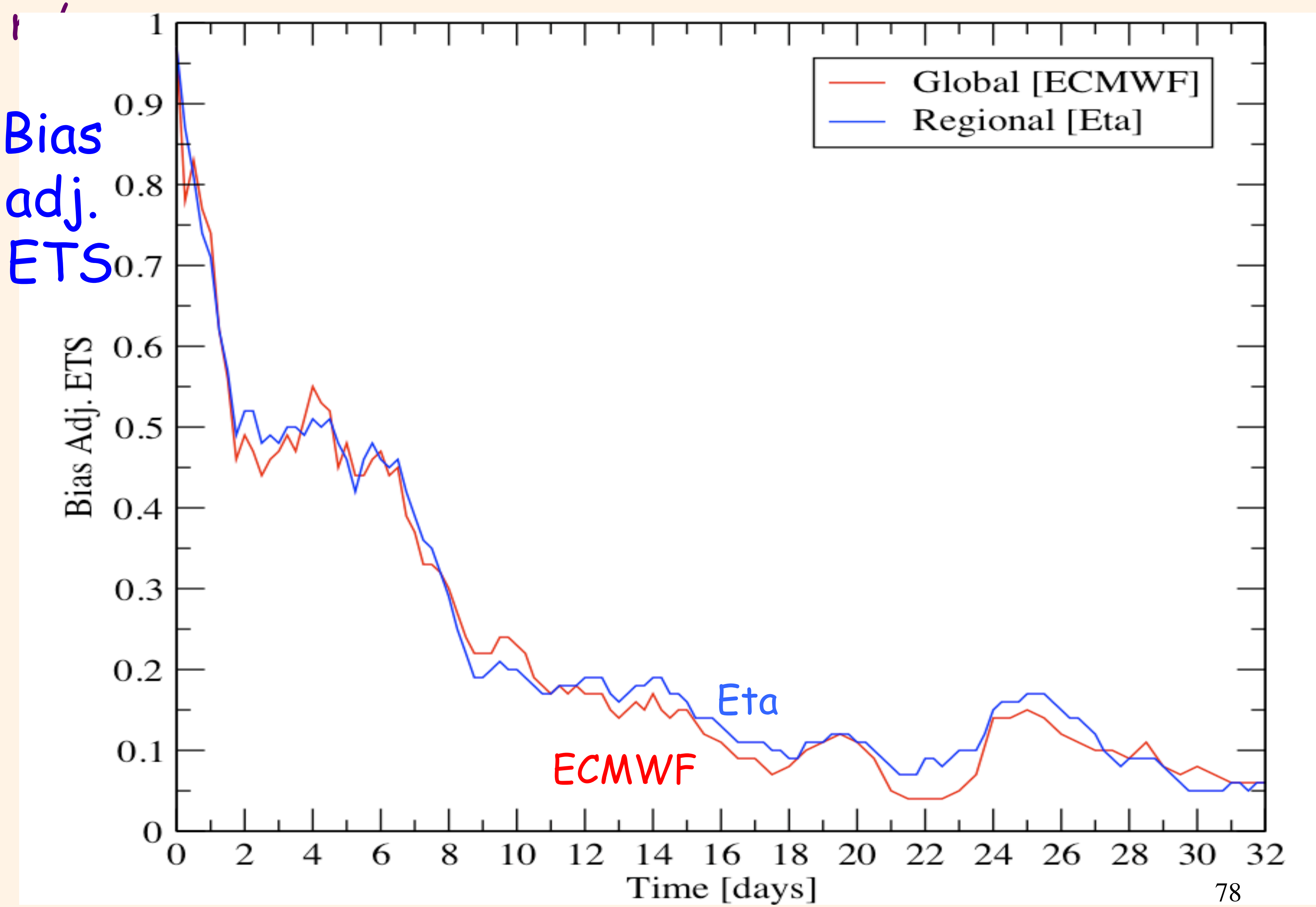
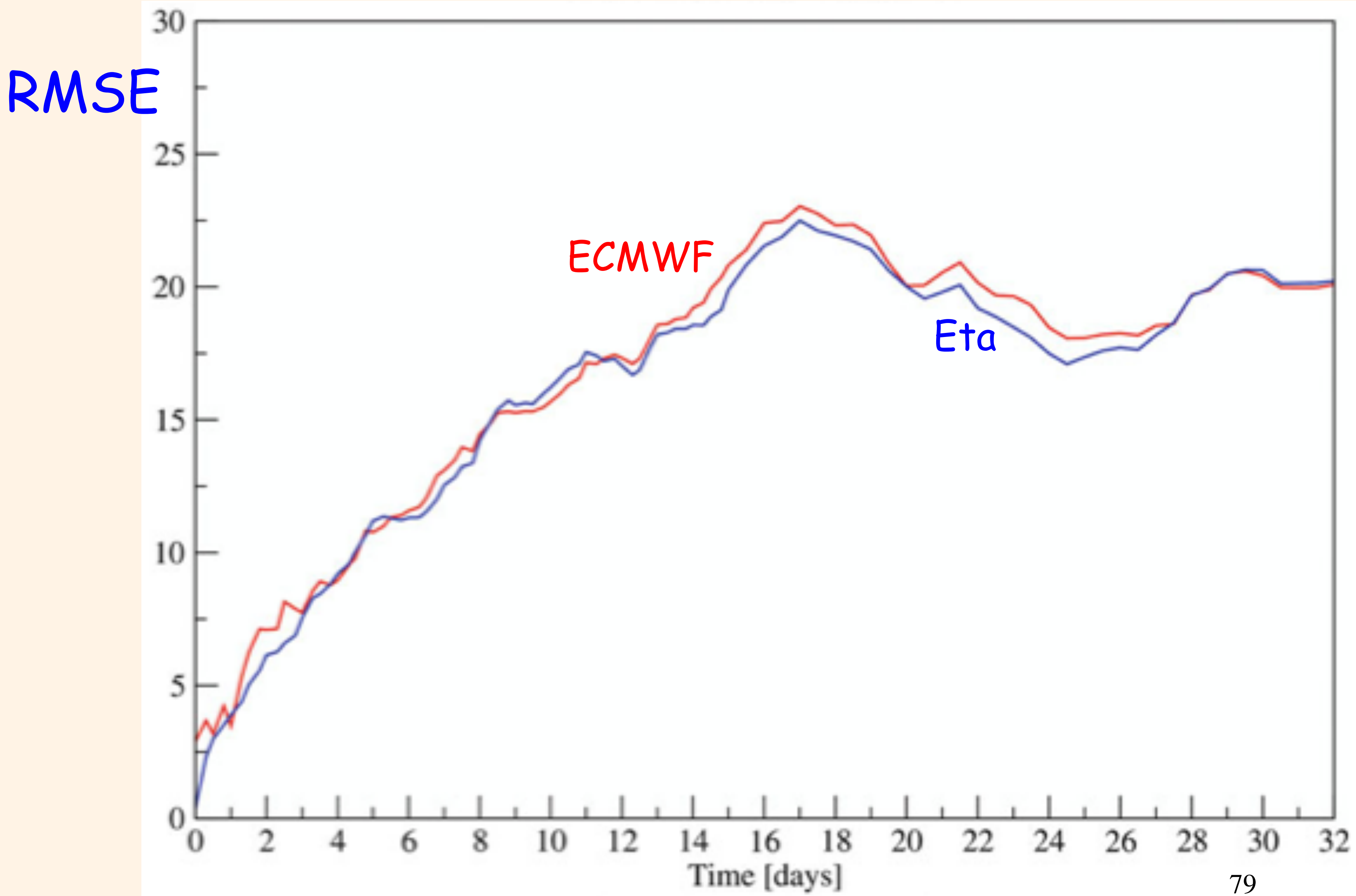
jet_stream analysis(ECMWF) 32nd day



Results, 2010: 26 members 32-day forecasts, winds > 45



Customary rms difference, m/s, all 26 forecasts:



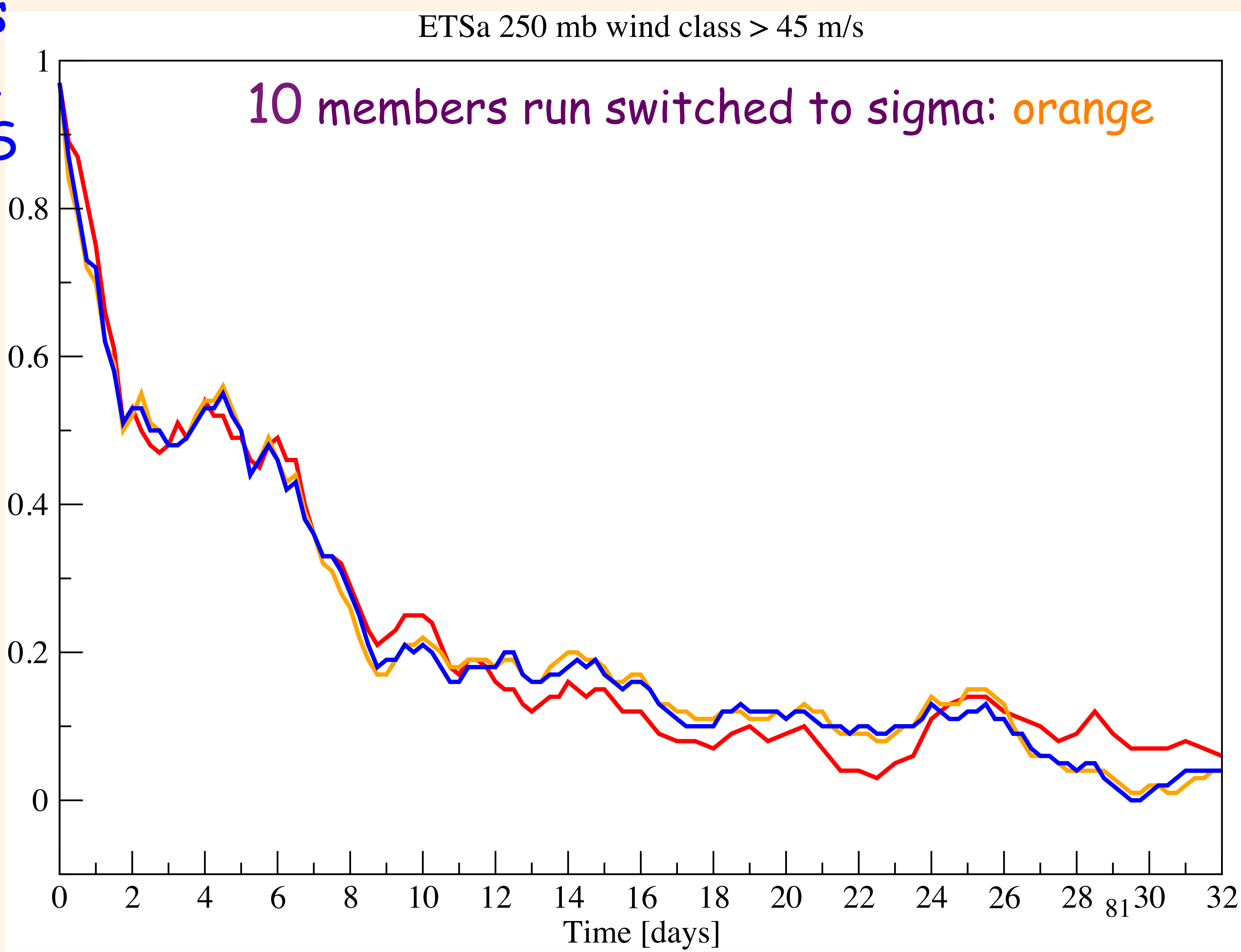
What made this possible ?

Recall the Eta has to absorb unavoidable LBC errors !

Specifically, why the Eta scores improve around day 12 compared to the ECMWF ones ?

10 members run switched to sigma

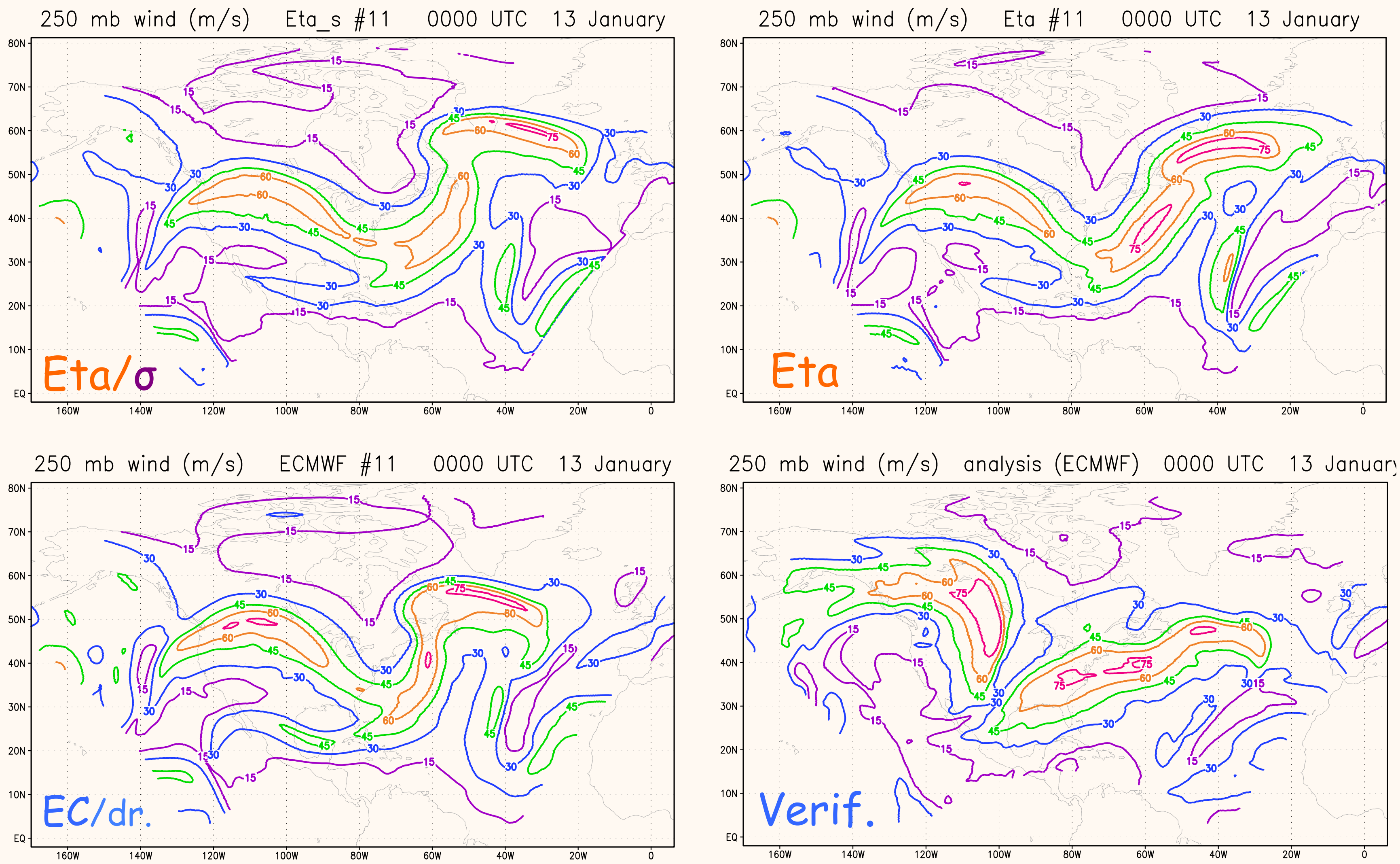
Bias adj. ETS



ETSa 250 mb wind class > 45 m/s
10 members run switched to sigma: orange
1
0.8
0.6
0.4
0.2
0
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
Time [days]

However: Inspecting wind speed maps at 12 days we could see Eta tending to produce a more accurate tilt of the 250 hPa trough compared to both ECMWF, and the Eta run as sigma

Example, member 11:



Speed contours of 250 hPa winds of 12 day forecasts, shown over the Eta members' domain: of the Eta member 11 but run using sigma coordinate, top left panel; same but using the eta, top right panel; same but of the ECMWF ensemble member 11 used to drive these Eta forecast, bottom left panel. Same except ECMWF analysis verifying at the same time, bottom right panel.

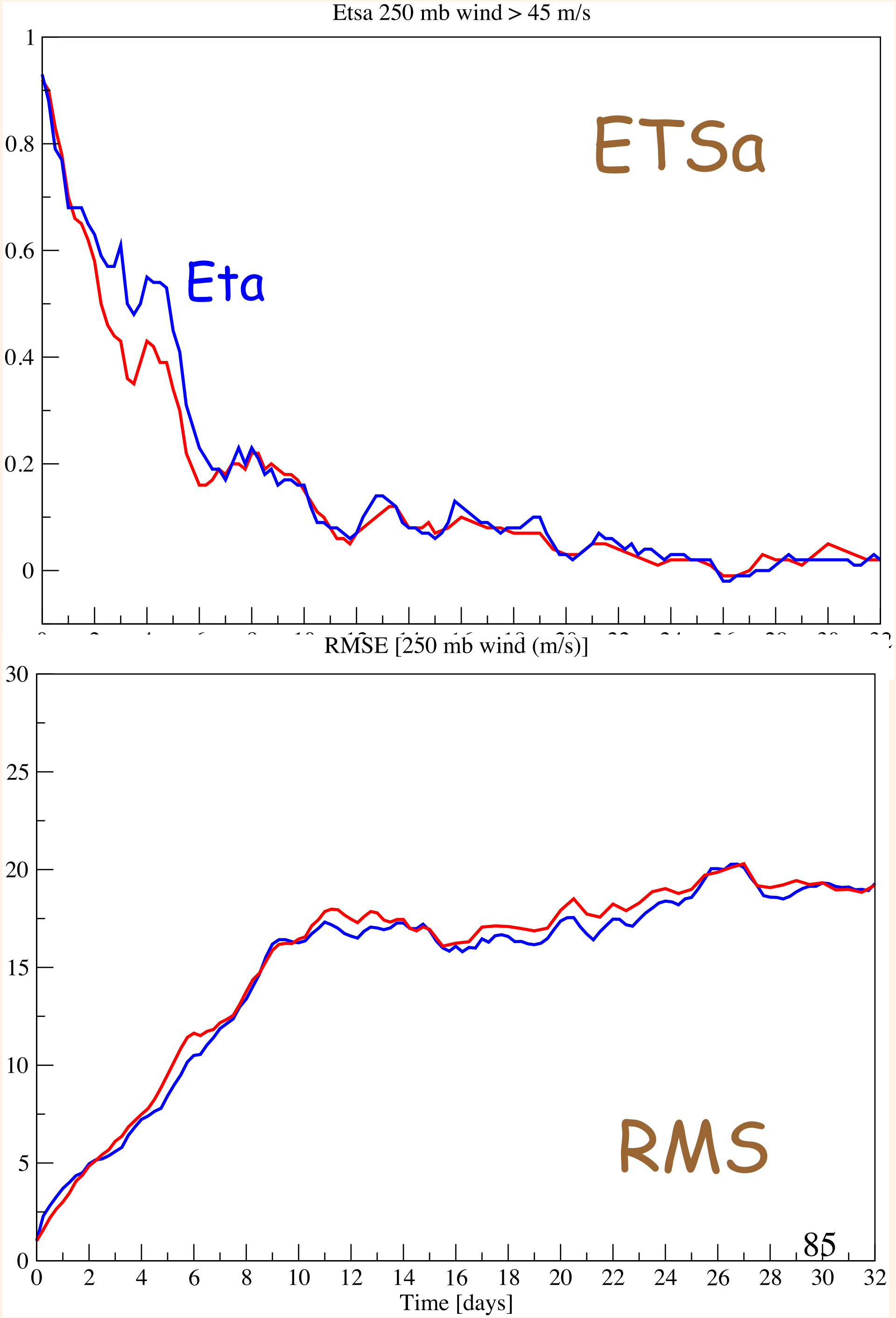
This kind of an advantage for Eta in 3 out of 10 members. In one member sigma had a more accurate tilt.

A 10-member Eta experiment rerun for a more recent ECMWF ensemble, one initialized 4 October 2012, when its resolution was higher than of that used previously:

32 km the first 10 days, 63 km thereafter

Bias adjusted ETS scores of wind speeds greater than 45 m s^{-1}, upper panel, and RMS wind difference, lower panel, of the driver ECMWF ensemble members (red) and Eta members (blue), both at 250 hPa and with respect to ECMWF analyses.

Initial time is 0000 UTC 4 October 2012



What was going on at about day 2-6 time?

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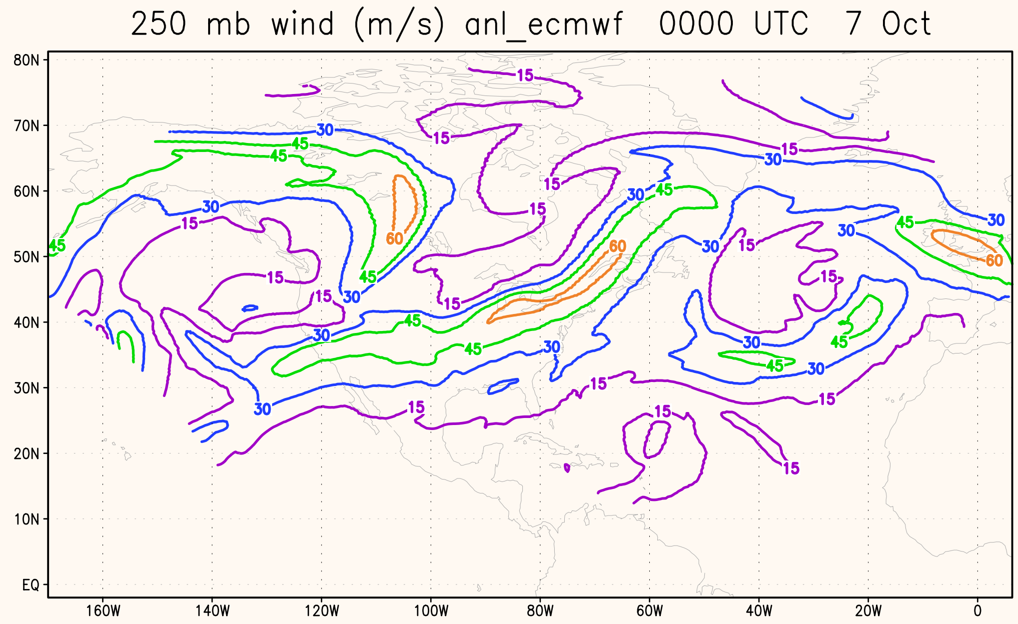
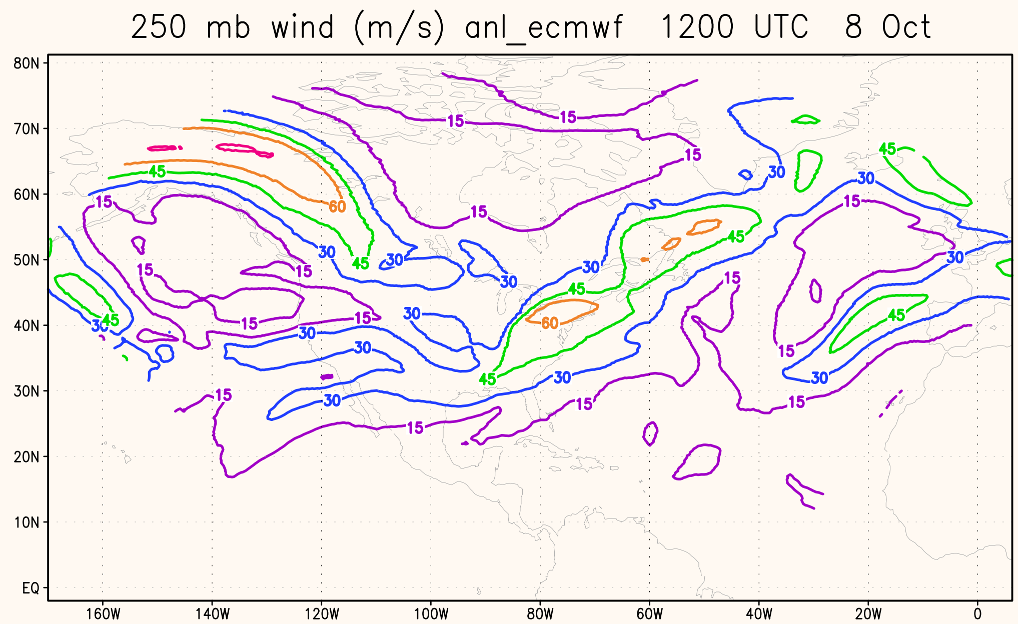
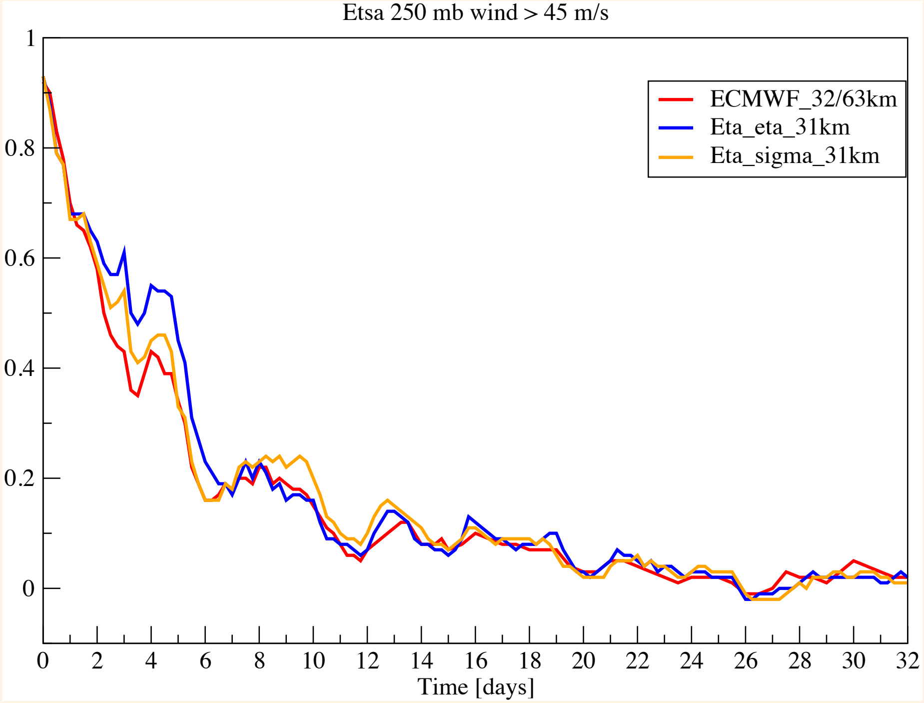
The plot times correspond to day 3.0, and 4.5, respectively, of the plots of the preceding slide

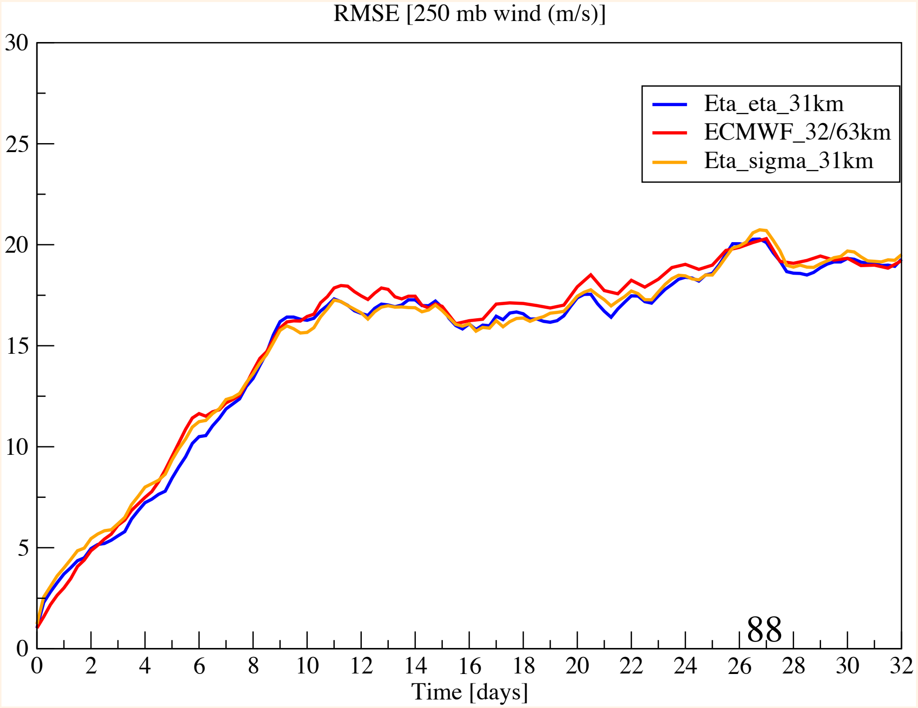




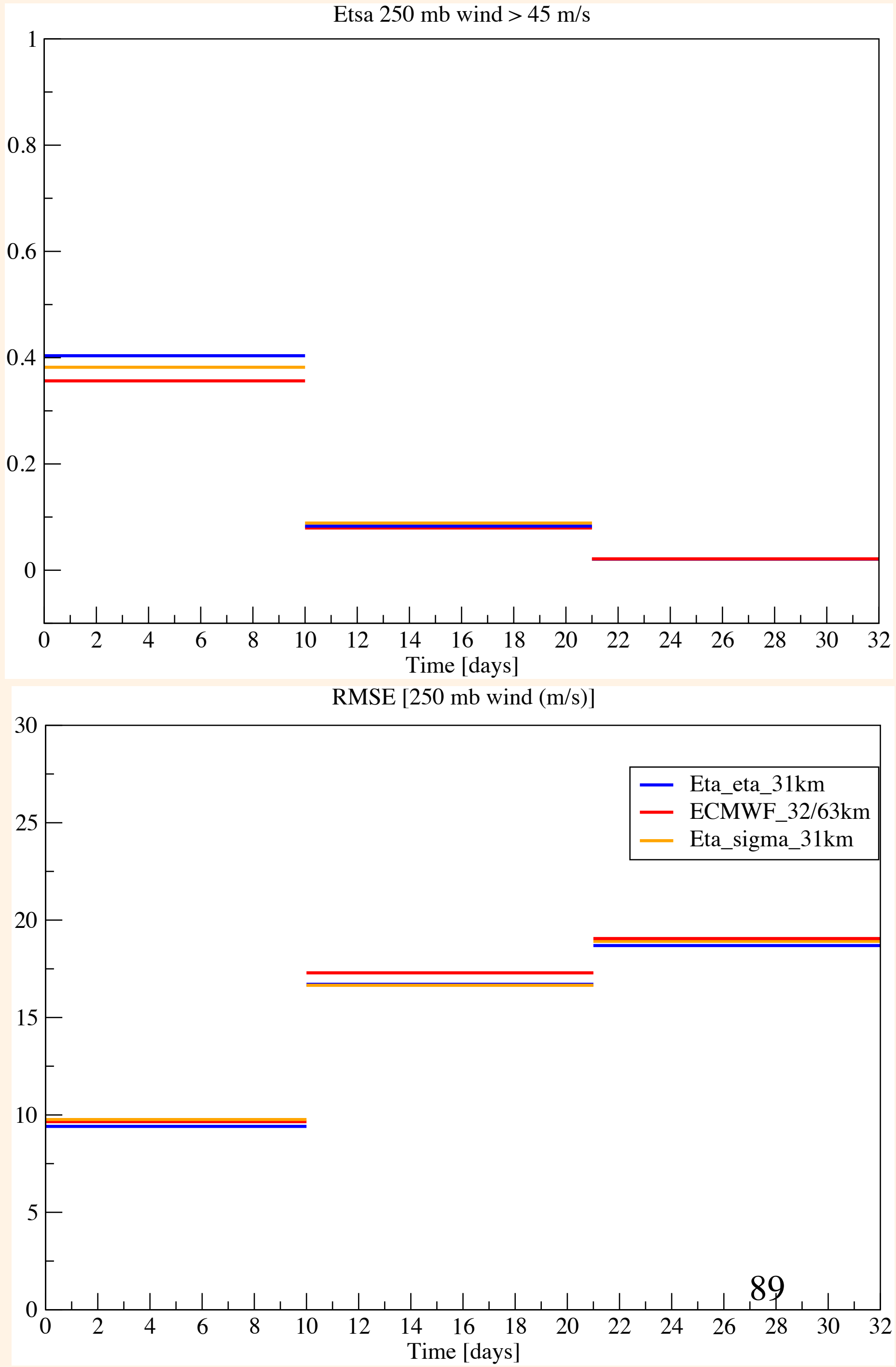
Eta coordinate ?

Eta switched to use sigma:

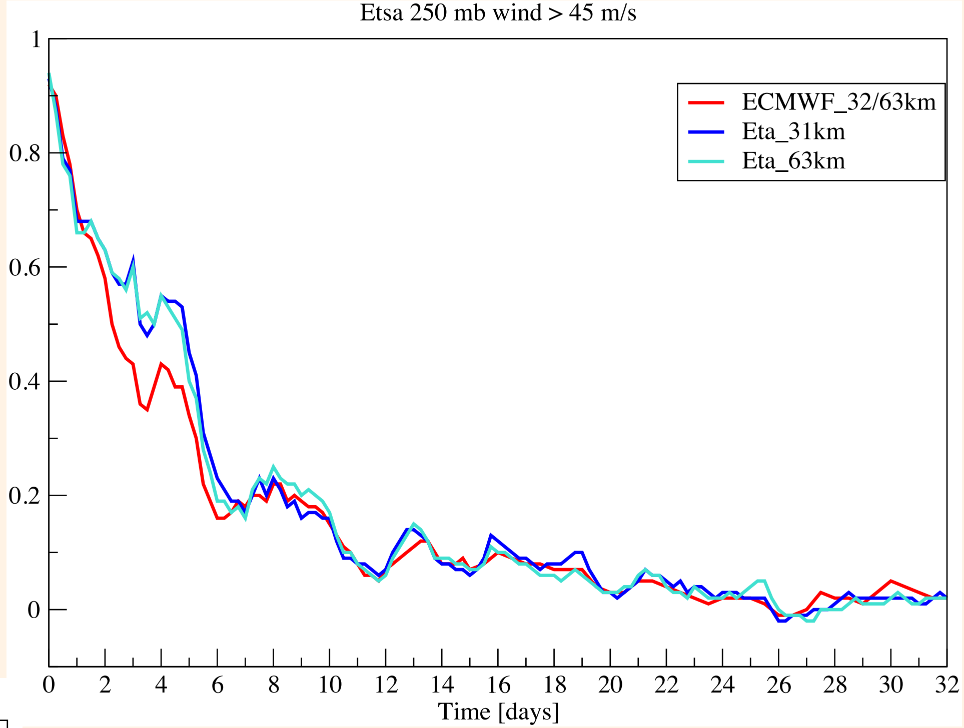


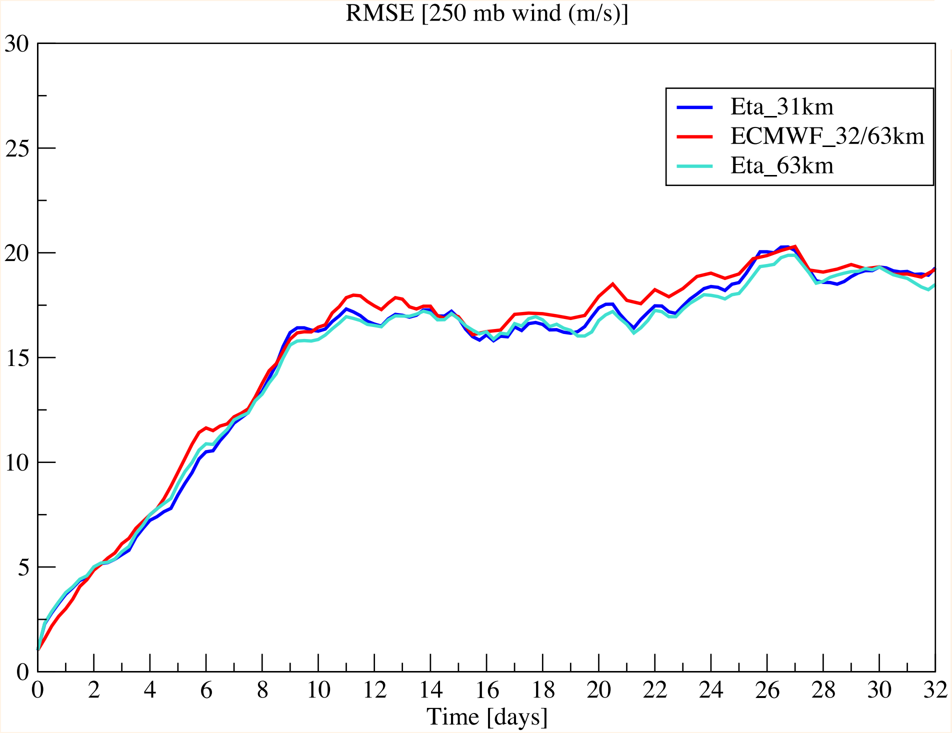


10, 11, 11 day averages:



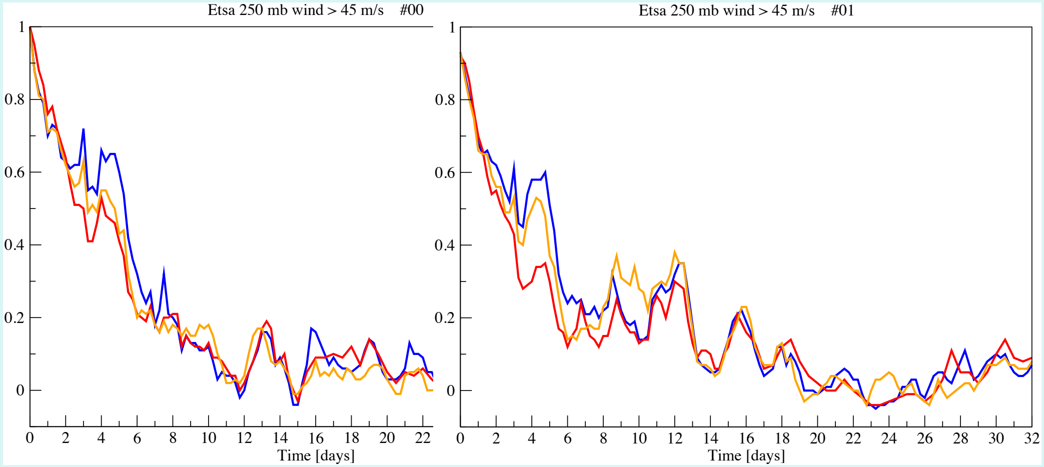
Resolution ?

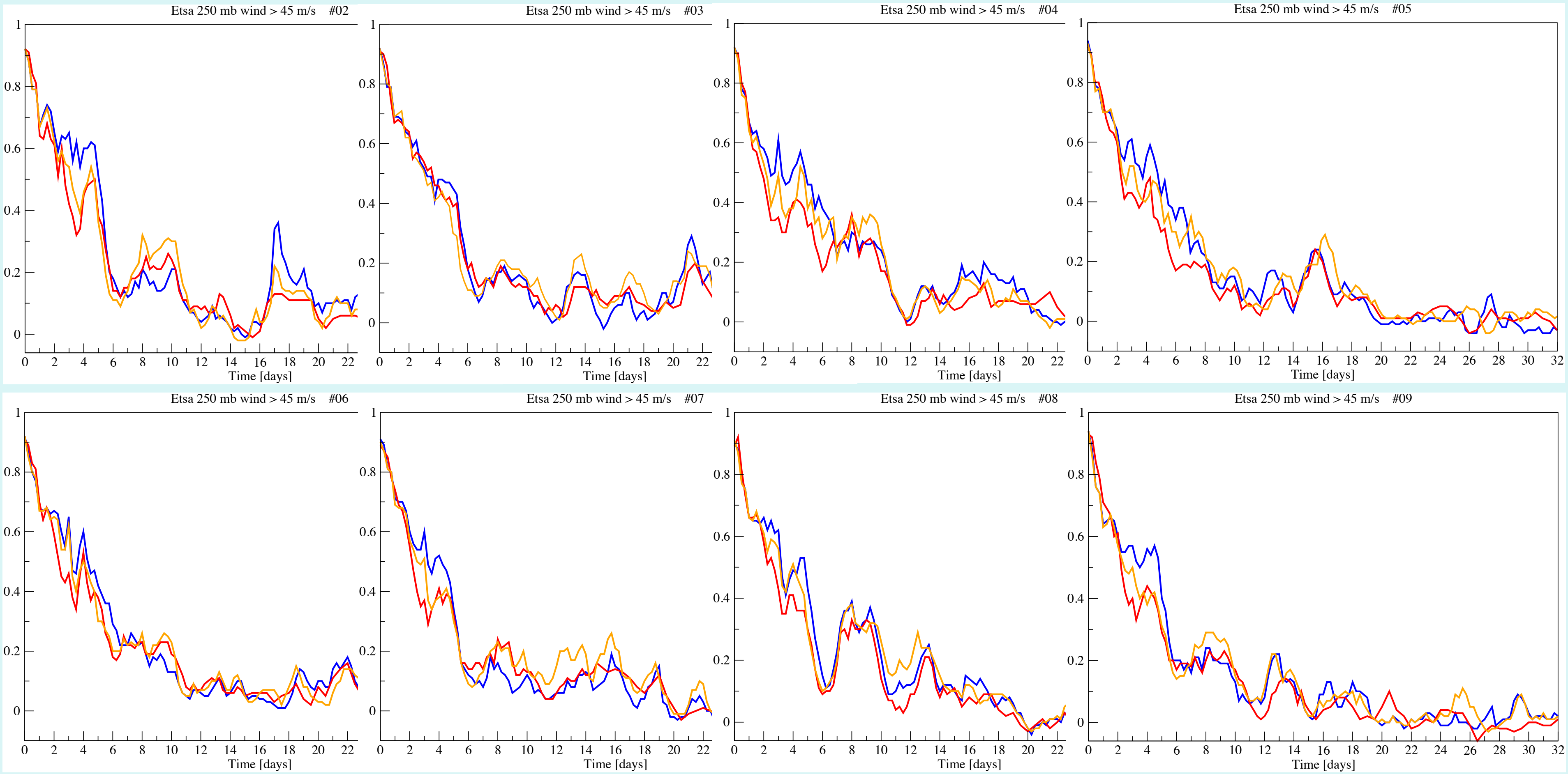




No visible impact !!

For insight into the advantage of the Eta/eta, also Eta/sigma consider plots for individual members:





Take home conclusions #1 (of 2)

Benefit from eta vs. sigma, robust evidence for

- More accurate precipitation forecasts;
  (Why? Limited evidence: Flow more around as opposed to too much up and down topography; e.g., McAfee et al. 2011, Chao 2012, …)
- Better placement of lee lows ahead of upper level troughs;
- Problem-free acceptance of realistically steep topography
- "Sloping steps": improved eta discretization, removes the Gallus-Klemp problem of flow separation in the lee of a bell-shaped mountain

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Take home conclusions #2

In ensemble experiments, Eta driven by 32-day ECMWF ensemble members

- In spite of absorbing unavoidable LBC errors, Eta did somewhat better than the EC in 250 hPa wind verifications.
  Why?
- Tests with Eta switched to use sigma, show that the eta coordinate made a significant contribution to the Eta's advantage;
- Advantage was NOT due to using higher resolution;
- The Eta using sigma seems to have done a little better than the driver EC ensemble as well. Why?
  (Maybe: finite-volume vertical advection, MY turbulence, grid-point topography, ...)
- People doing large-scale nudging in RCM work would do well to reconsider reasons as to why do they need to do that, or believe they need to do that.

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Large scale / or "spectral nudging" of RCMs done by many people. E.g.:

QJ 2012:

Spectral nudging in regional climate modelling: how strongly should we nudge?

Hiba Omrani,* Philippe Drobinski and Thomas Dubos
Institut Pierre Simon Laplace/Laboratoire de Météeorologie Dynamique,
Ecole Polytechnique/ENS/UPMC/CNRS,
Palaiseau, France

Many more . . .

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Some of the references that might have been 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., Acad. 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.

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", Acad. 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.

Mesinger, F., and K. Veljovic, 2013: Limited area NWP and regional climate modeling: A test of the relaxation vs Eta lateral boundary conditions. *Meteor. Atmos. Phys.*, **119**, 1-16, doi: 10.1007/s00703-012-0217-5.

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.

Some of the references that might have been 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 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 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. *Large-Scale Computations in Fluid Mechanics*, B. E. Engquist, S. Osher, and R. C. J. Somerville, Eds. Lect. Appl. Mathematics, **22**, 81-120.

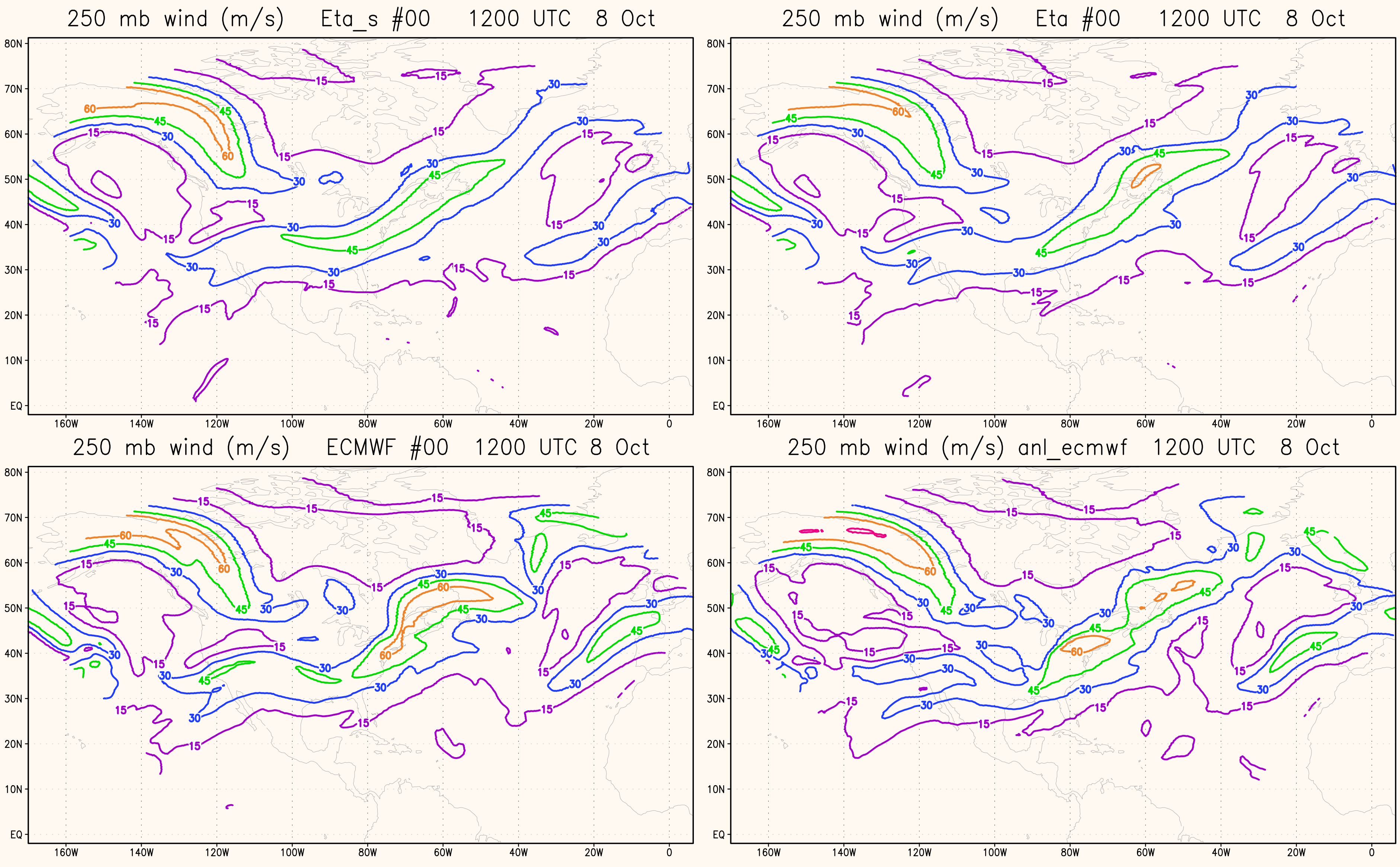
Mesinger, F., and D. Jovic, 2002: The Eta slope adjustment: Contender for an optimal steepening in a piecewise-linear advection scheme? Comparison tests. NCEP Office Note 439, 29 pp (Available at http://wwwt.emc.ncep.noaa.gov/officenotes).

Mesinger, F., S. C. Chou, J. Gomes, D. Jovic, P. Bastos, J. F. Bustamante, L. Lazic, A. A. Lyra, S. Morelli, I. Ristic, and K. Veljovic, 2012: An upgraded version of the Eta model. *Meteor. Atmos. Phys.*, **116**, 63-79 [Available at http://www.springerlink.com/content/0177-7971/116/3-4/.]

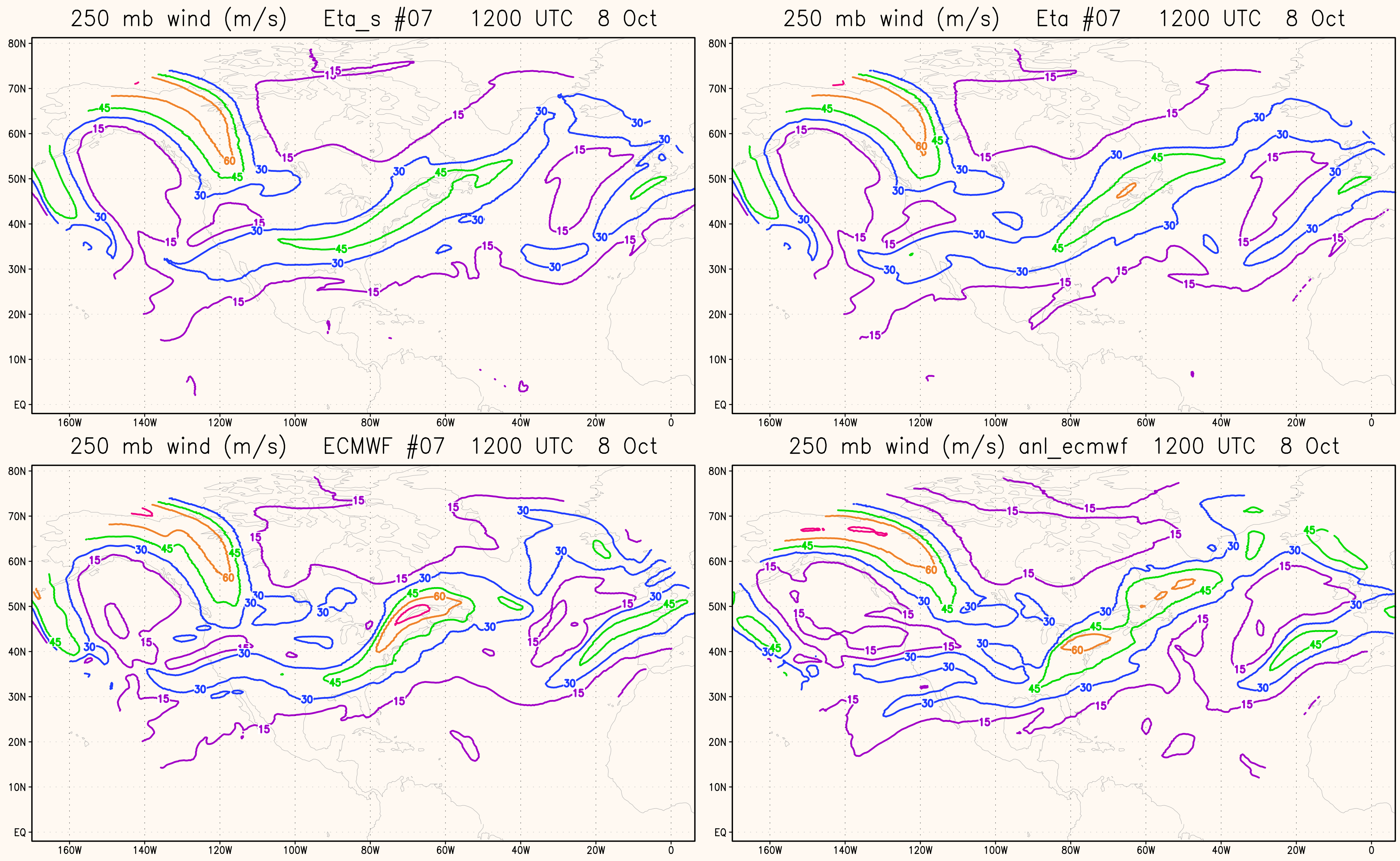
Russell, G. L., 2007: Step-mountain technique applied to an atmospheric C-grid model, or how to improve precipitation near mountains. *Mon. Wea. Rev.*, **135**, 4060–4076.

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.



Ensemble members 00 at 4.5 day time: Eta/sigma top left, Eta top right, EC driver bottom left, EC verification analysis bottom right.



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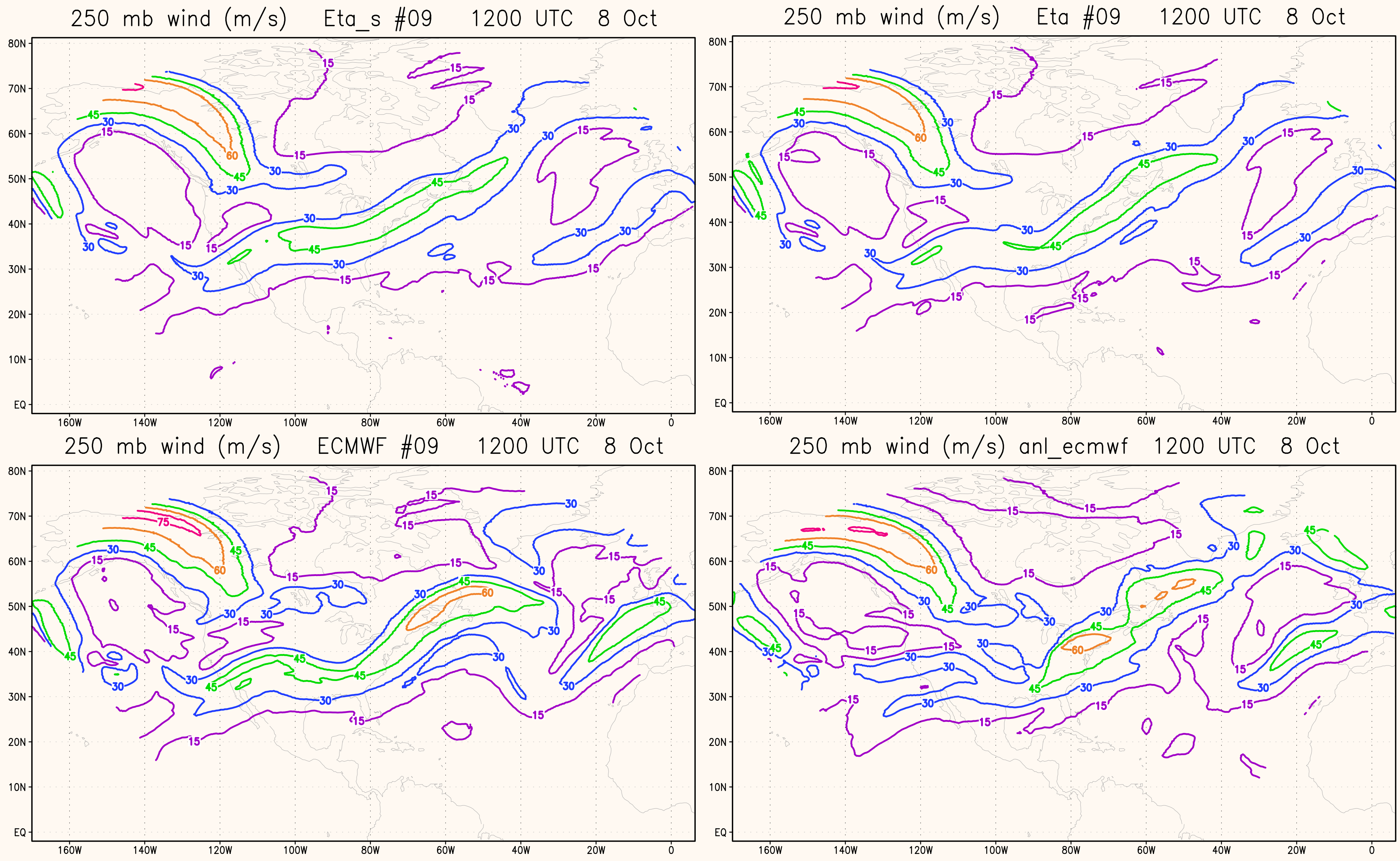

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