An upgraded version of the Eta model and an ECMWF driven 32-day Eta ensemble: Can a nested model improve on large scales?

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with contributions from Sin Chan Chou, Gorge Gomes, Dusan Jovic, Ivan Ristic, Katarina Veljovic, . . .

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Canadian Meteorological Centre/RPN,
Environment Canada, Montreal, May 13, 2011

A brief summary of the Eta model dynamical core design:

"Philosophy": "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:

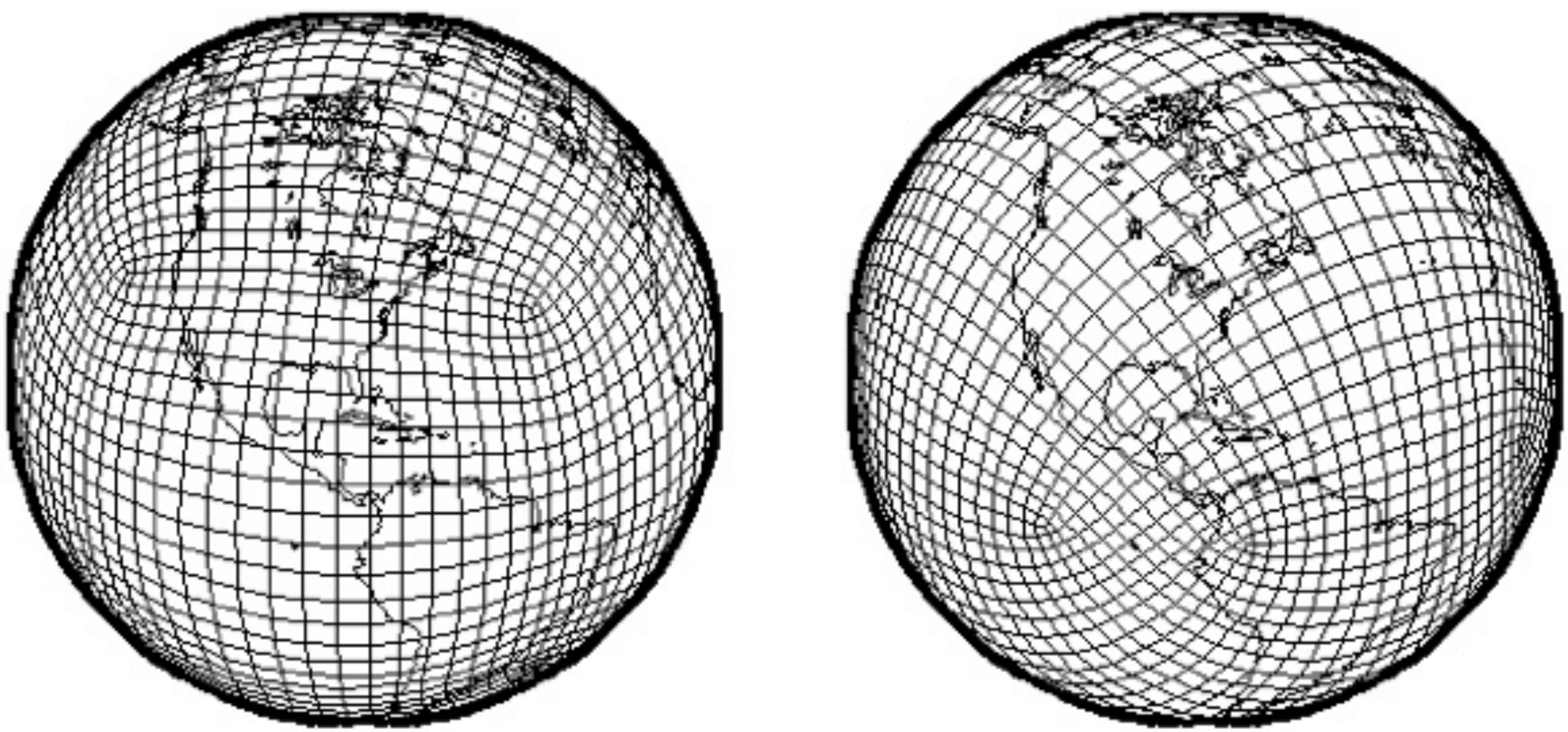
Lateral boundary conditions (LBCs) are needed;

The Eta scheme:

variables updated at the outermost row only, and at the outflow points tangential velocity is extrapolated from the inside

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;

- 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)

- **Horizontal advection**

The famous Arakawa horizontal advection scheme:

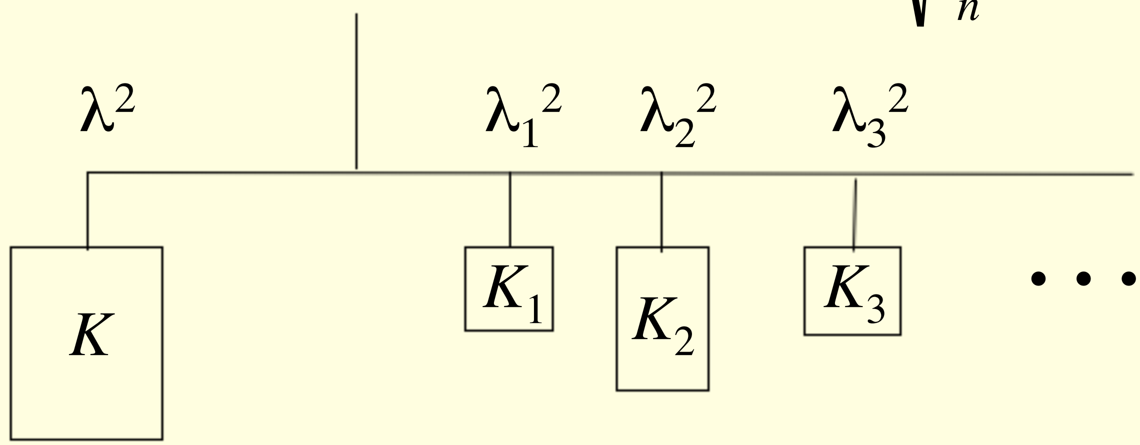
For two-dimensional and nondivergent flow:

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 !!!

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

Primitive equations ?

Note:

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

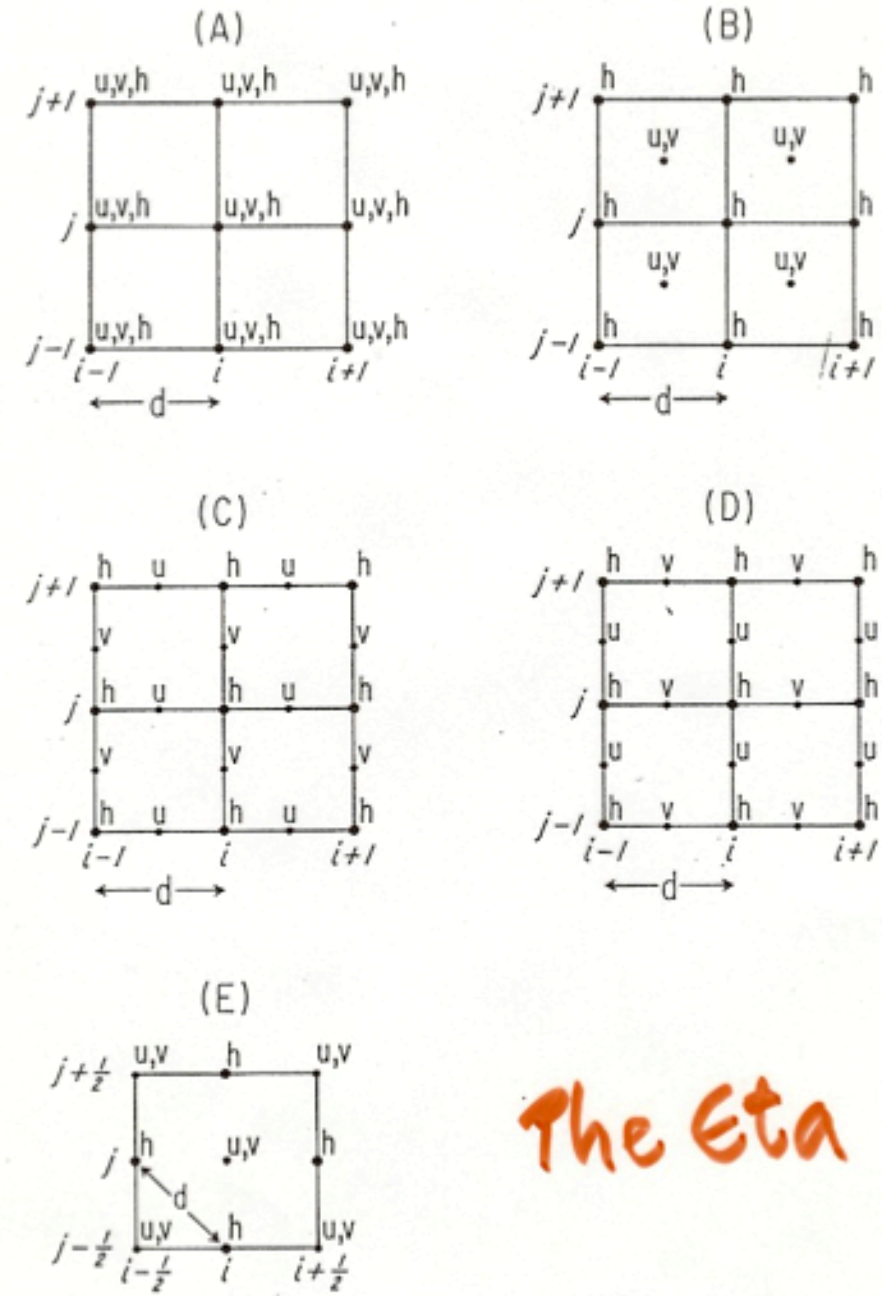


FIG. 3. Spatial distributions of the dependent variables on a square grid.

From ECMWF Seminar 1983:

The horizontal advection scheme:

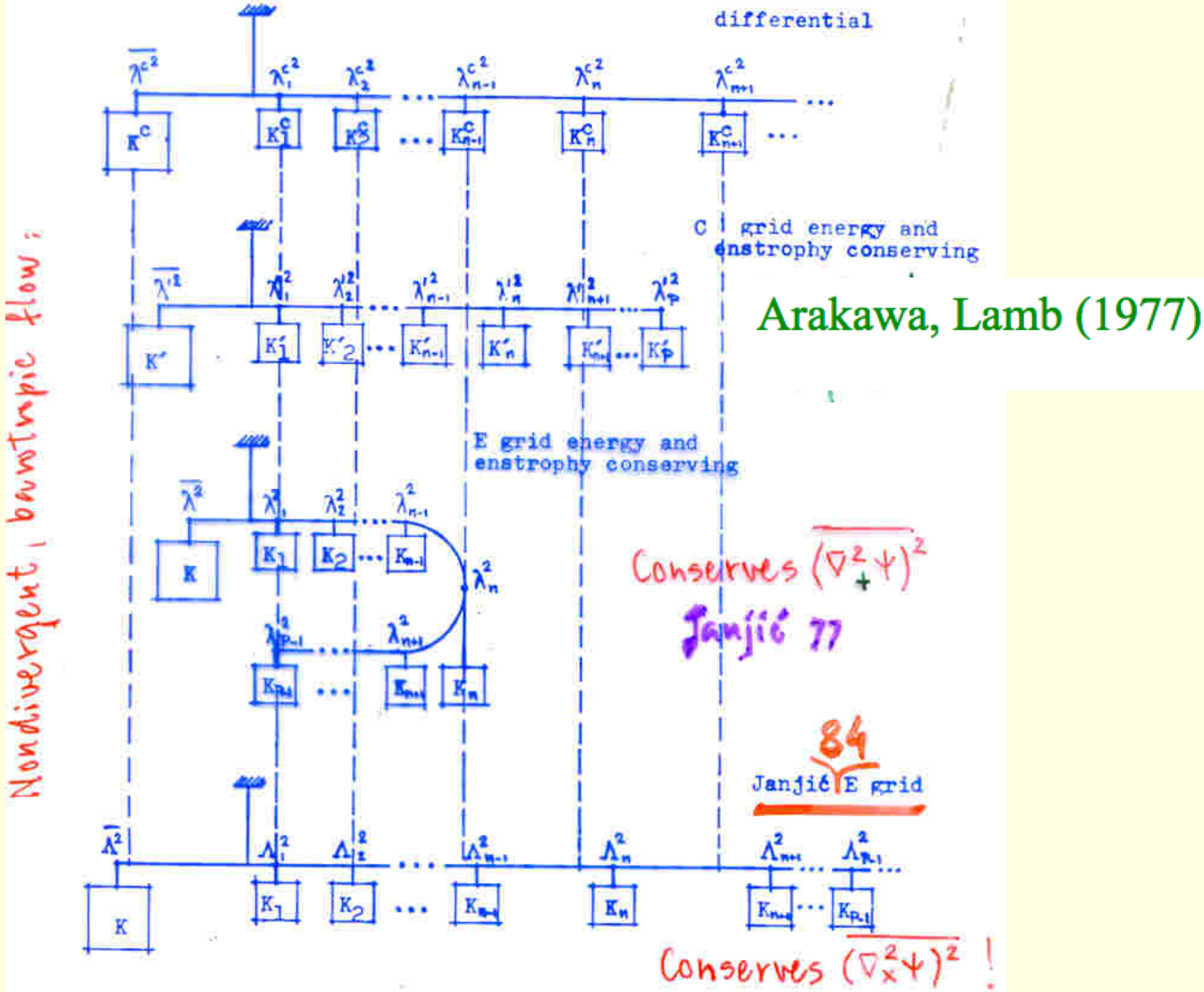


Fig. 3.12. Mechanical analogies of the constraints imposed on the non-linear energy cascade in the continuous case, in the case of the C-grid energy and enstrophy conserving scheme, in the case of the E-grid energy and enstrophy conserving scheme, and in the case of the scheme due to Janjić (1984).

(ECMWF Seminar '83)

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

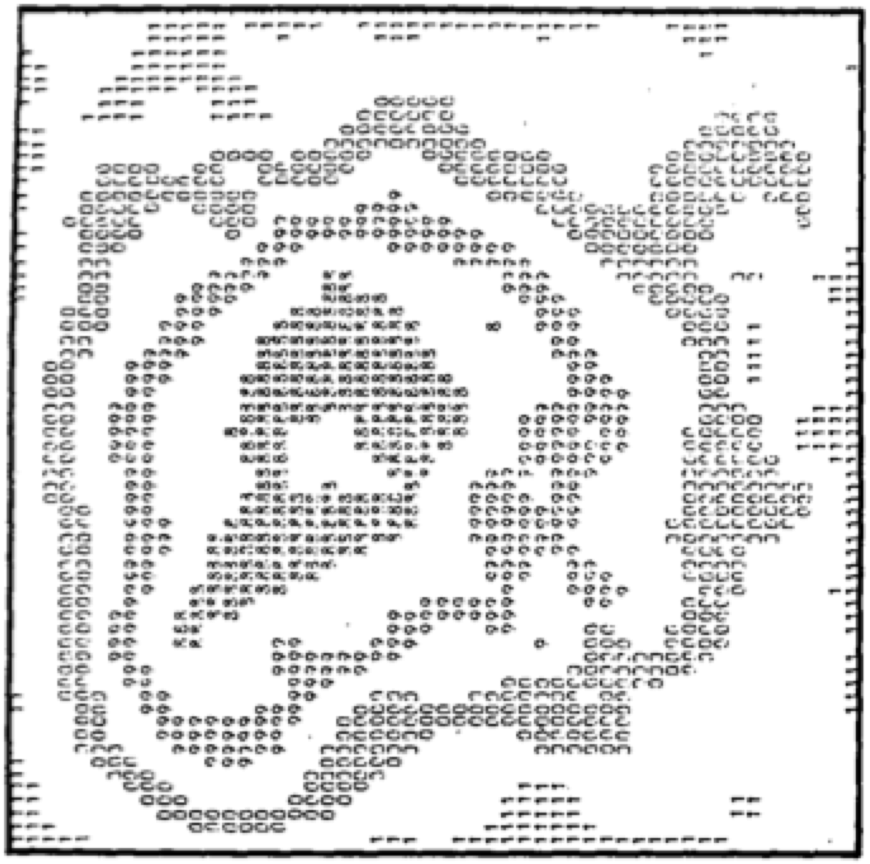


FIG. 13. Height field after 10 000 time steps in the control experiment. The shading interval is 160 m.

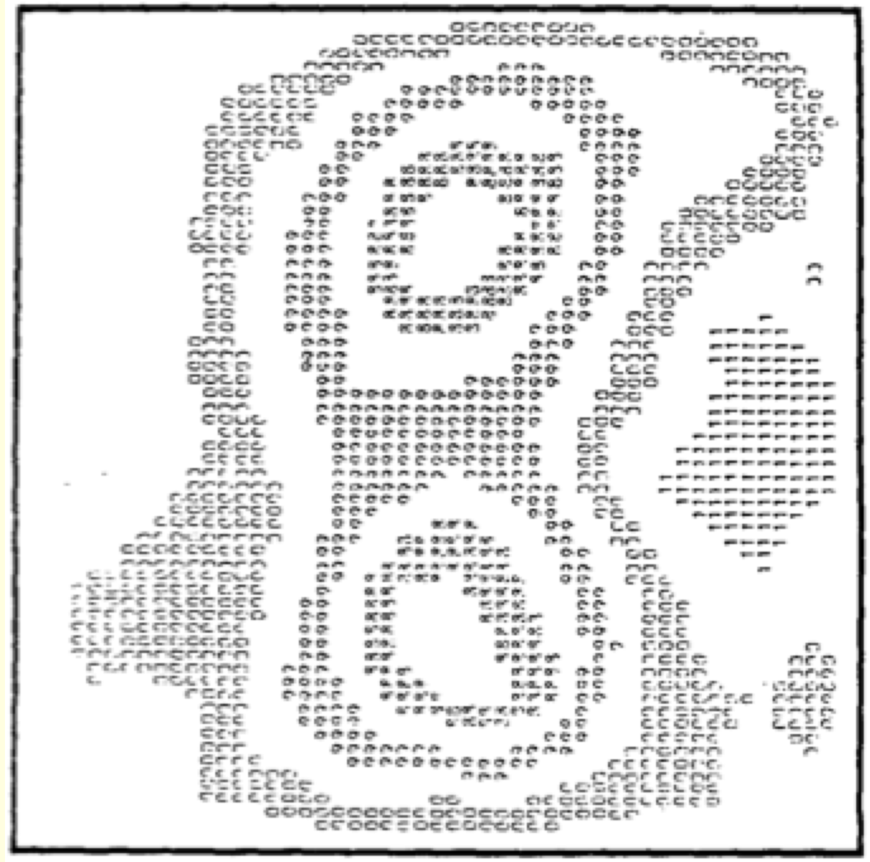


FIG. 12. Height field after 10 000 time steps in the main experiment. The shading interval is 160 m.

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:

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

- Pressure-gradient force, eta coordinate;

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,

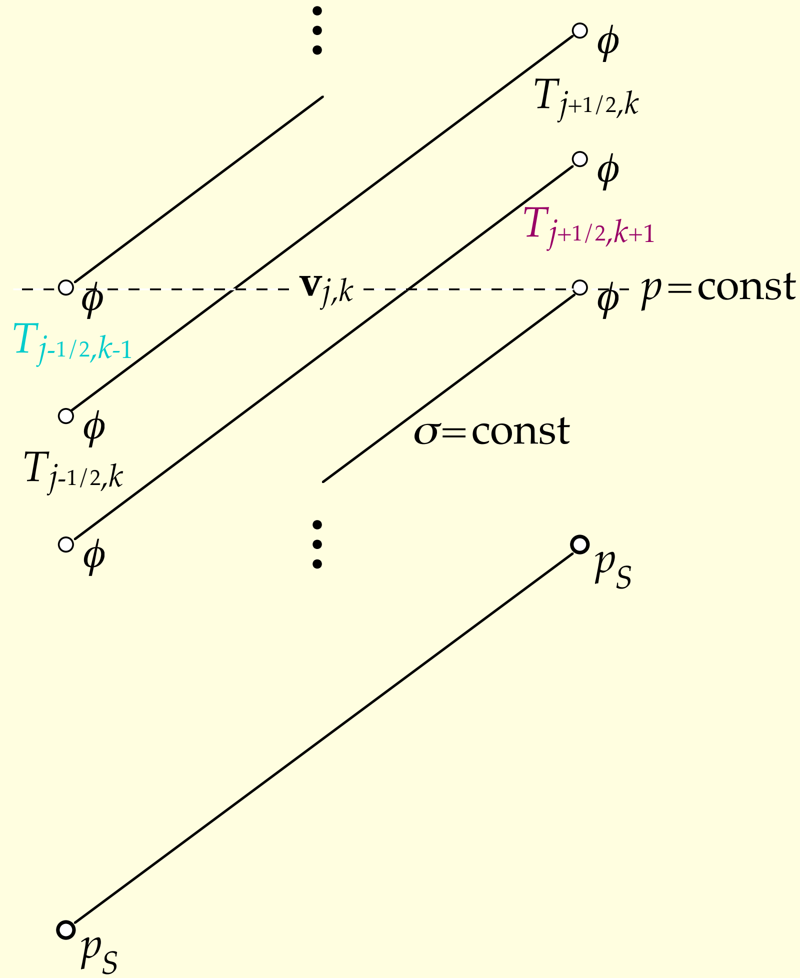
$$\phi = \phi_S - R_d \int_{p_S}^{p} T_v d \ln p$$

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!

“Step-topography” eta:

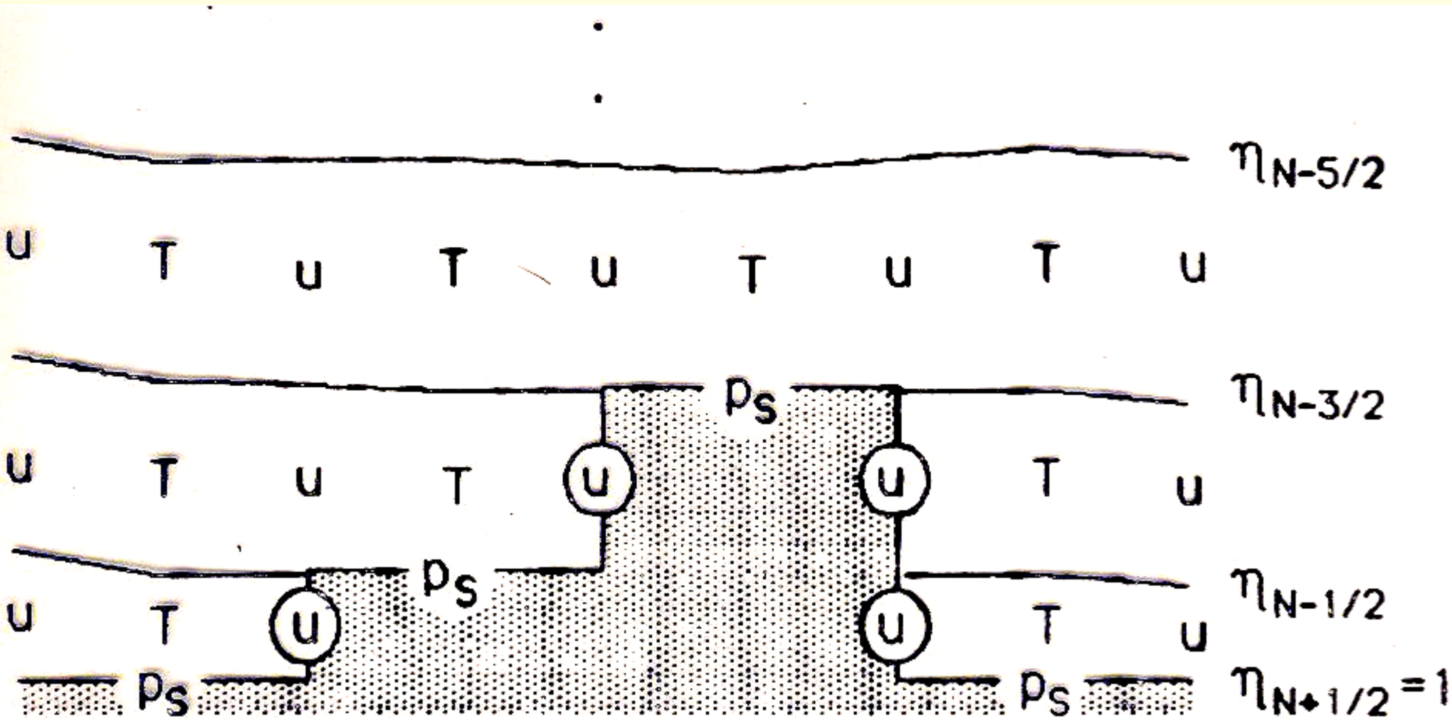


FIG. 1. Schematic representation of a vertical cross section in the eta coordinate using step-like representation of mountains. Symbols u, T and p_s represent the u component of velocity, temperature and surface pressure, respectively. N is the maximum number of the eta layers. The step-mountains are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

Downsides? #1:

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#2:

The flow down the slopes noticed to have been in some situations not realistic – tendency for flow separation. Wasatch downslope windstorm, Gallus, Klemp (MWR 2000), a case of Santa Ana wind.

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

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

All very convincingly favoring the eta !

The very first:

Sigma Eta

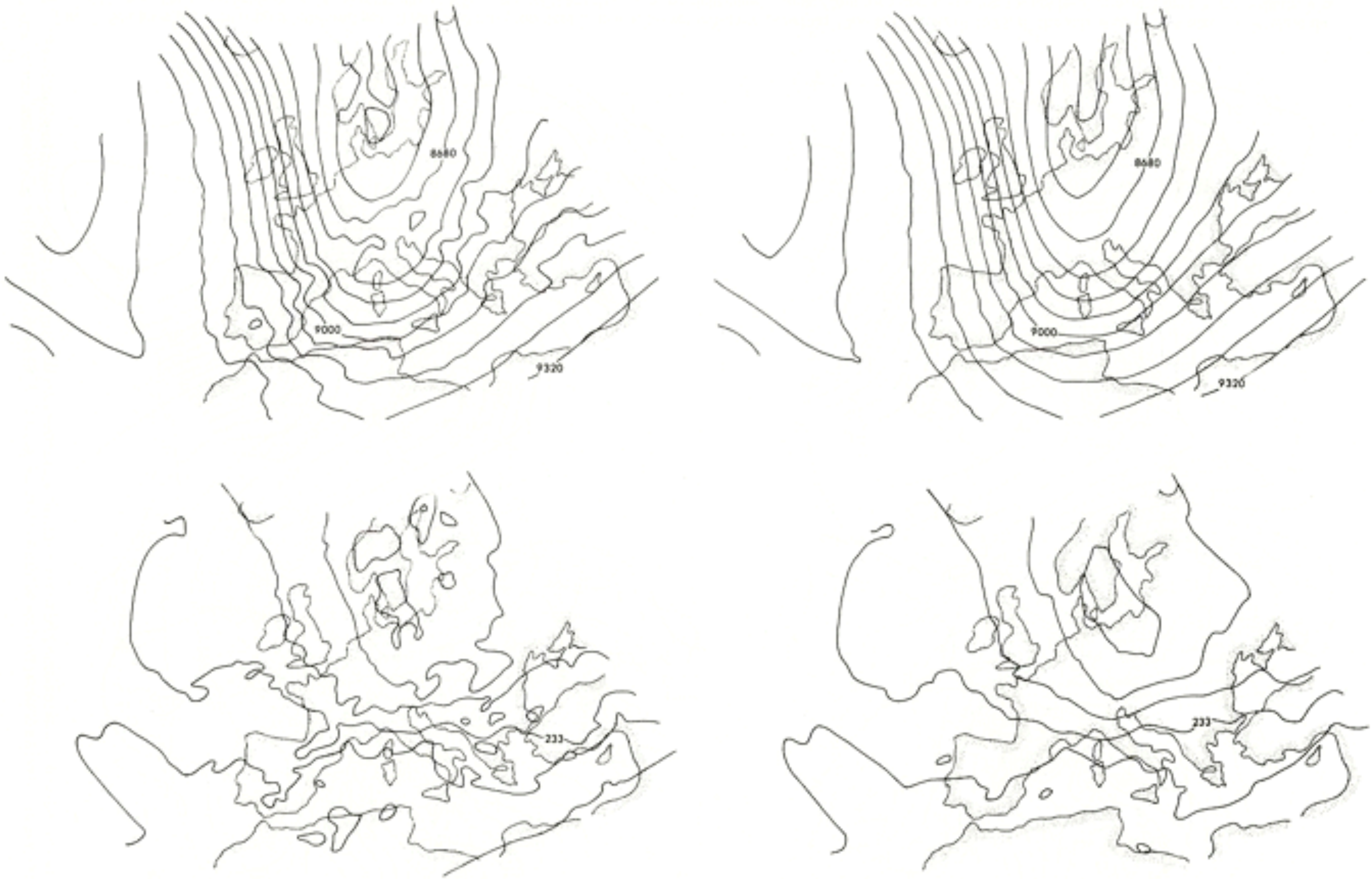

FIG. 6. 300 mb geopotential heights (upper panels) and temperatures (lower panels) obtained in 48 h simulations using the sigma system (left-hand panels) and the eta system (right-hand panels). Contour interval is 80 m for geopotential height and 2.5 K for temperature.

Some addressing precipitation scores, e.g.,

André Robert Memorial Volume:

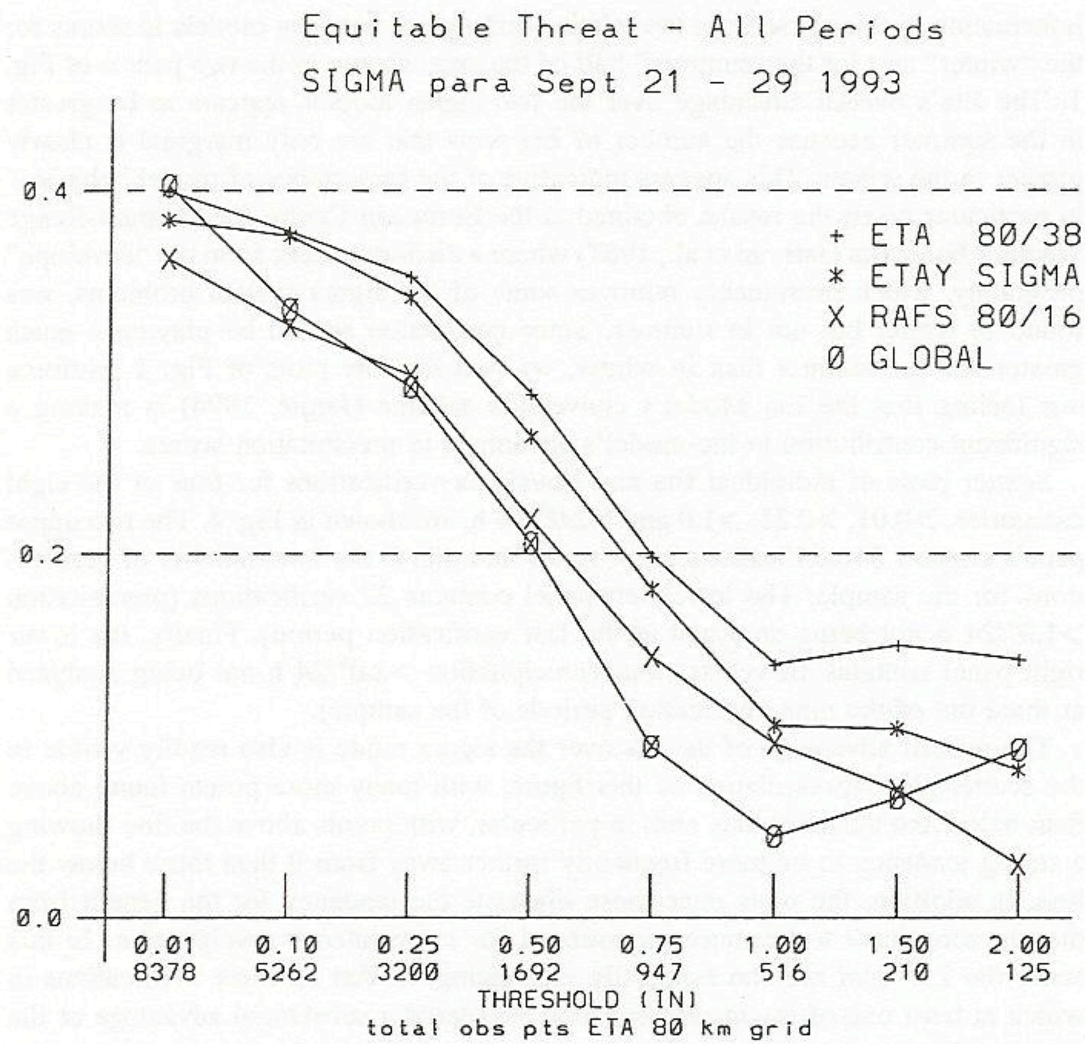

Fig. 3 Equitable precipitation threat scores for two versions of the Eta Model: Eta 80 km/38 layers ("ETA"), and the same version of the Eta Model but run using sigma coordinate ("ETAY"), and for the NGM (RAFS), and the Avn/MRF ("global") Model; for a sample of 16 forecasts verifying 1200 UTC 21 September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

Note also:

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

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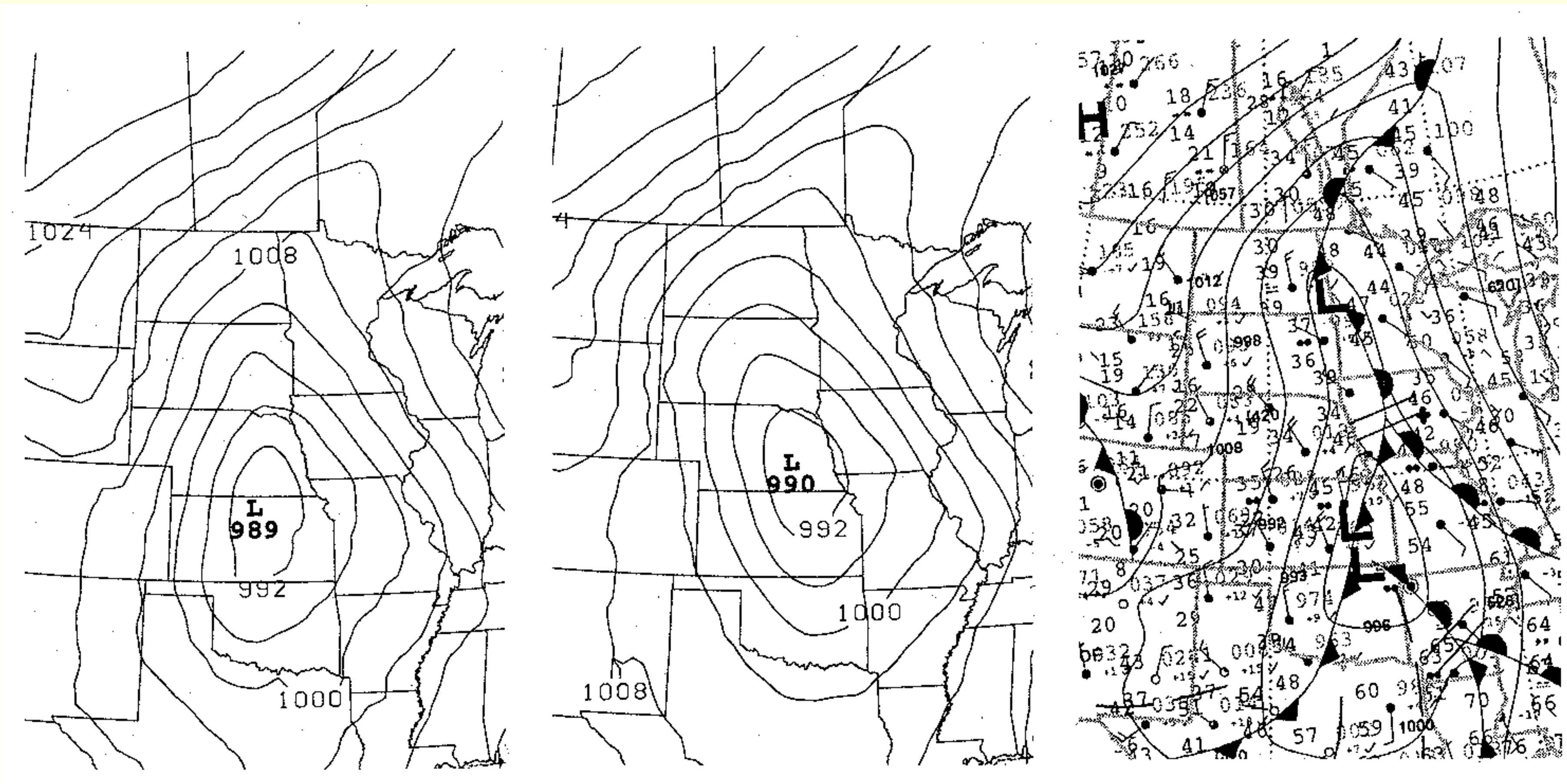
A number of tests on positions of low centers, such as in the lee of the Rockies… The most recent one:

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



~ Just as in earlier experiments at lower resolution

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

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

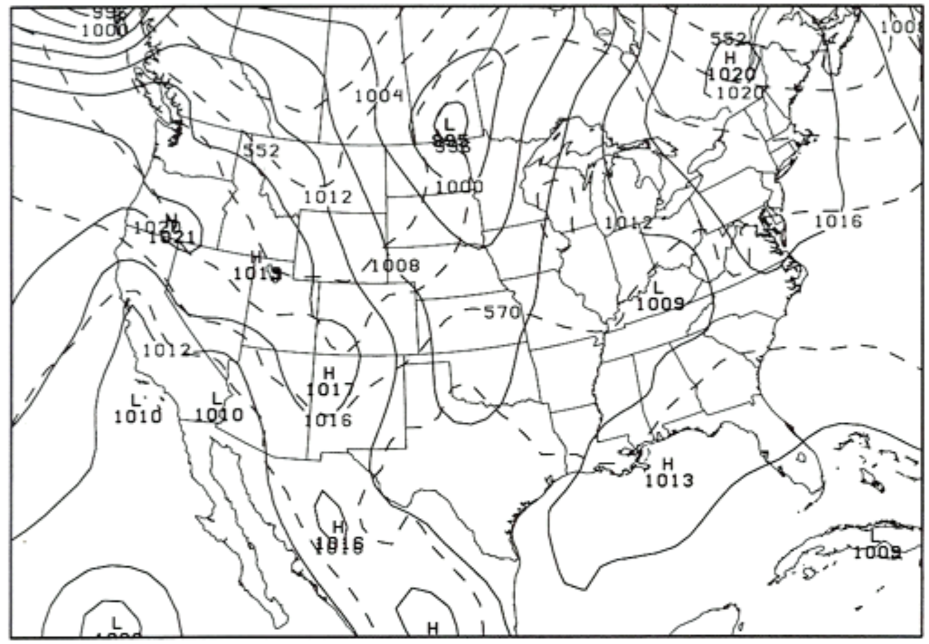
- The three low centers case;

The three low centers case

Valid at

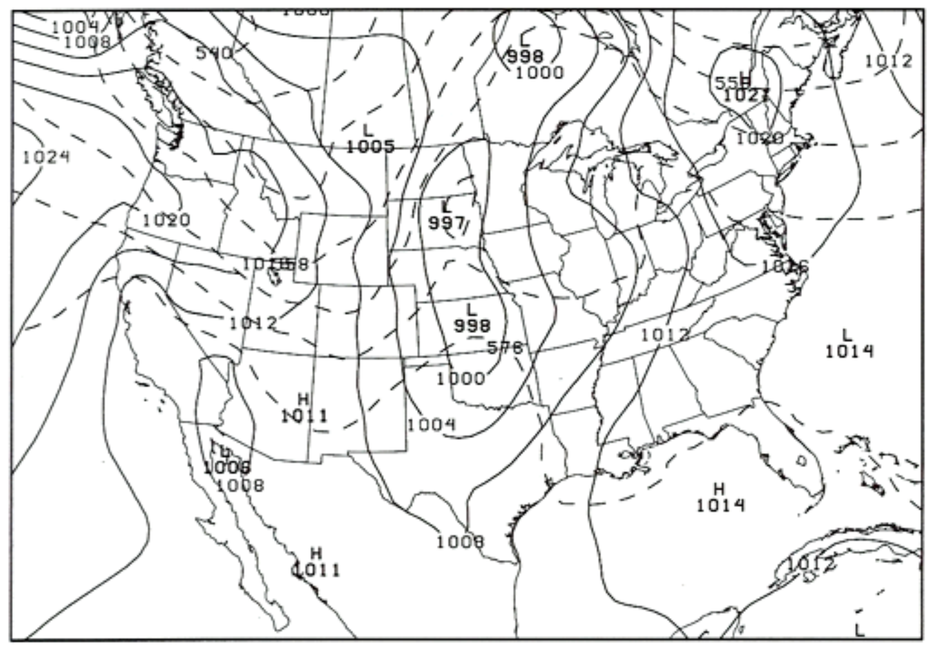
12z 18 September 2002

Avn



020918/1200V060 SFC MSLP & THCK -- AVN

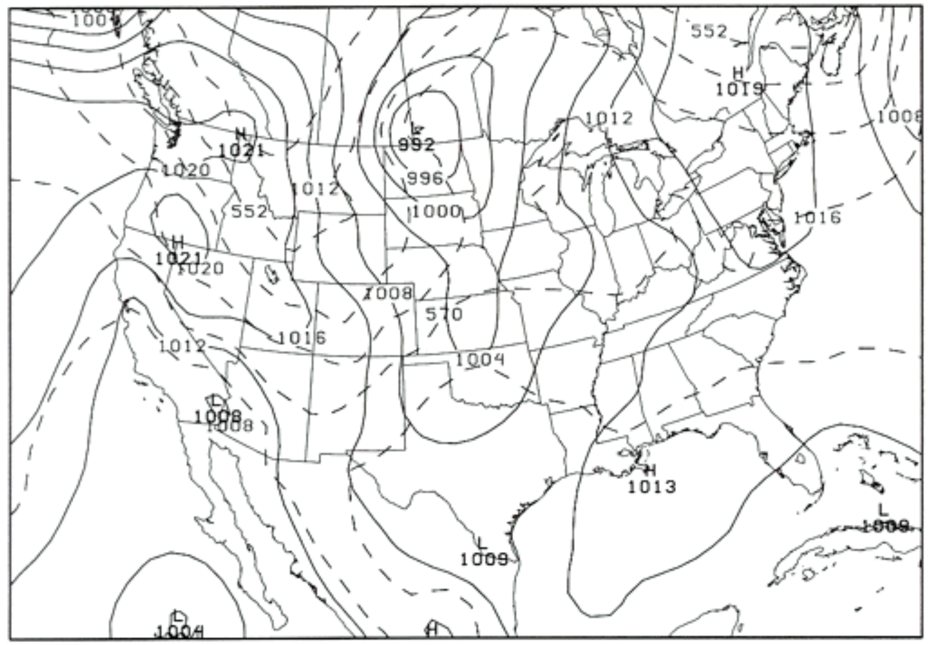
Eta



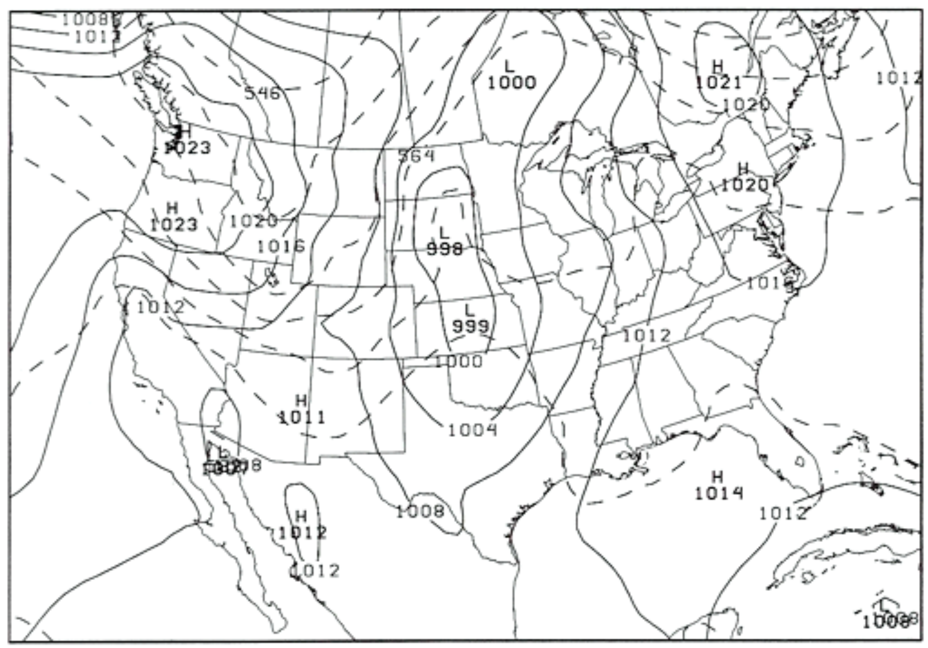
020918/1200V060 SFC MSLP & THCK -- ETA

60 h fcsts

Avn

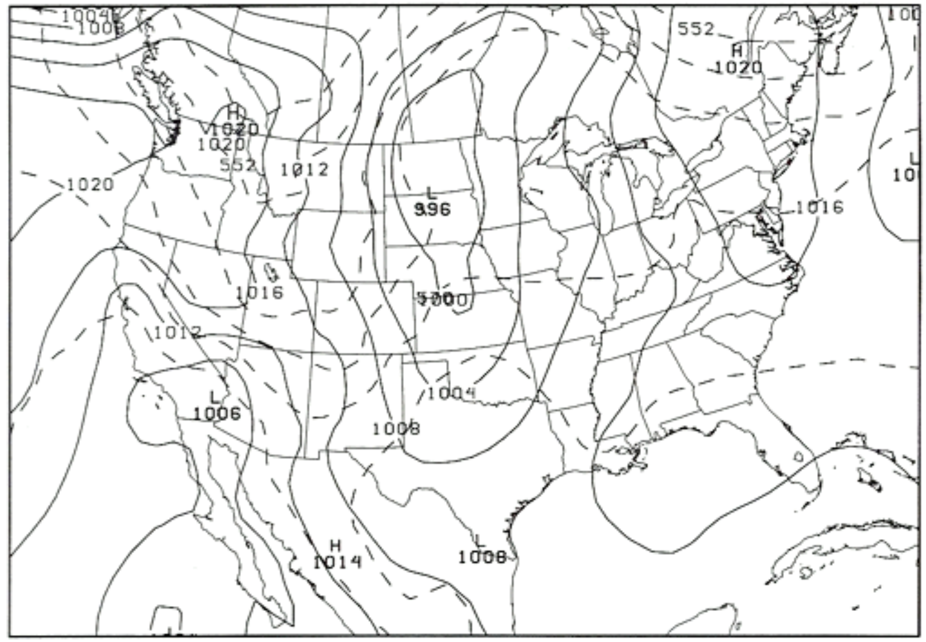


Eta



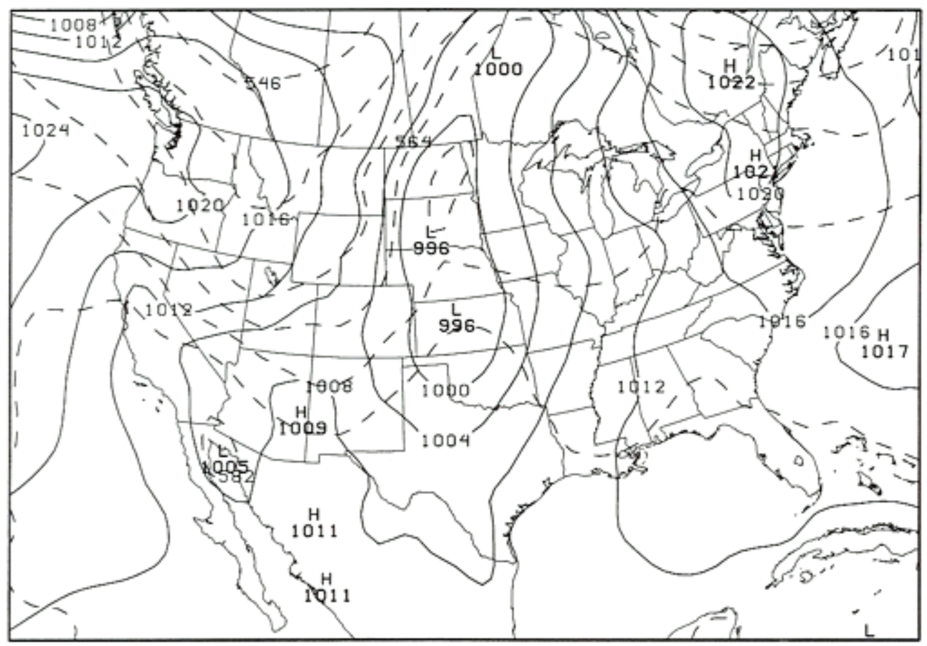
48 h fcsts

Avn



020918/1200V036 SFC MSLP & THCK -- AVN

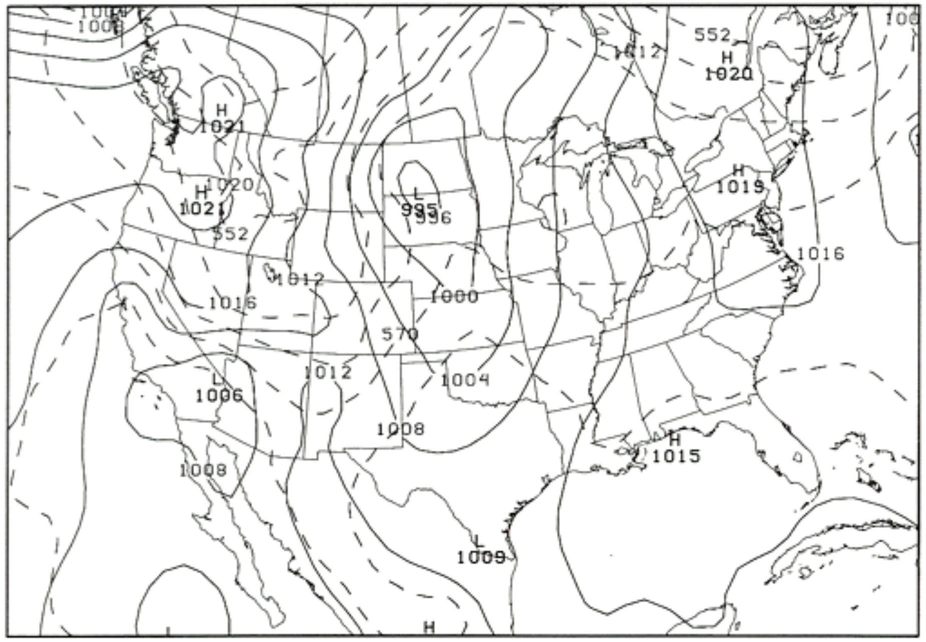
Eta



020918/1200V036 SFC MSLP & THCK -- ETA

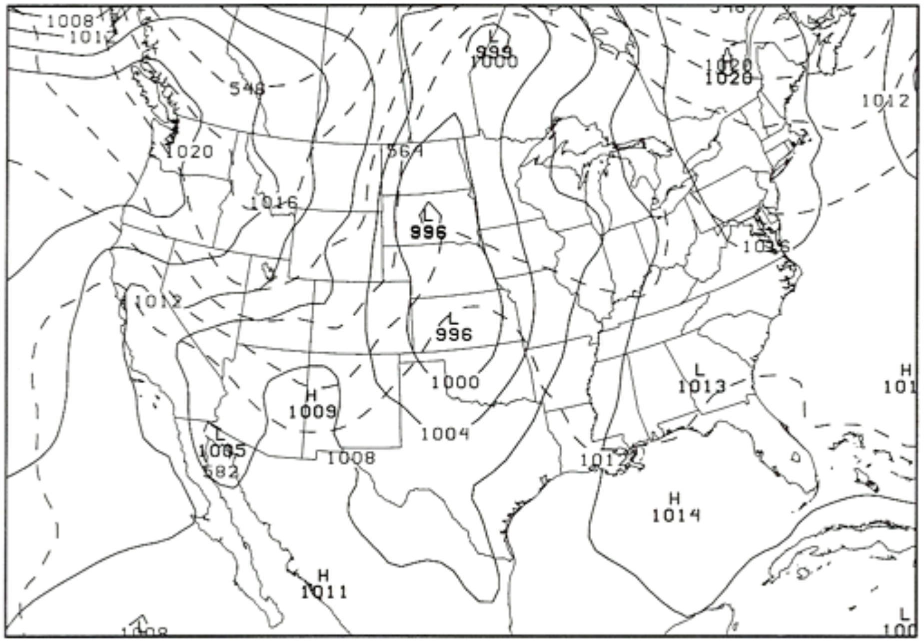
36 h fcsts

Avn



020918/1200V024 SFC MSLP & THCK -- AVN

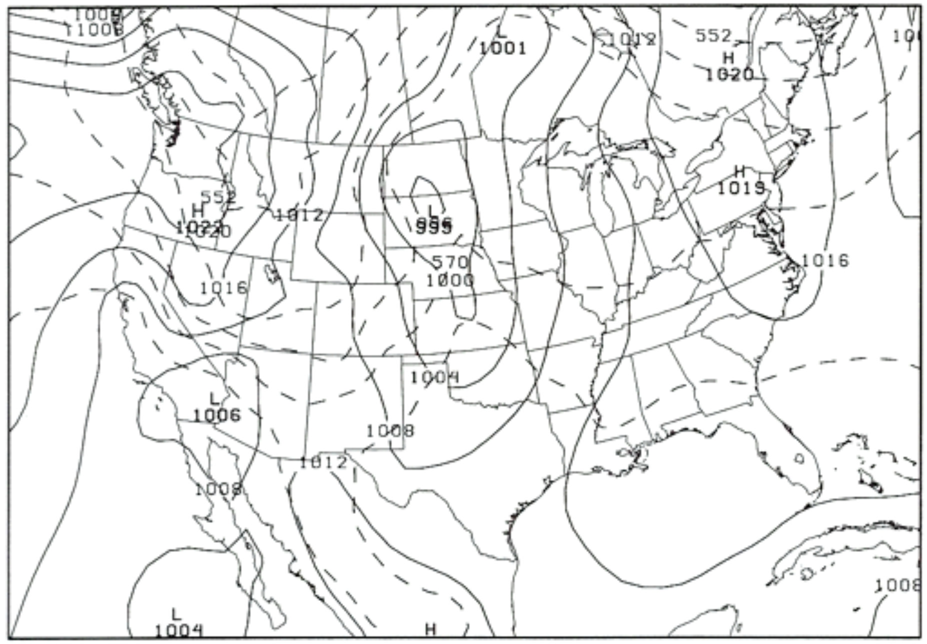
Eta



020918/1200V024 SFC MSLP & THCK -- ETA

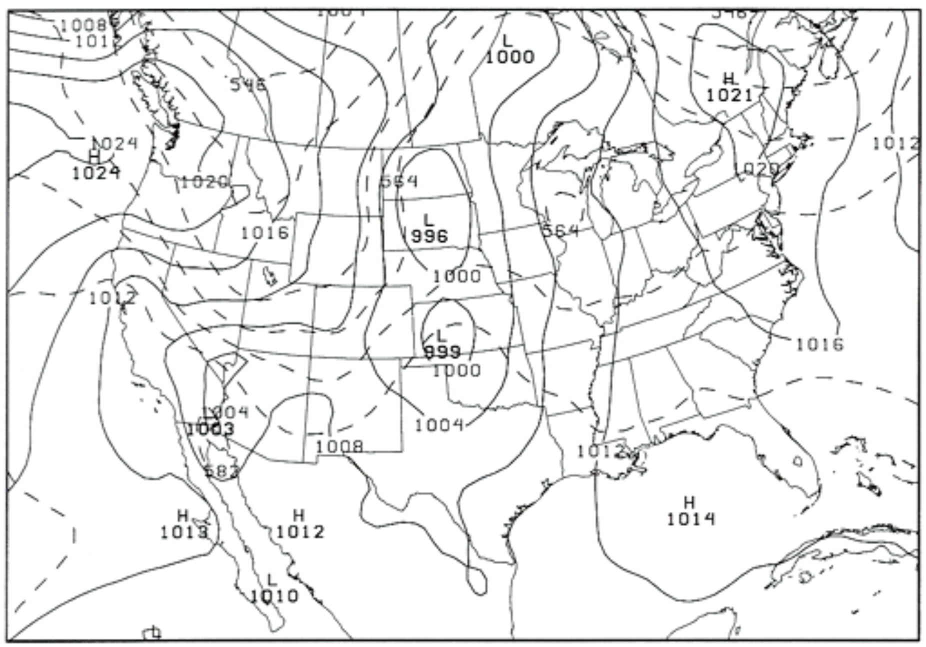
24 h fcsts

Avn



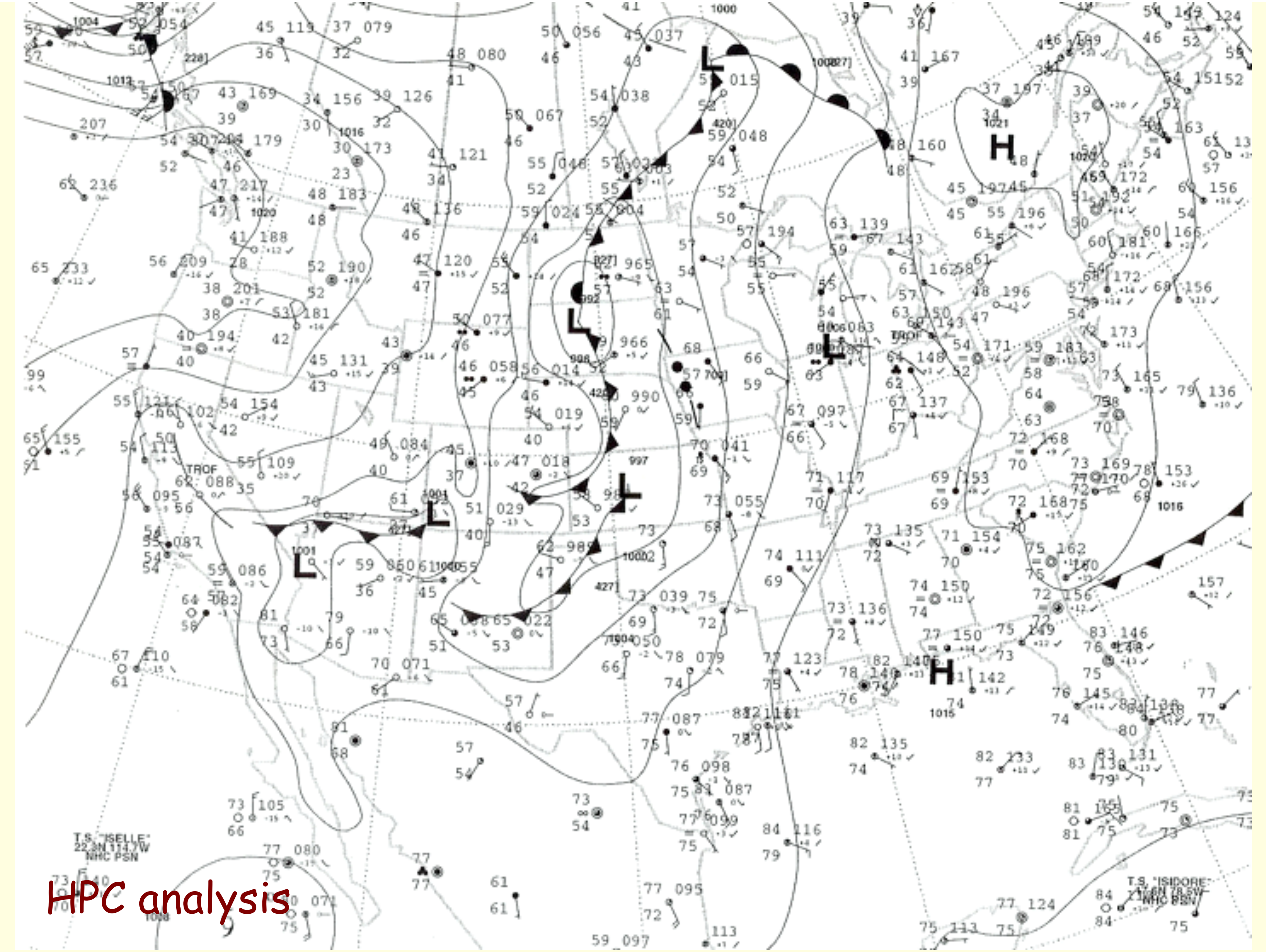
020918/1200V012 SFC MSLP & THCK -- AVN

Eta

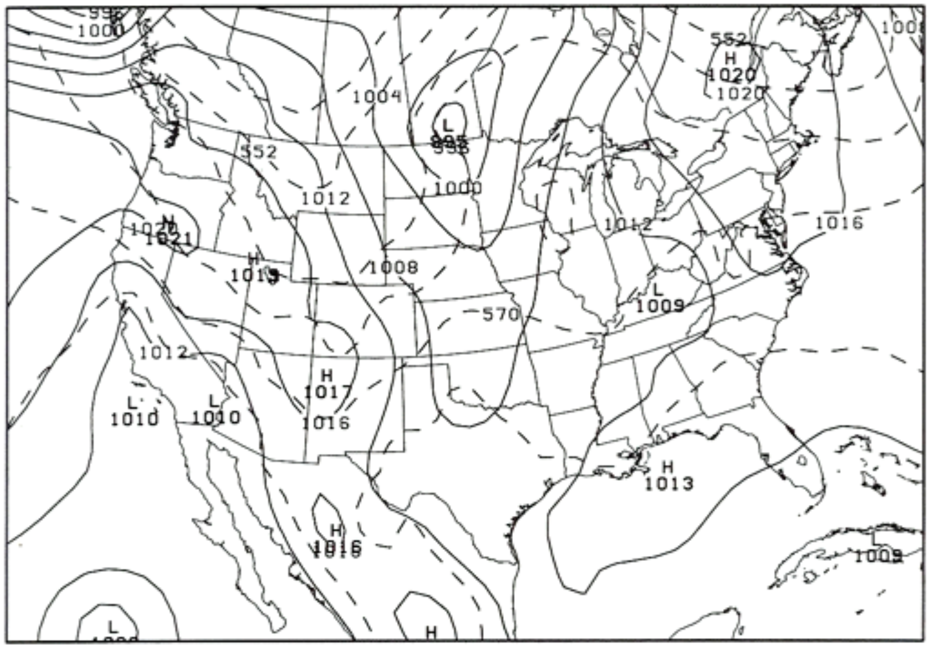


020918/1200V012 SFC MSLP & THCK -- ETA

12 h fcsts

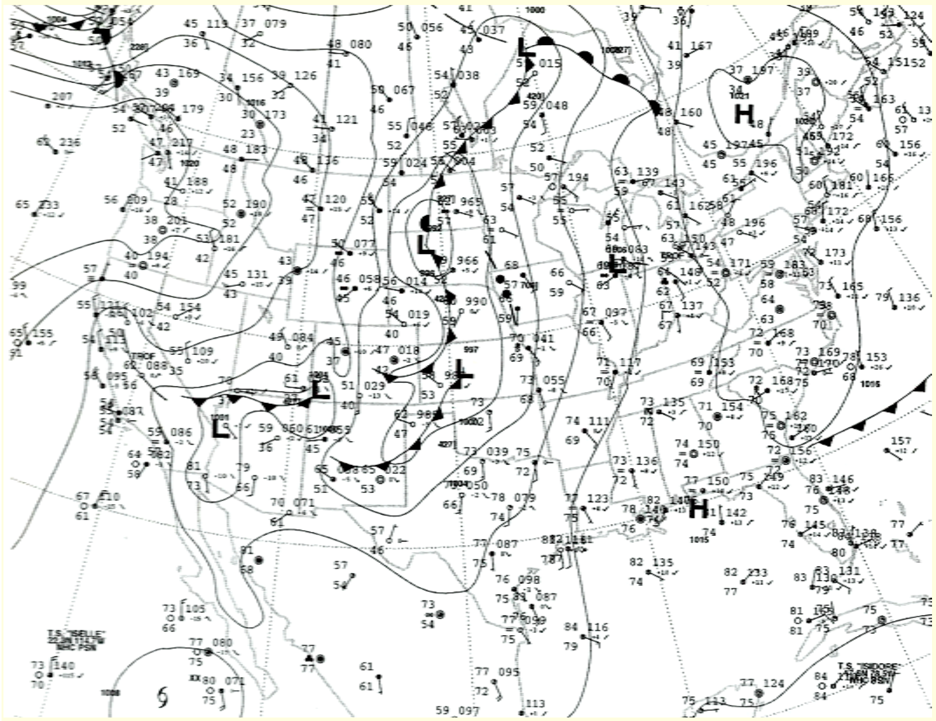


HPC analysis

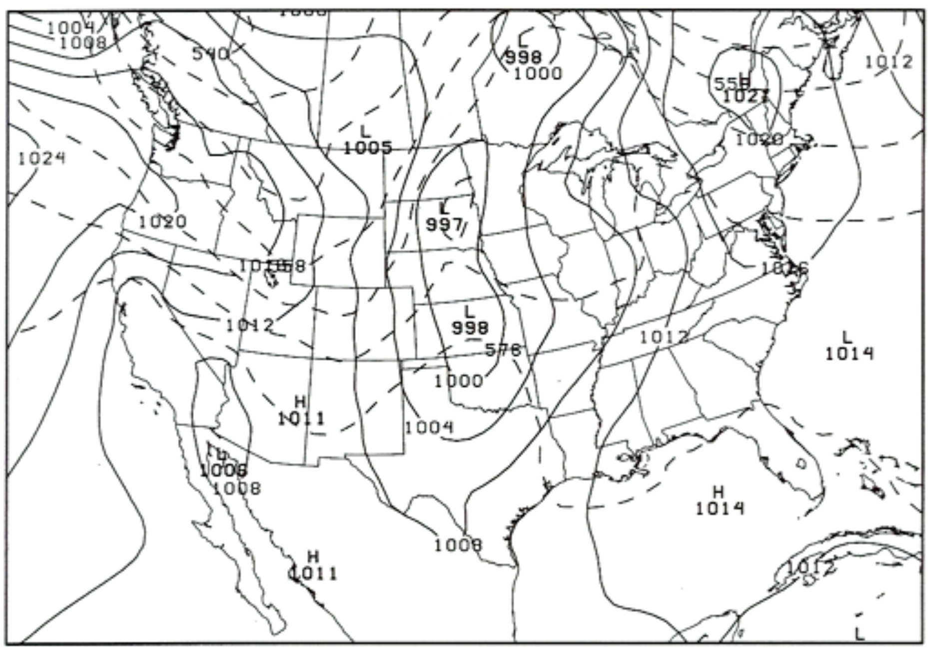


020918/1200V060 SFC MSLP & THCK -- AVN

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)

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

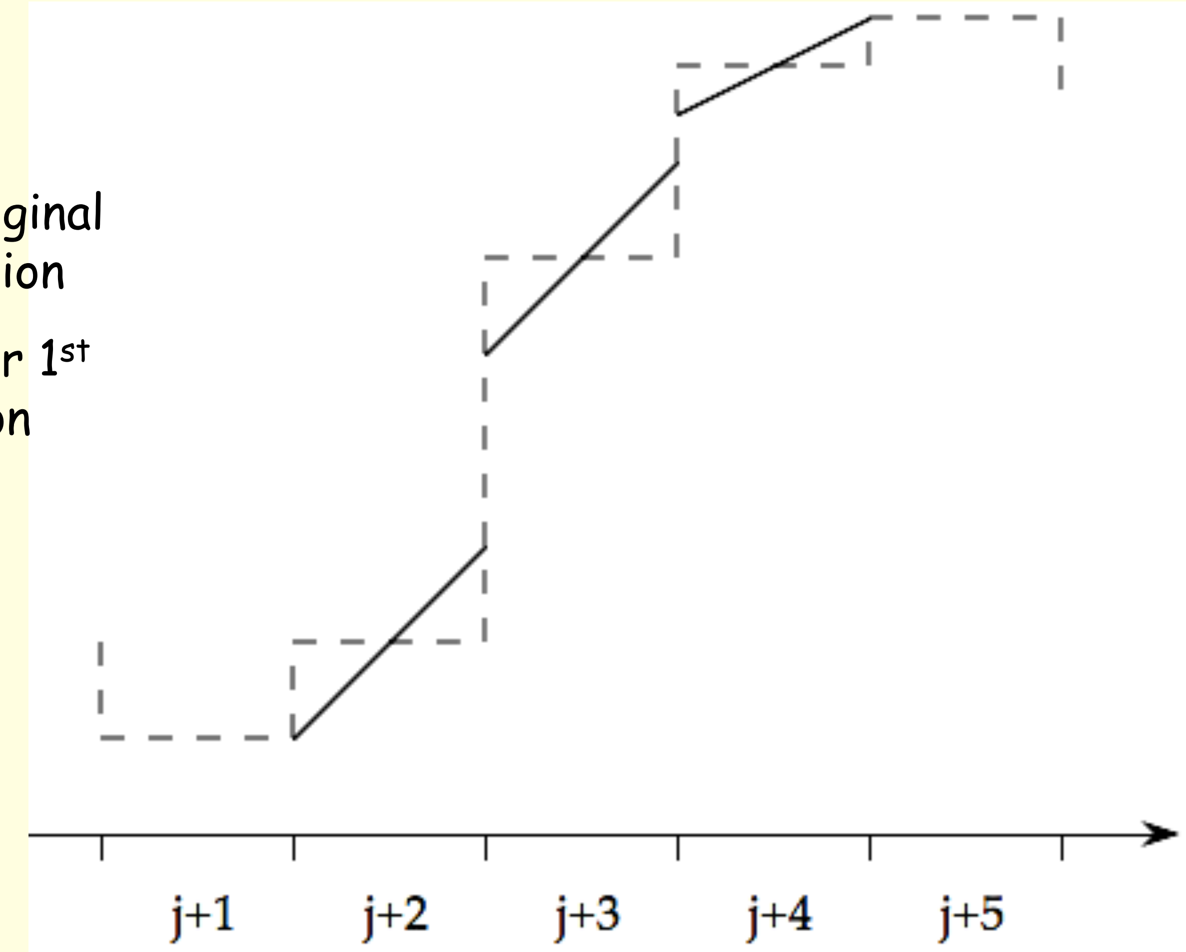


Figure 1. An example of the Eta iterative slope adjustment algorithm. The initial distribution is illustrated by the dashed line, with slopes in all five zones shown equal to zero. Slopes resulting from the first iteration are shown by the solid lines. See text for additional detail.

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:

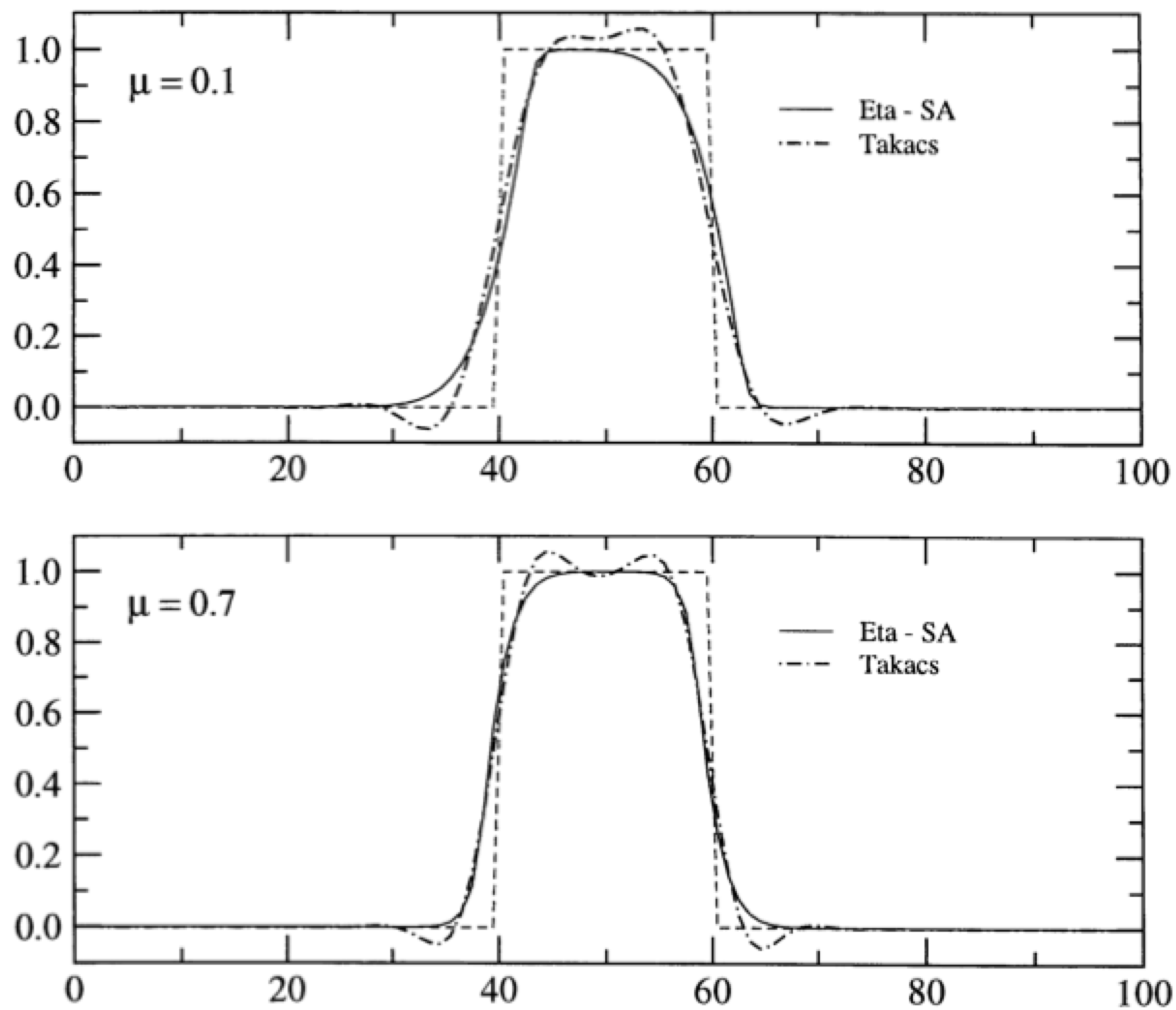


Figure 9. Same as Fig. 2, except for the Eta slope-adjustment scheme results (SA, solid line) compared against those using the Takacs (1985) third-order "minimized dissipation and dispersion errors" scheme (dot-dashed line). See text for definitions of schemes.

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.

"Finite-volume +"

Summary:

Eta dynamical core presumably strongest features:

- The quasi-horizontal eta coordinate surfaces;
- Finite-volume + approach in dynamics whereby in many respects grid point values are treated as cell averages, same as we do in "physics"

An upgraded Version of the Eta Model

Fedor Mesinger [1], Sin Chan Chou [2], Jorge Gomes [2],
Dusan Jovic [3], Lazar Lazic [4], André Lyra [2],
Josiane Bustamante [2], Paulo Bastos [5],
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6)Univ. Modena and Reggio Emilia, Modena, Italy

7)Weather2Umbrella Co., Belgrade, Serbia

EGU Assembly, Vienna, 8 April 2011

Why eta (or any other system with quasi-horizontal or horizontal surfaces, e.g., z)?

With terrain-following coordinates there is no solution for the PGF problem

Upgrades compared to NCEP "Workstation Eta" (contains the Janjic (2003) nonhydrostatic option as used in NCEP's NMM):

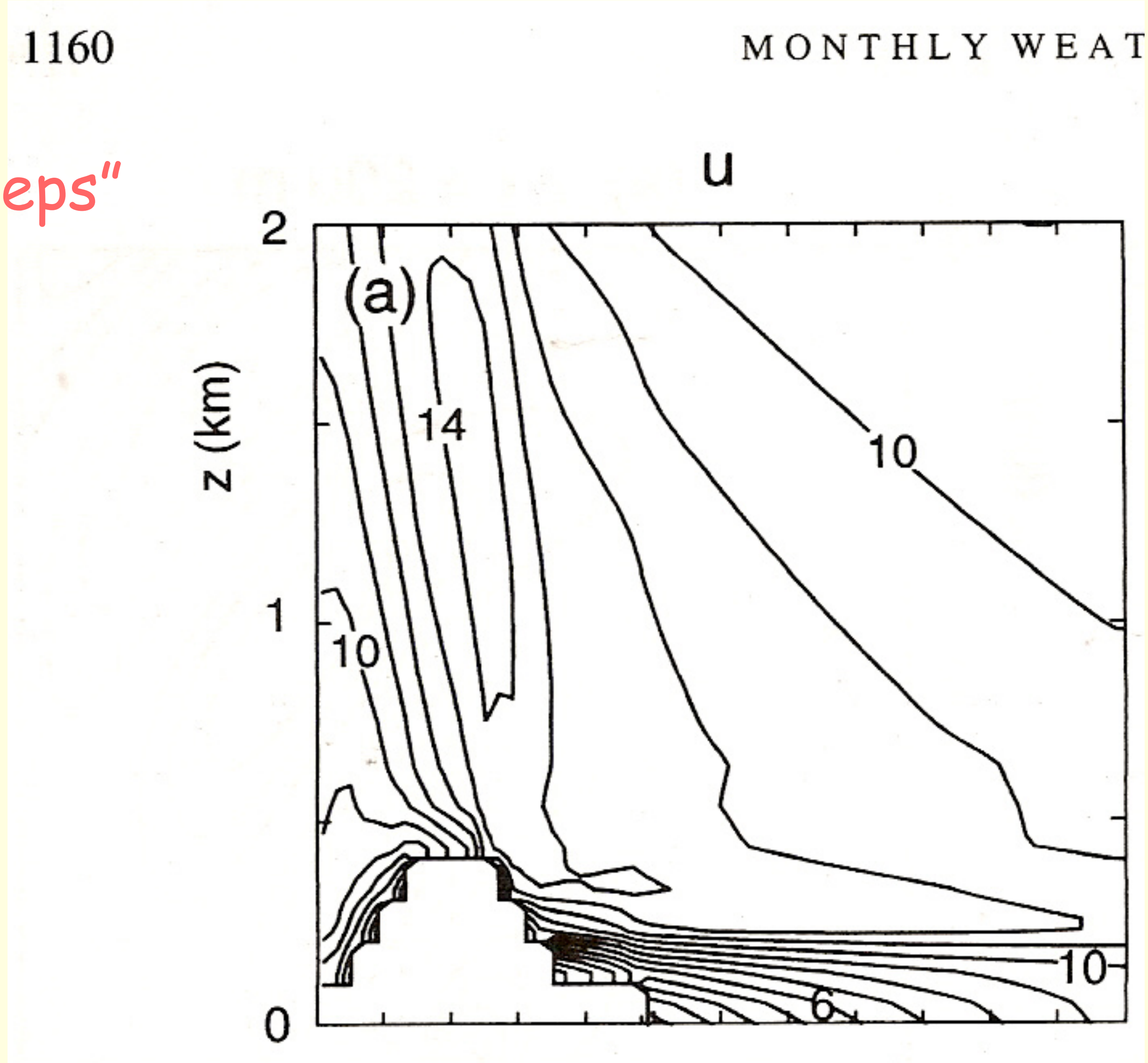
- "Sloping steps";
- Piecewise linear vertical advection of **v**, T;
- Code refinements involving near surface winds and calculation of surface exchange coefficients;
- Conservation in the vertical diffusion;
- Water vapor sources and sinks and hydrometeor loading;
- Betts-Miller-Janjic convection adjustments;
- Momentum transport with the Kain-Fritsch scheme;
- Molecular sublayer thickness using the suggestion of Brutsaert (1982) and his summary of experimental data

Examples of successful overall performance:

- Hindcasts of severe downslope zonda winds;
- RCM ensemble experiments driven by ECMWF 32-day ensemble members (Veljovic et al. 2010)

Code available at http://etamodel.cptec.inpe.br/

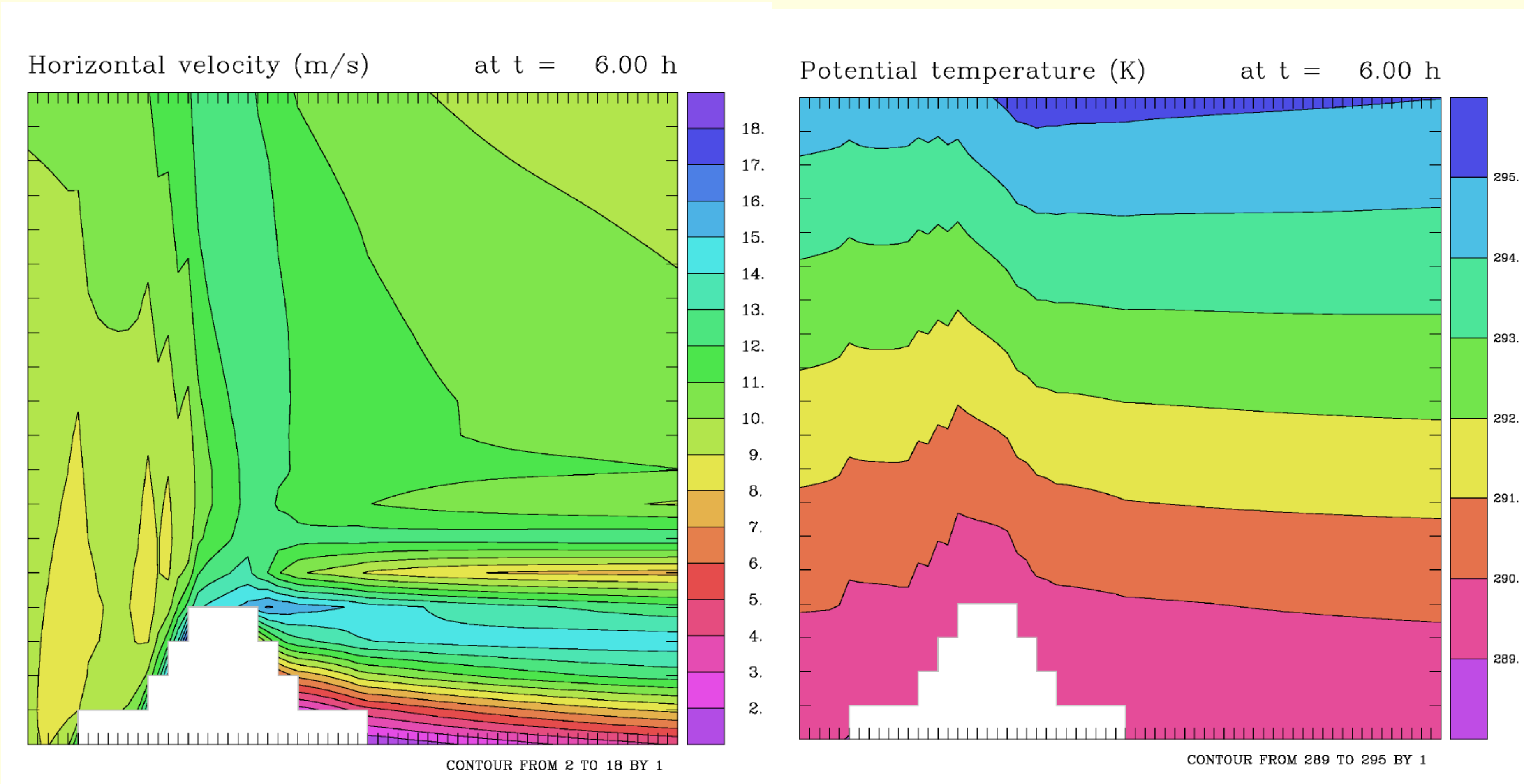
- "Sloping steps"



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

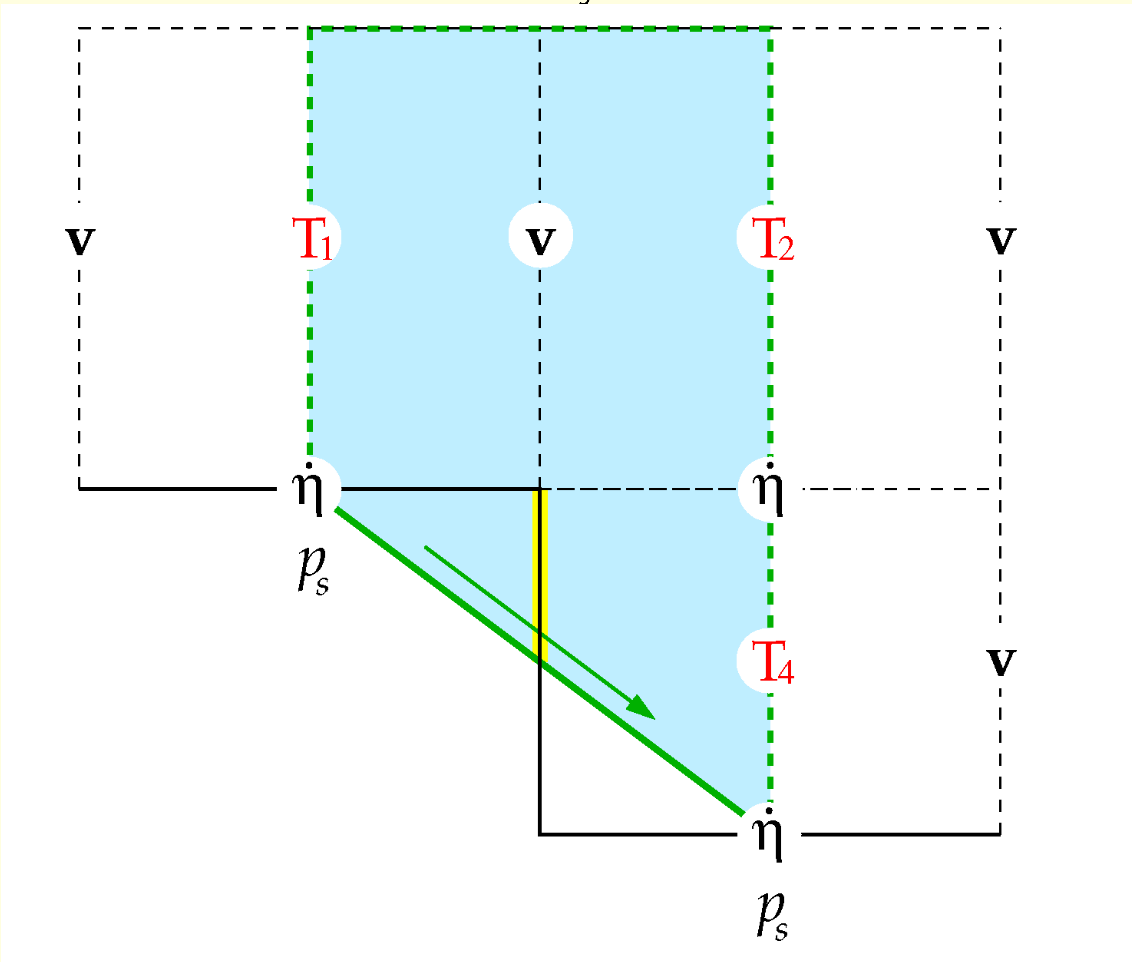
("Witch of Agnesi" mountain)

Emulation using recent Eta code (hydrostatic):



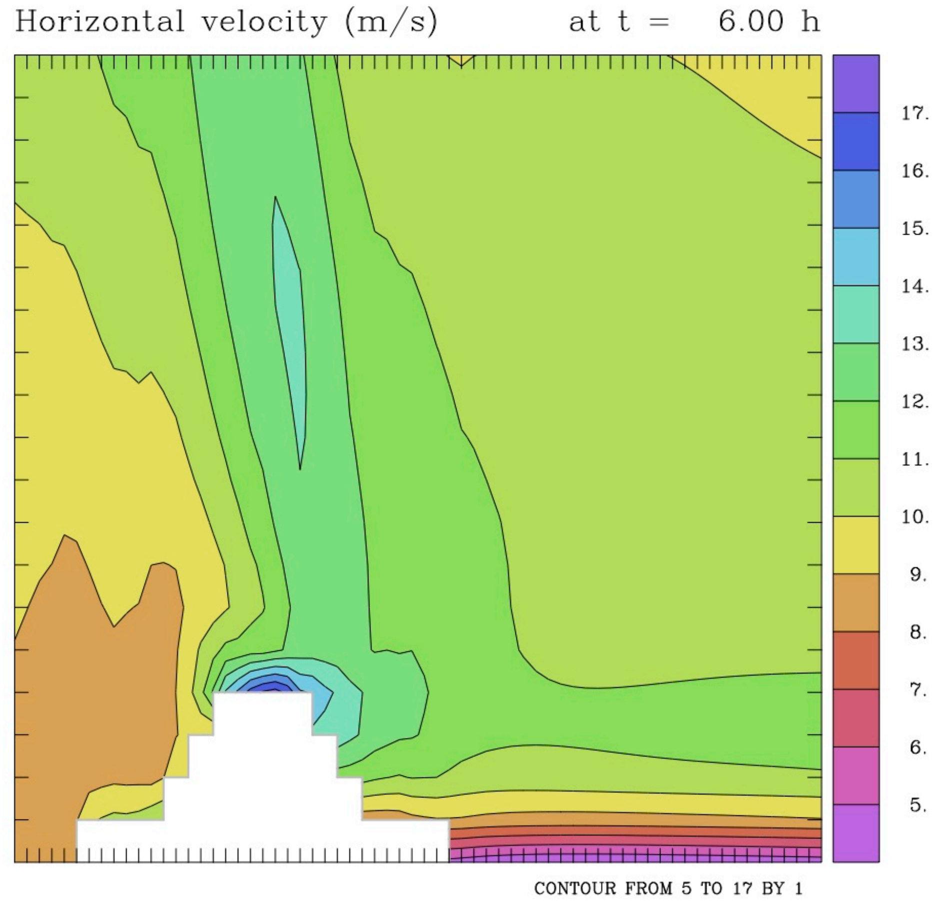
The sloping steps, vertical grid

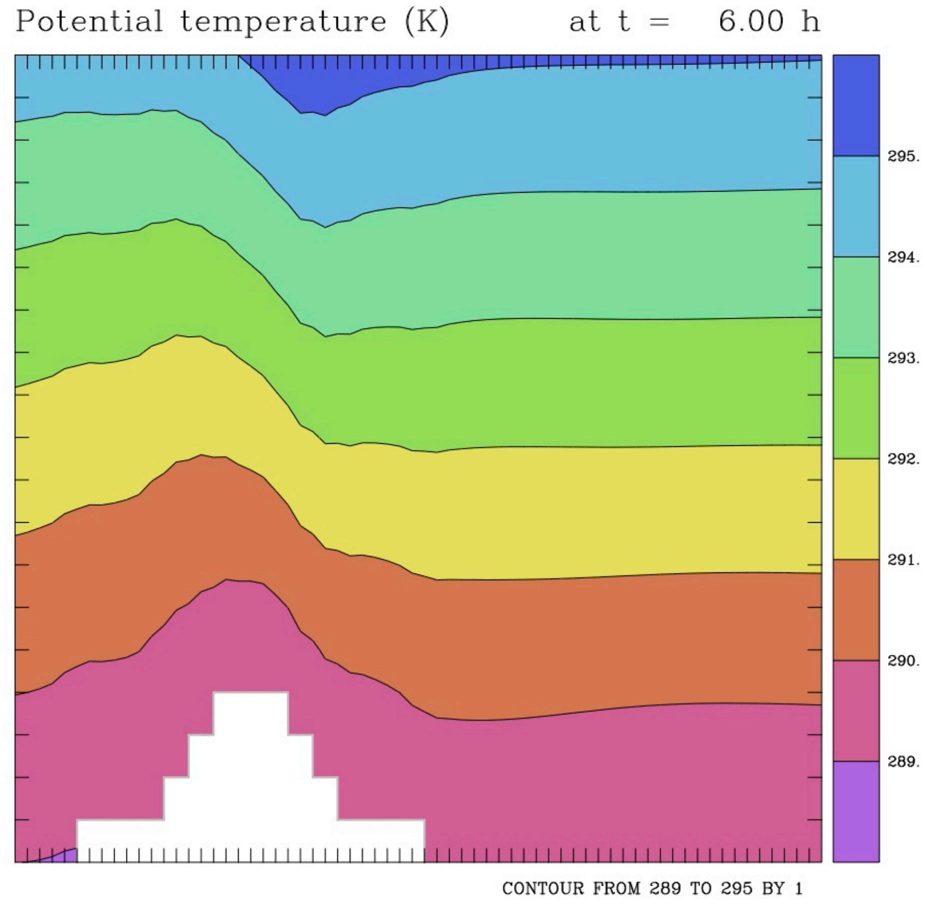
The central **v** box exchanges momentum, on its right side, with **v** boxes of two layers:



Also: slantwise T advection

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





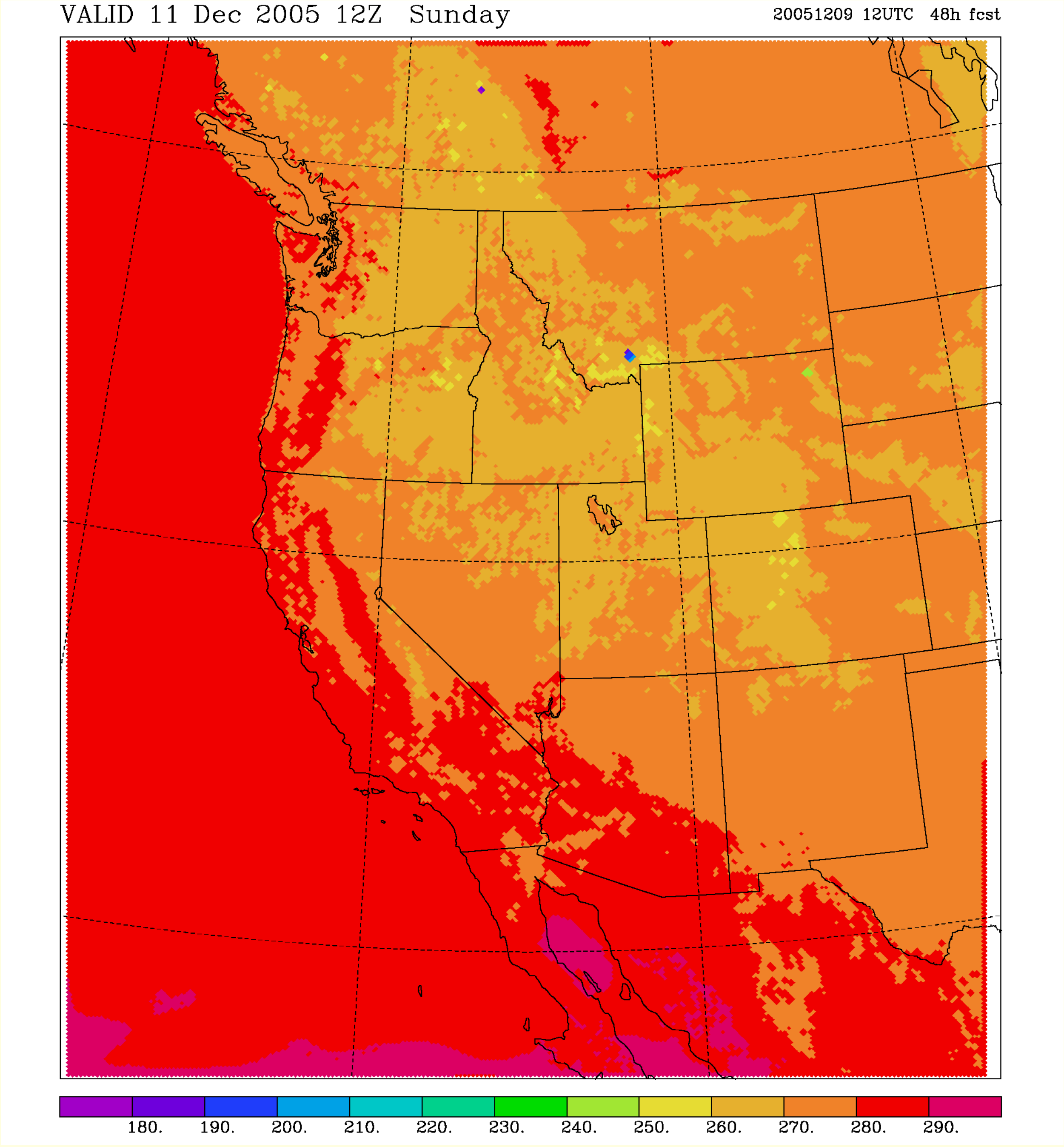
Velocity at the ground immediately behind the mountain increased from between 1 and 2, to between 4 and 5 m/s. "lee-slope separation" much reduced. Zig-zag features in isentropes at the upslope side removed.

- Piecewise linear (finite-volume) vertical advection of **v**, T

(as in Mesinger and Jovic 2002)

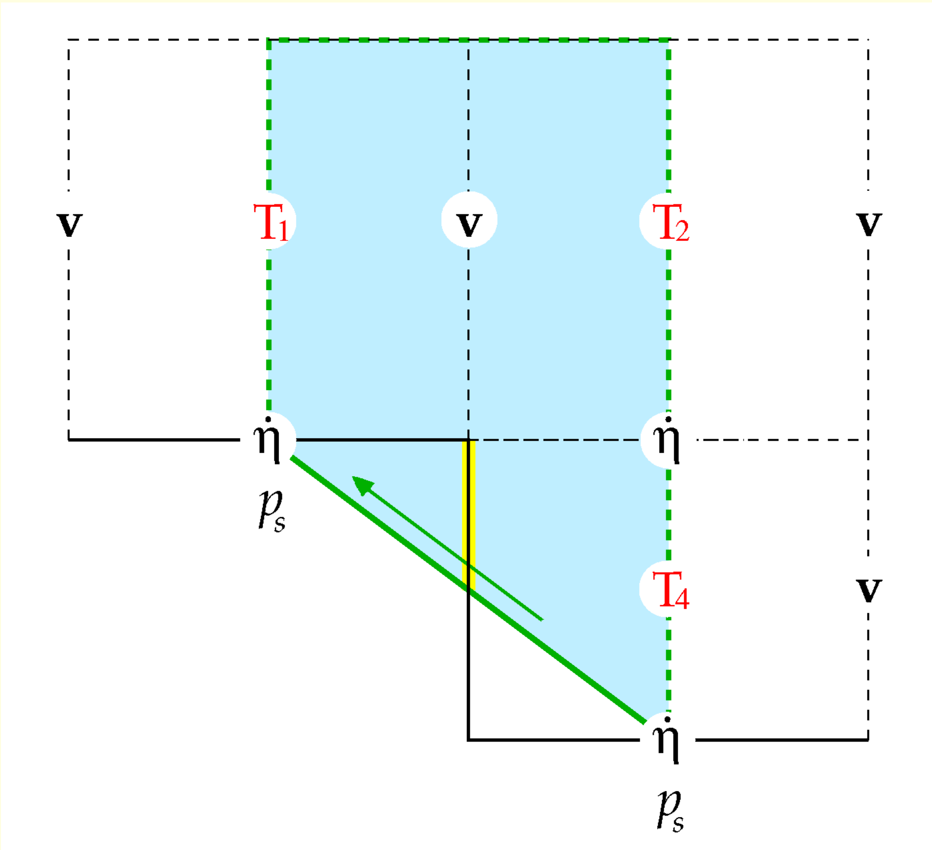
Motivation: result obtained with an earlier version of the sloping steps code:

Lowest layer temperature, 48 h fcst



8 km, 60 lyr resolution

Slantwise T advection between boxes 1 and 4:



The scheme used:

[Lorenz-Arakawa (?) "the green book", p. 222]

centered vertical advection:

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

A problem: false advection possible from below ground !

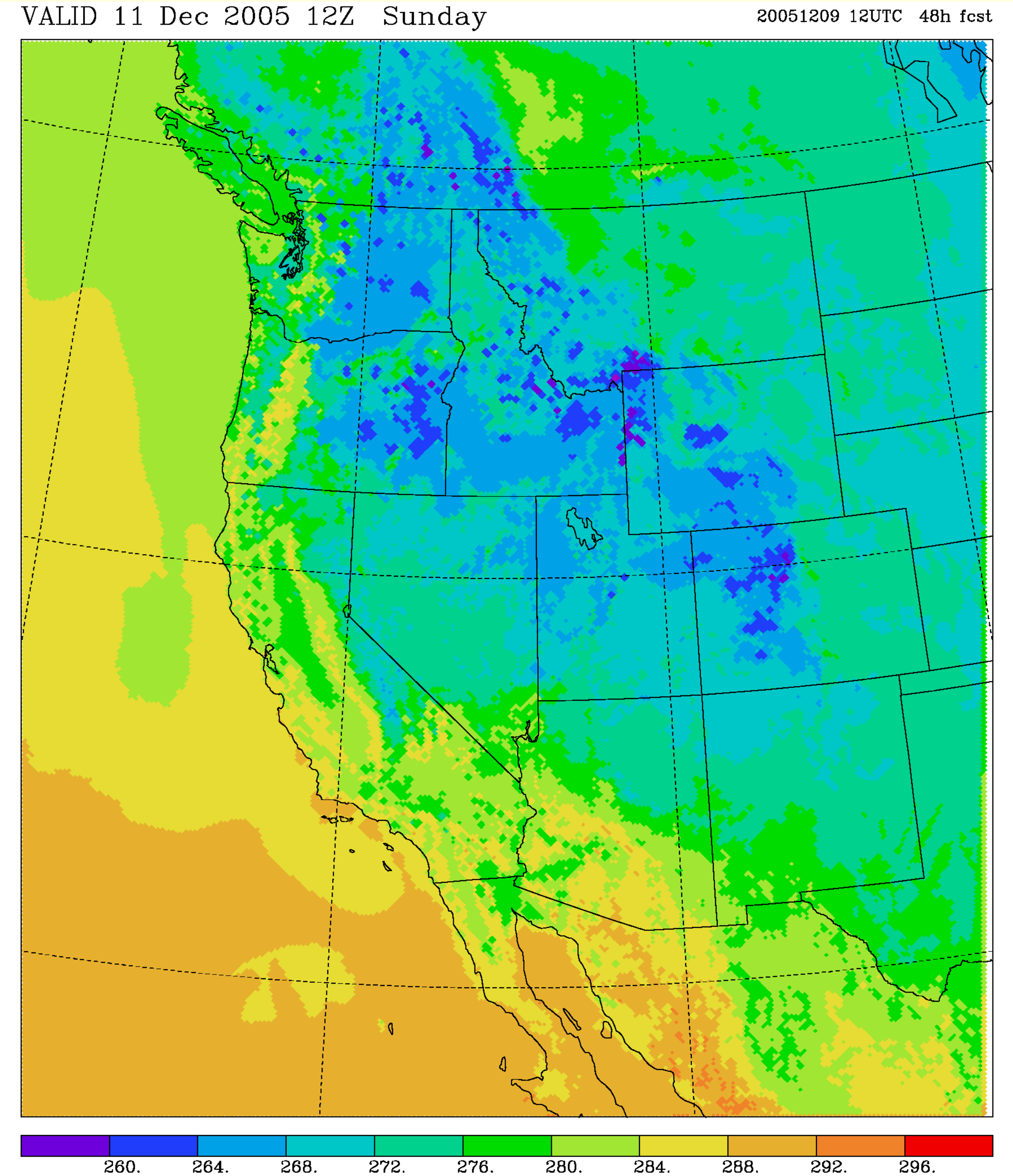
If a slantwise inversion happens along with upward velocity, inversion will grow, feeding on this false advection :(

Replaced by strictly conserving Lagrangian scheme

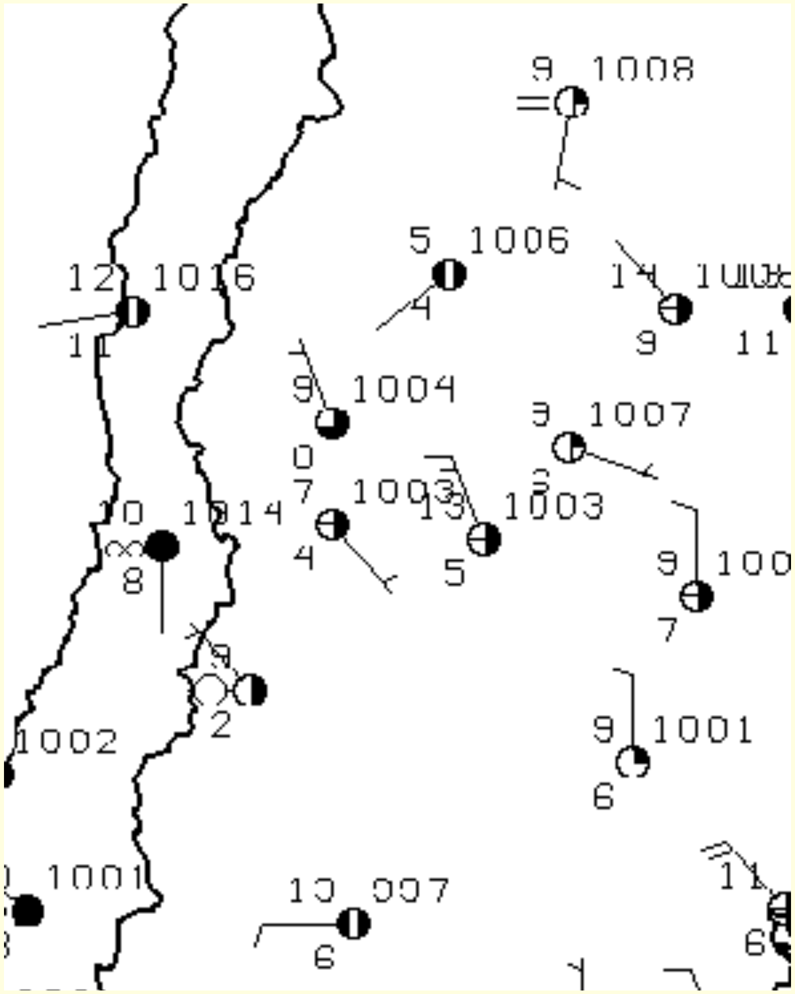
(we know the slantwise velocity);

Replaced by strictly conserving Lagrangian scheme

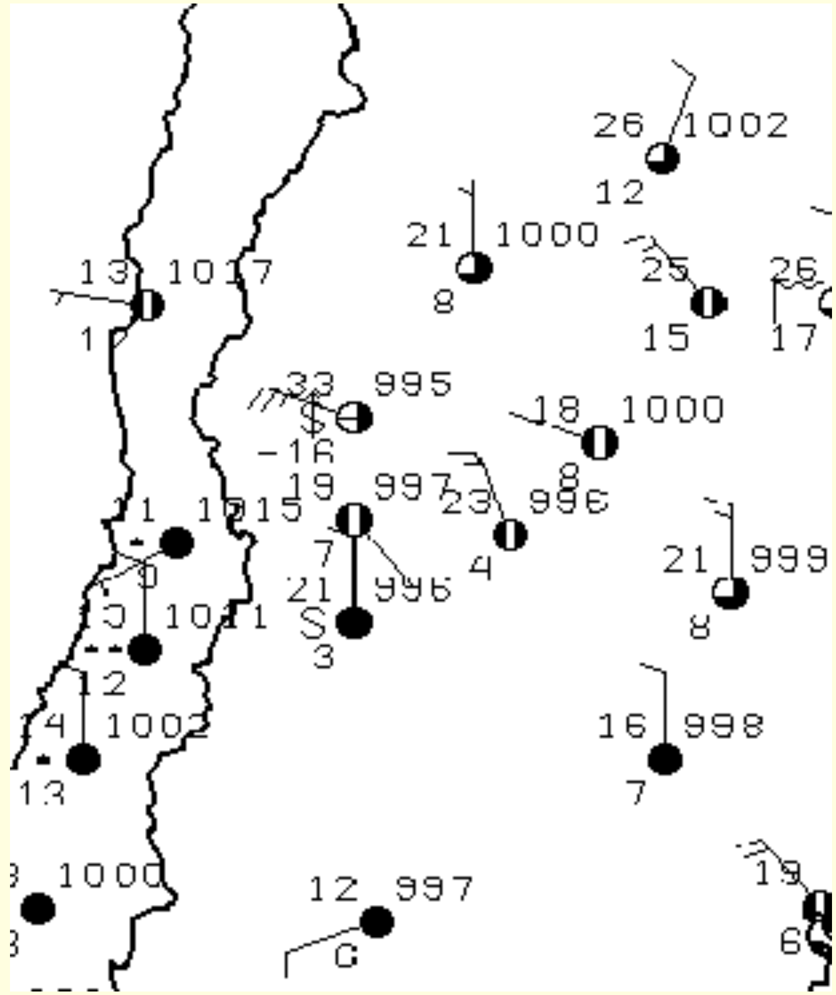
(we know the slantwise velocity);



Performance in a zonda downslope windstorm case



1200 UTC 11 July 2006



1800 UTC 11 July 2006

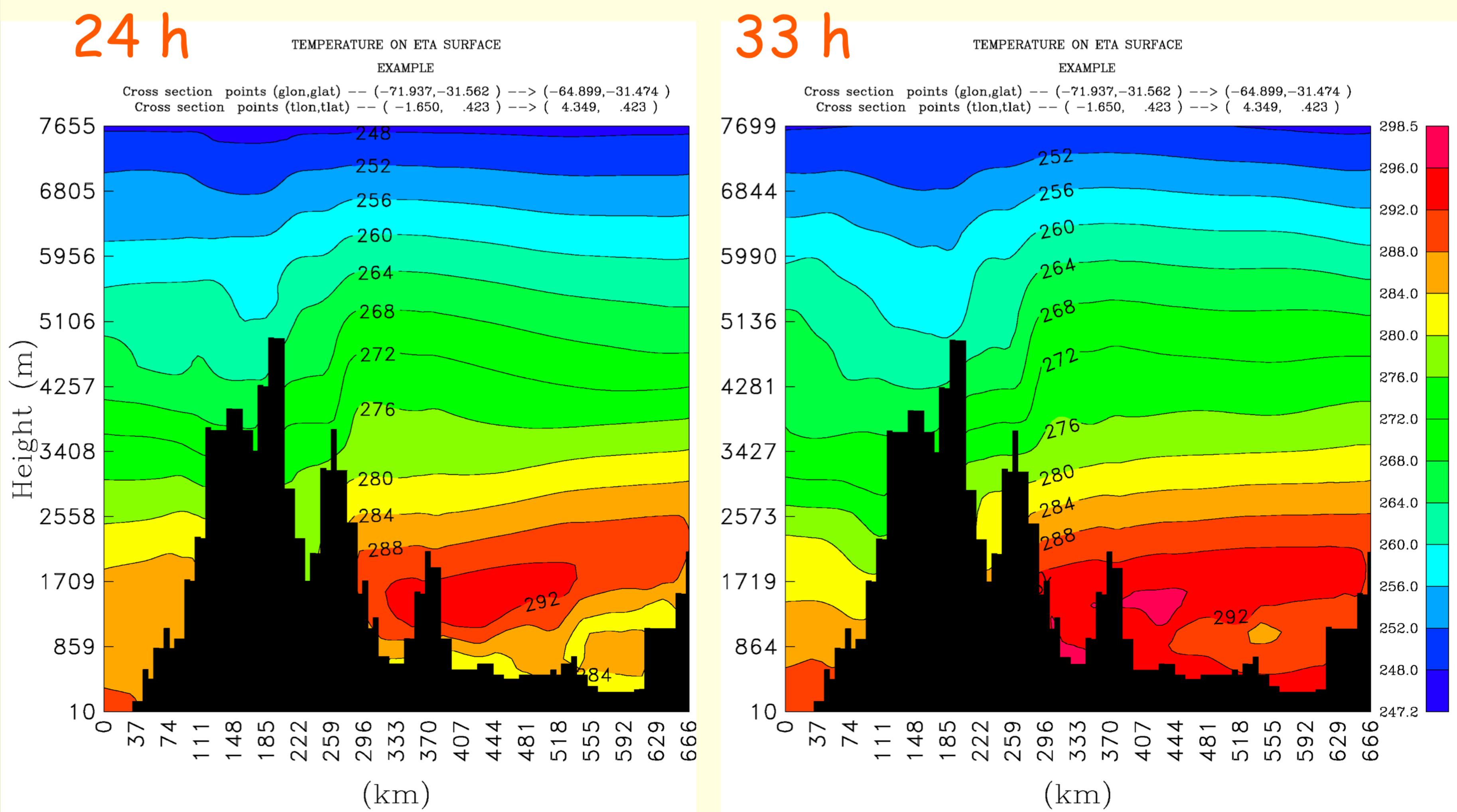
Note the station San Juan with the 2 m T increase from 9 to 33°C in 6 hours !

The Zonda Case of the 11-12 July 2006

Acknowledgement:

. . .

Initial condition: 1200 UTC 10 July 2006



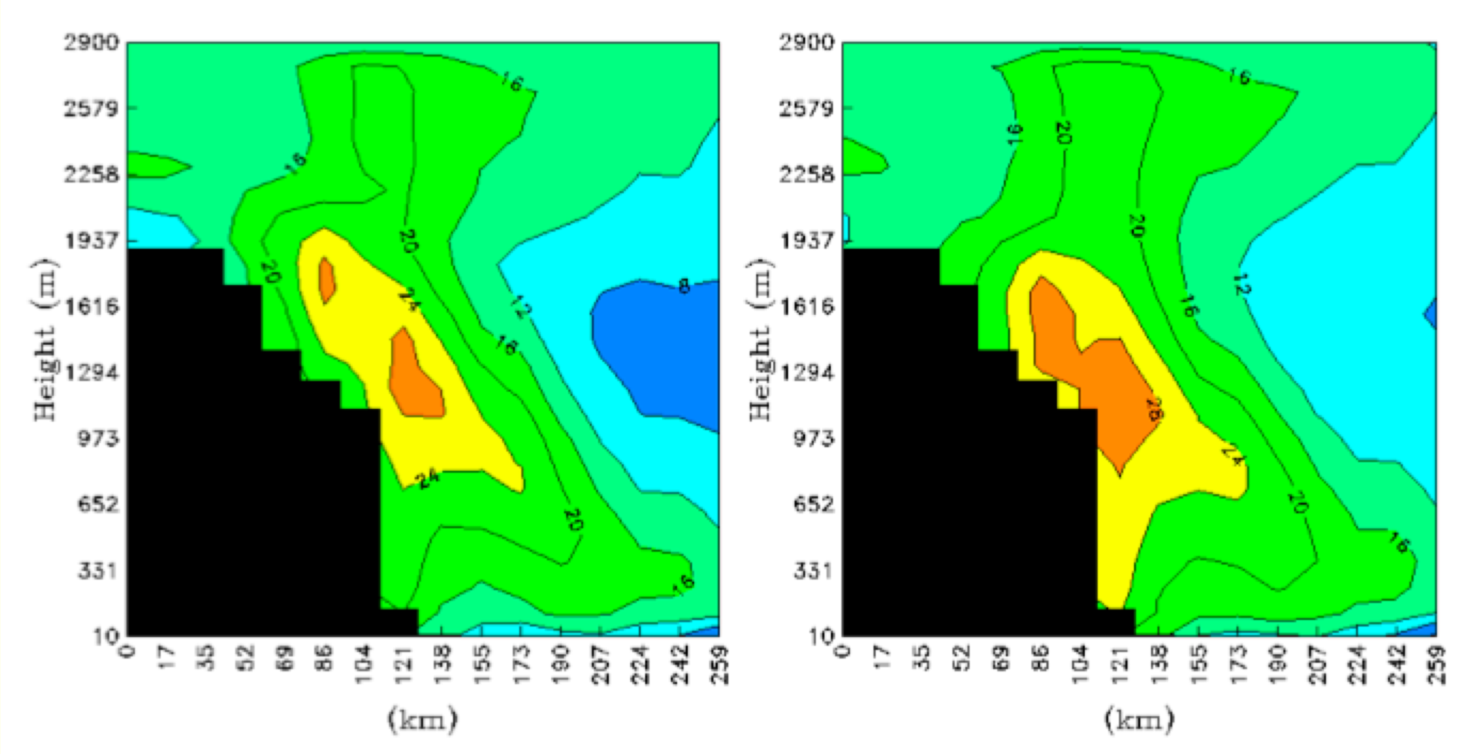
T change in the San Juan area from < 284 K to > 296 K !

Domain size and resolution as on slide 9 (resolution 8 km/60 layer)

- Near surface winds and calculation of surface exchange coefficients

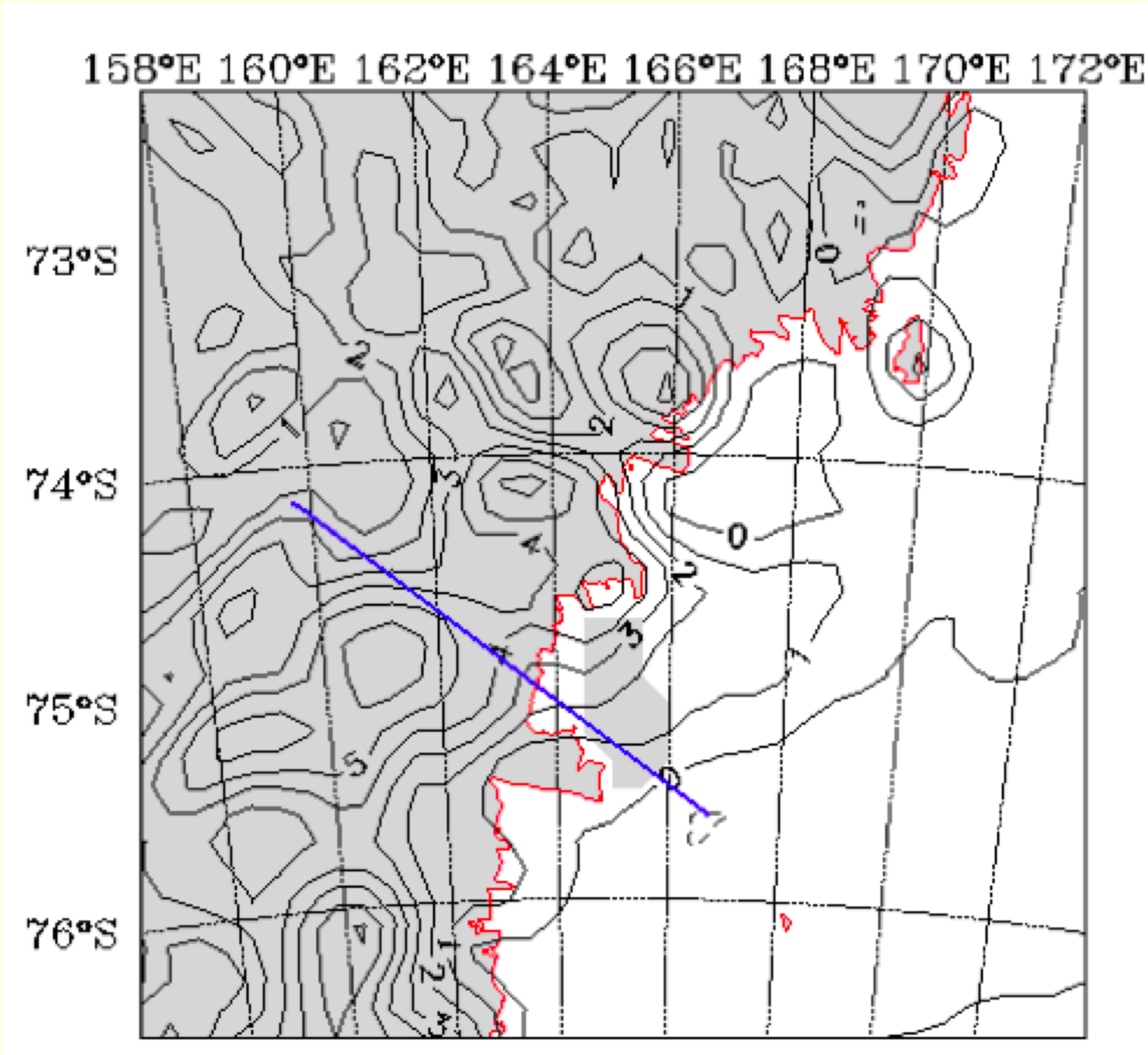
Four point averaging to obtain winds at h points, including blocked winds; used to calculate surface exchange coefficients

Impact, including that of sloping steps; wind speed cross section, before and after:



Katabatic flow over the Reeves Glacier, Antarctica, valid 21 UTC 15 July 2006

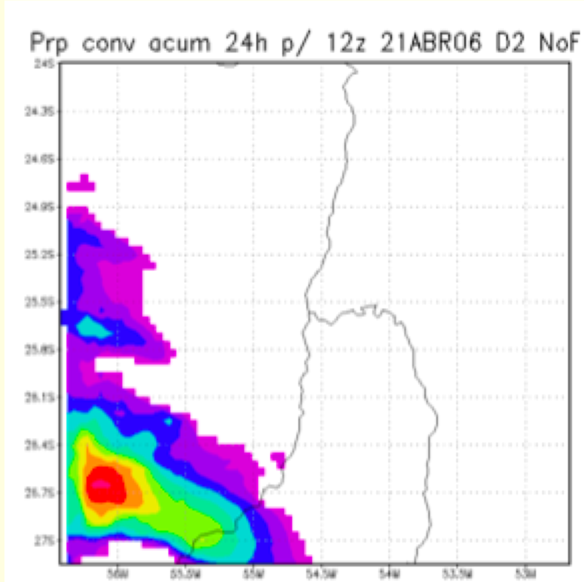
In horizontal: Lowest layer wind speed difference resulting from the changes listed:



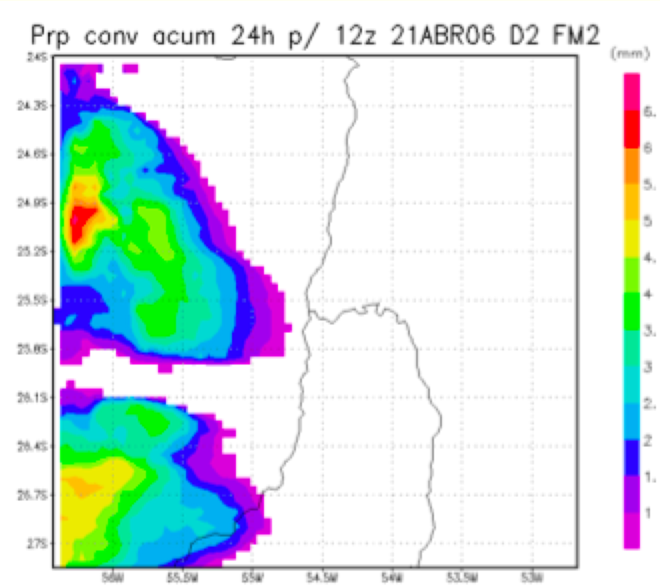
Blue line: position of the cross section just shown

Betts-Miller-Janjic convection: adjustments of the parameters to address its problem – as of the mid past decade – of insufficient heavy rain

Momentum transport with the Kain-Fritsch scheme



No momentum transport



Mom. transport included (verifies better)

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

(RCM: should one attempt
improving on the large scales ?)

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

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Upgraded Eta
driven by ECMWF 32-
ensemble membe
(Katarina Veljovic, …., 2

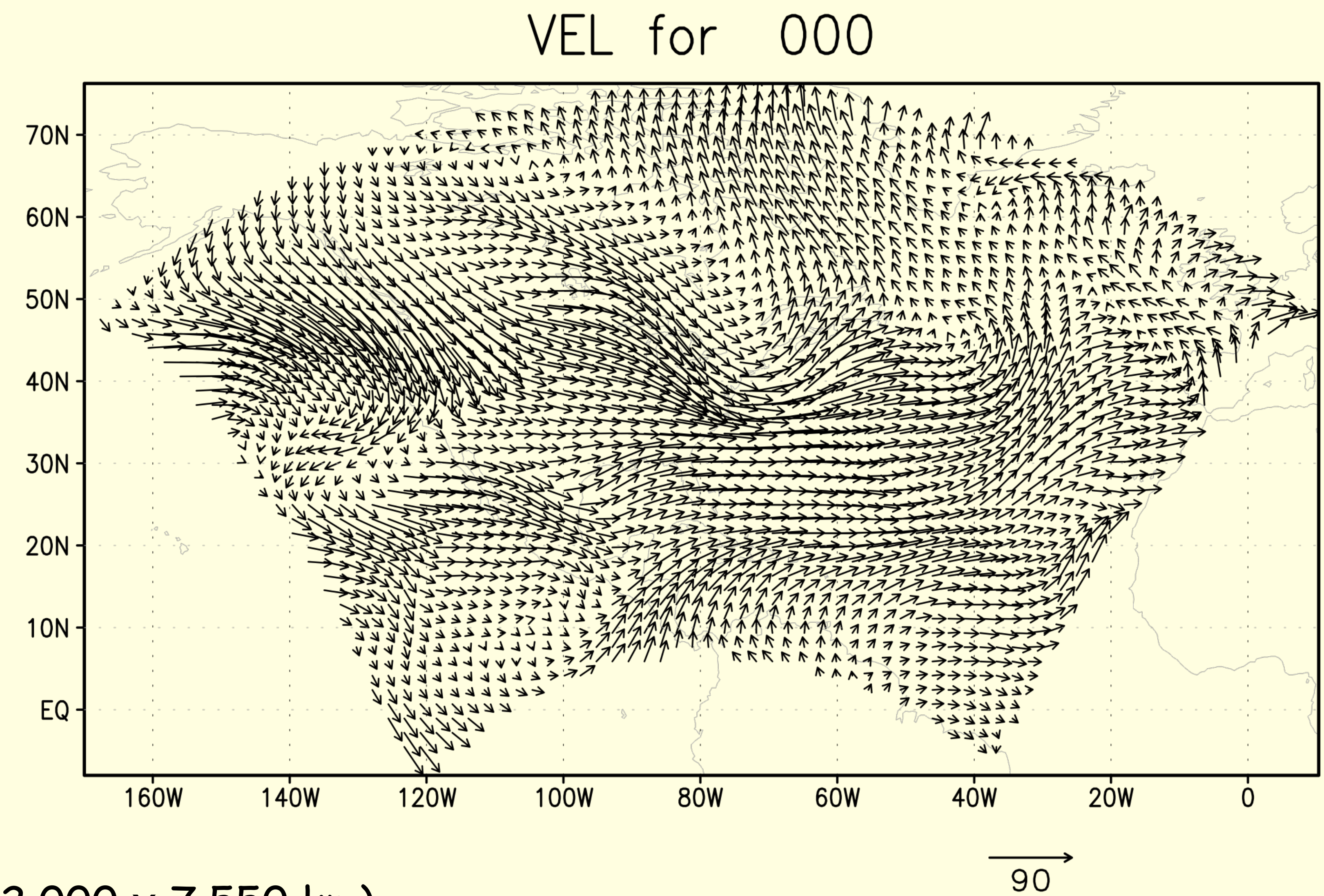
T399 (~50 km)/62 level to 15 days, lower resolution later;

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

Verification against ECMWF analyses

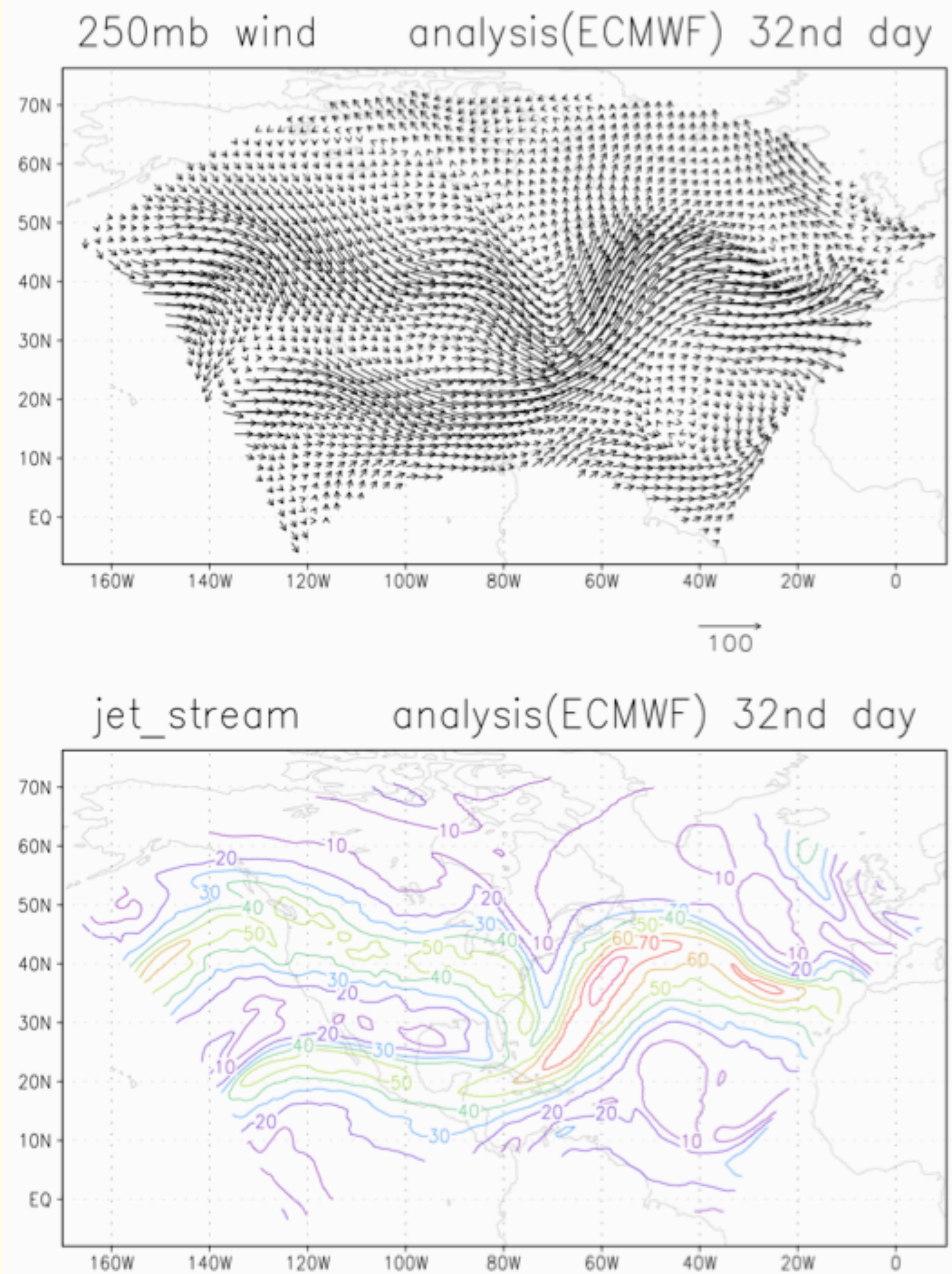
Eta driven by ECMWF 32 day ensemble control + 25 ensemble members;

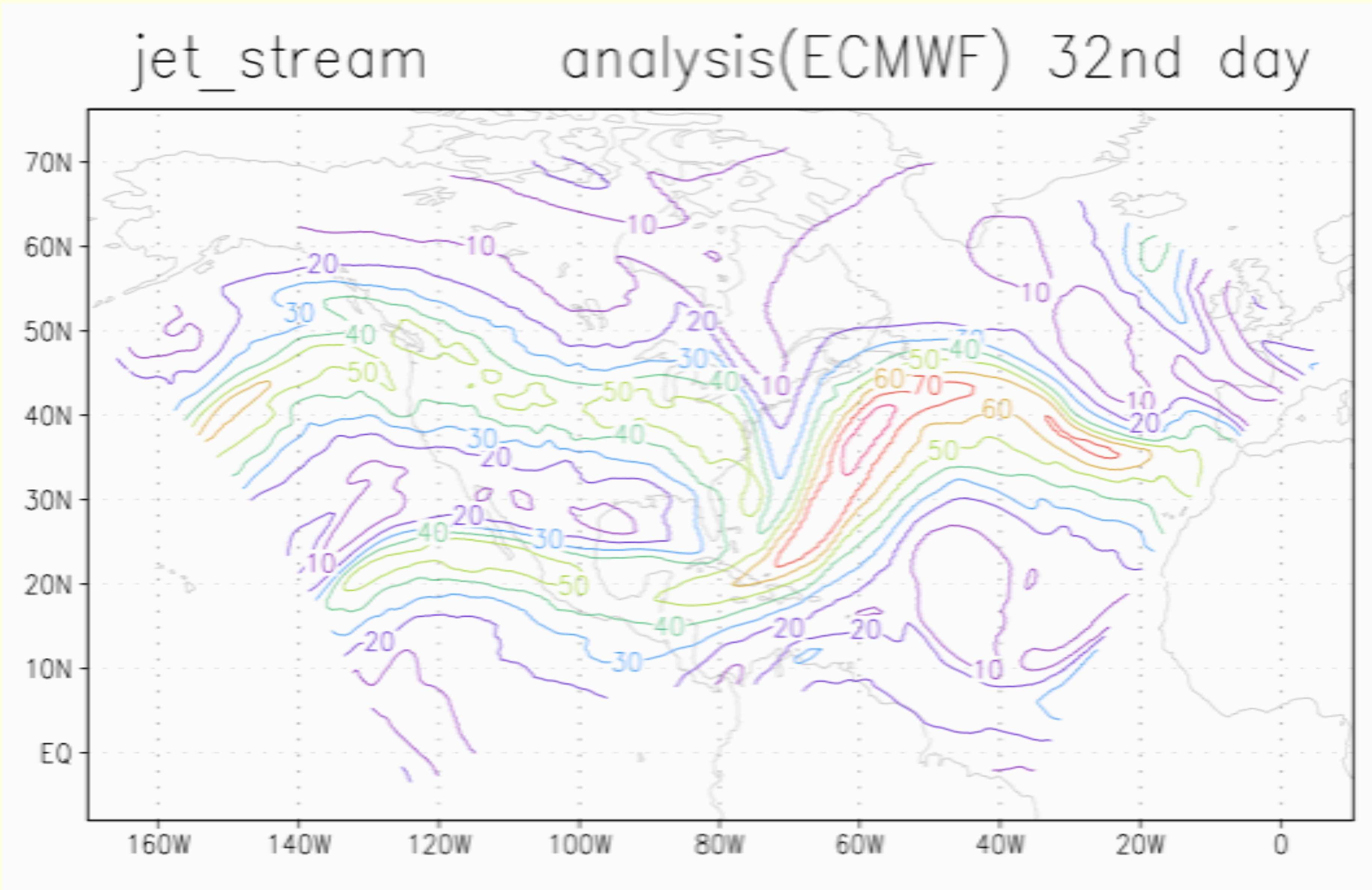
The domain:



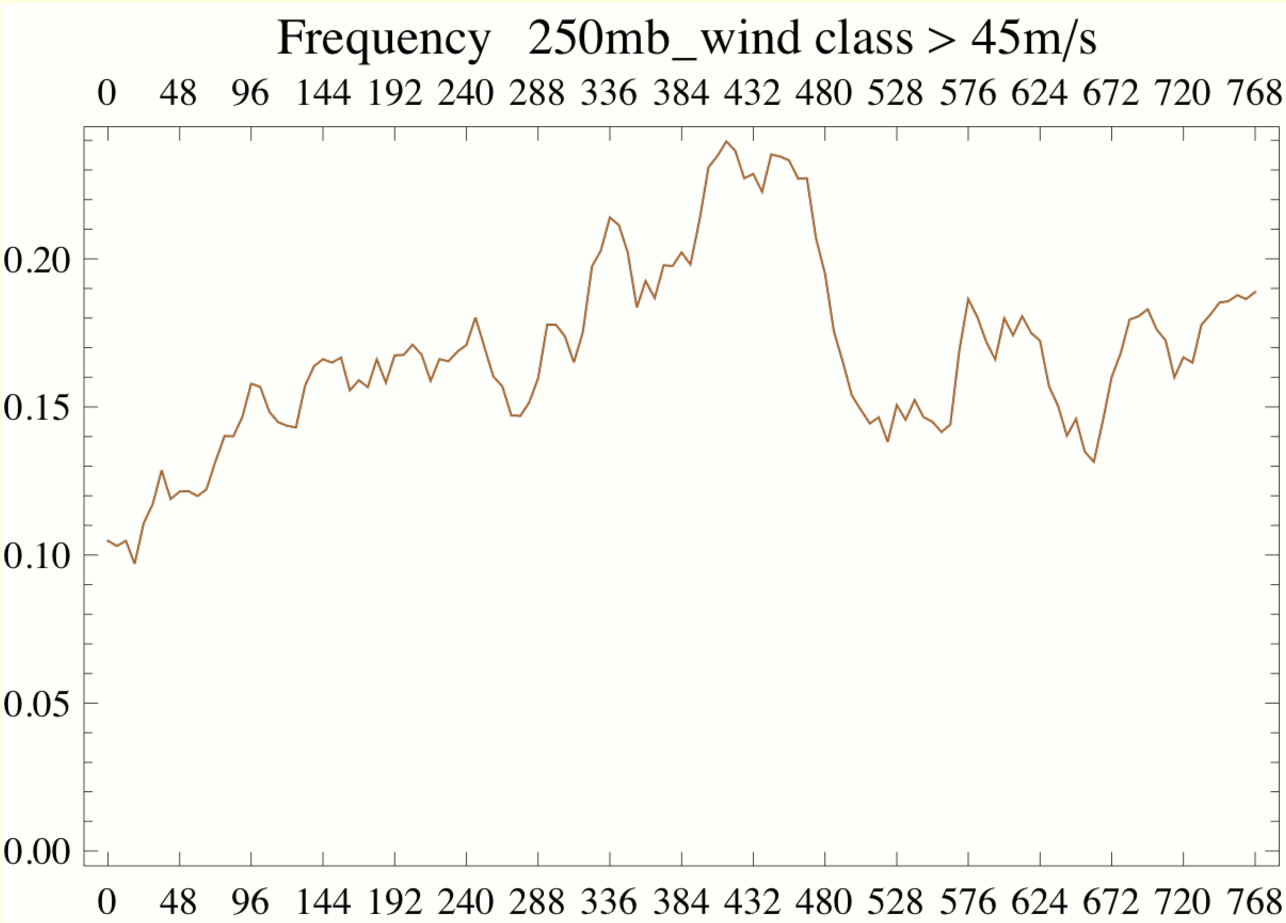
(12,000 x 7,550 km)

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
70N
60N
50N
40N
30N
20N
10N
EQ
160W
140W
120W
100W
80W
60W
40W
20W
0
10
20
30
40
50
60
70

What speeds should we look at ?



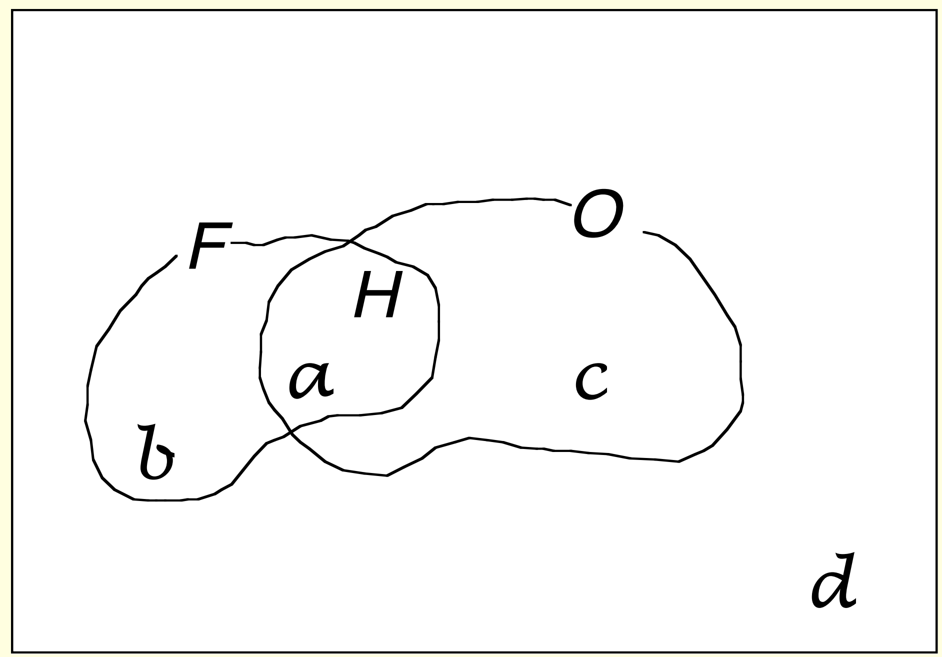
> 45 m/s

What should one do to assess the skill of an *ensemble* of forecasts ?

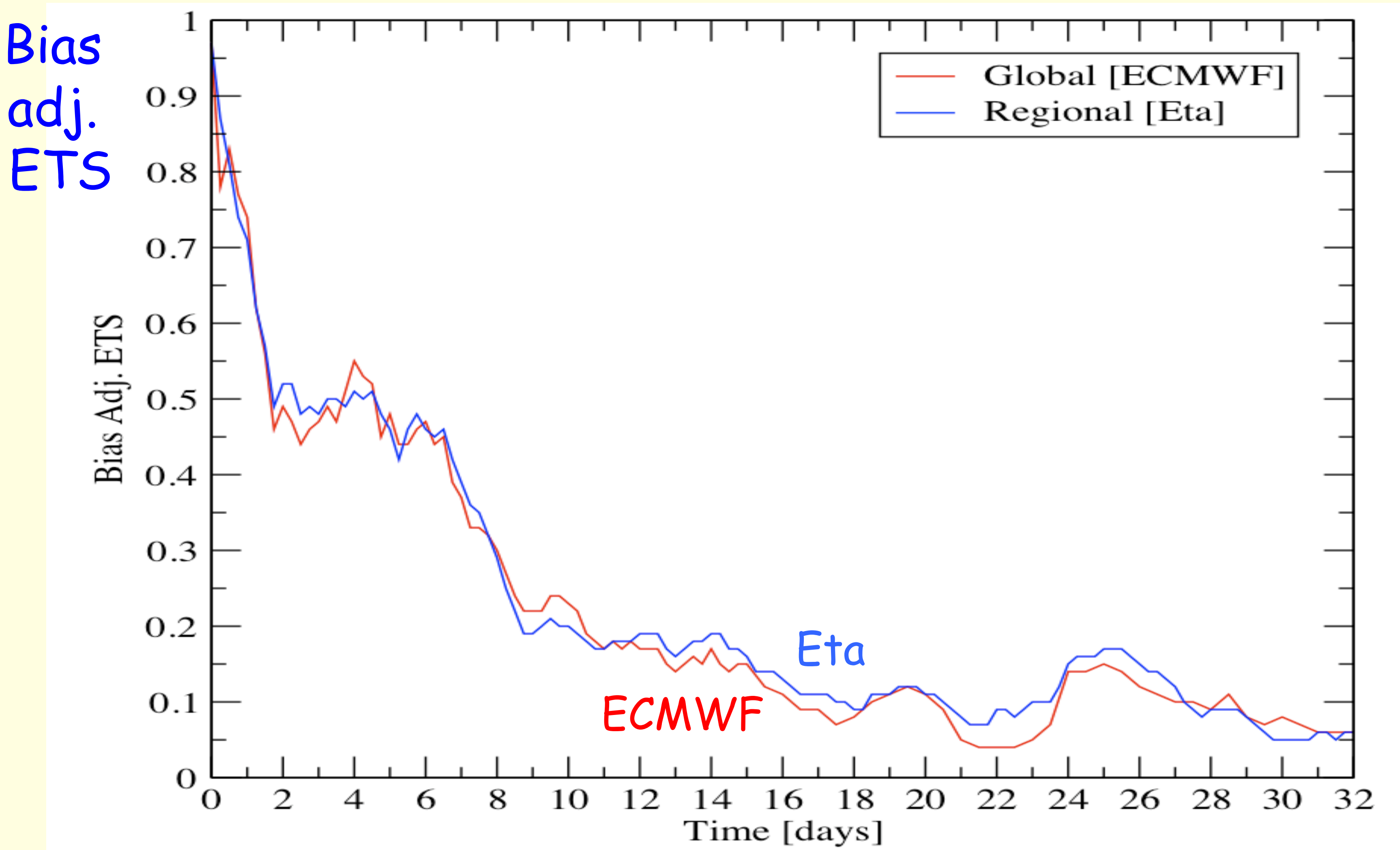
Same as what is done with precipitation:

add all of the values of *F*, *H*, and *O*

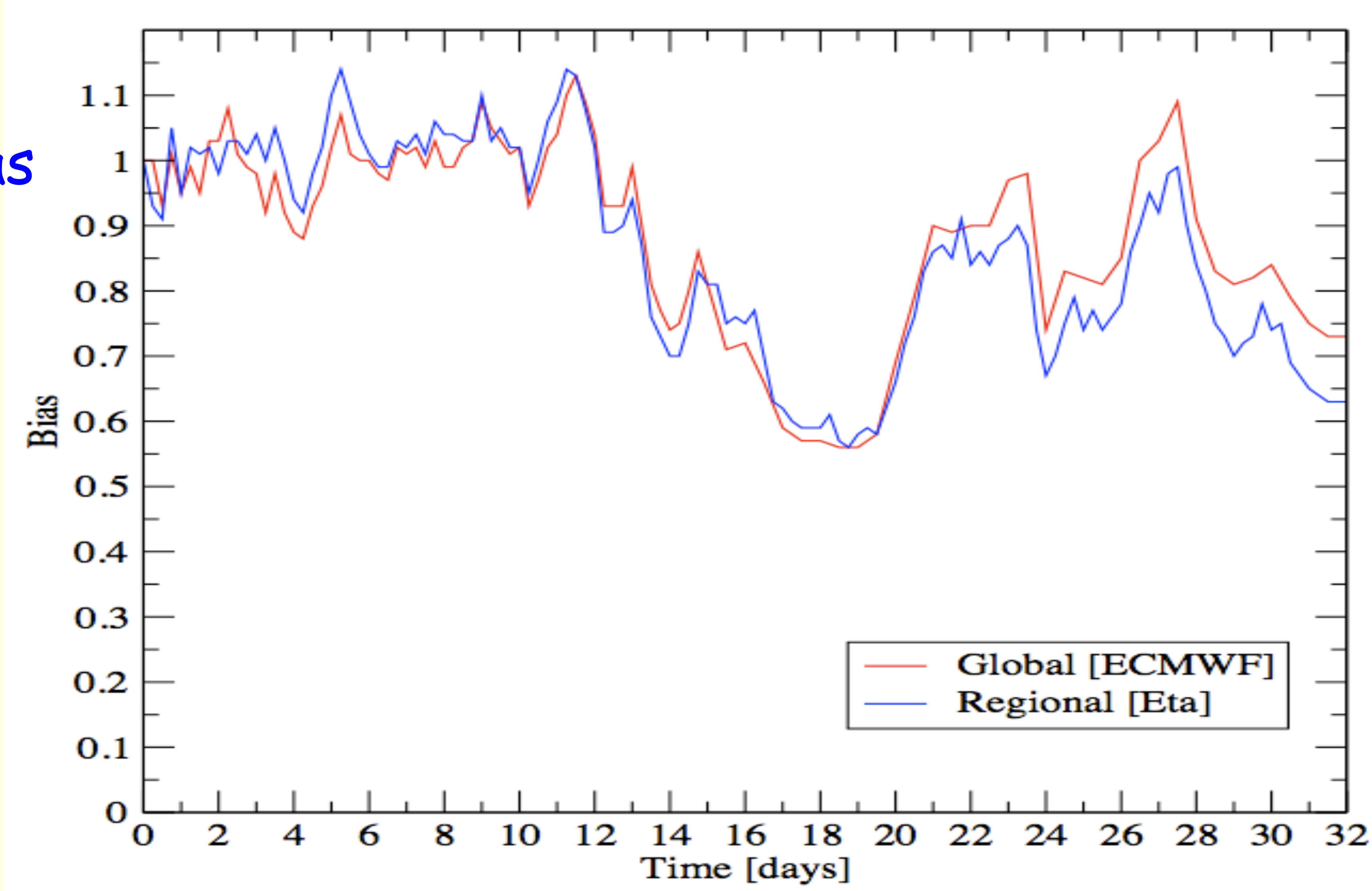
F : forecast,
H : correctly forecast: "hits"
O : observed



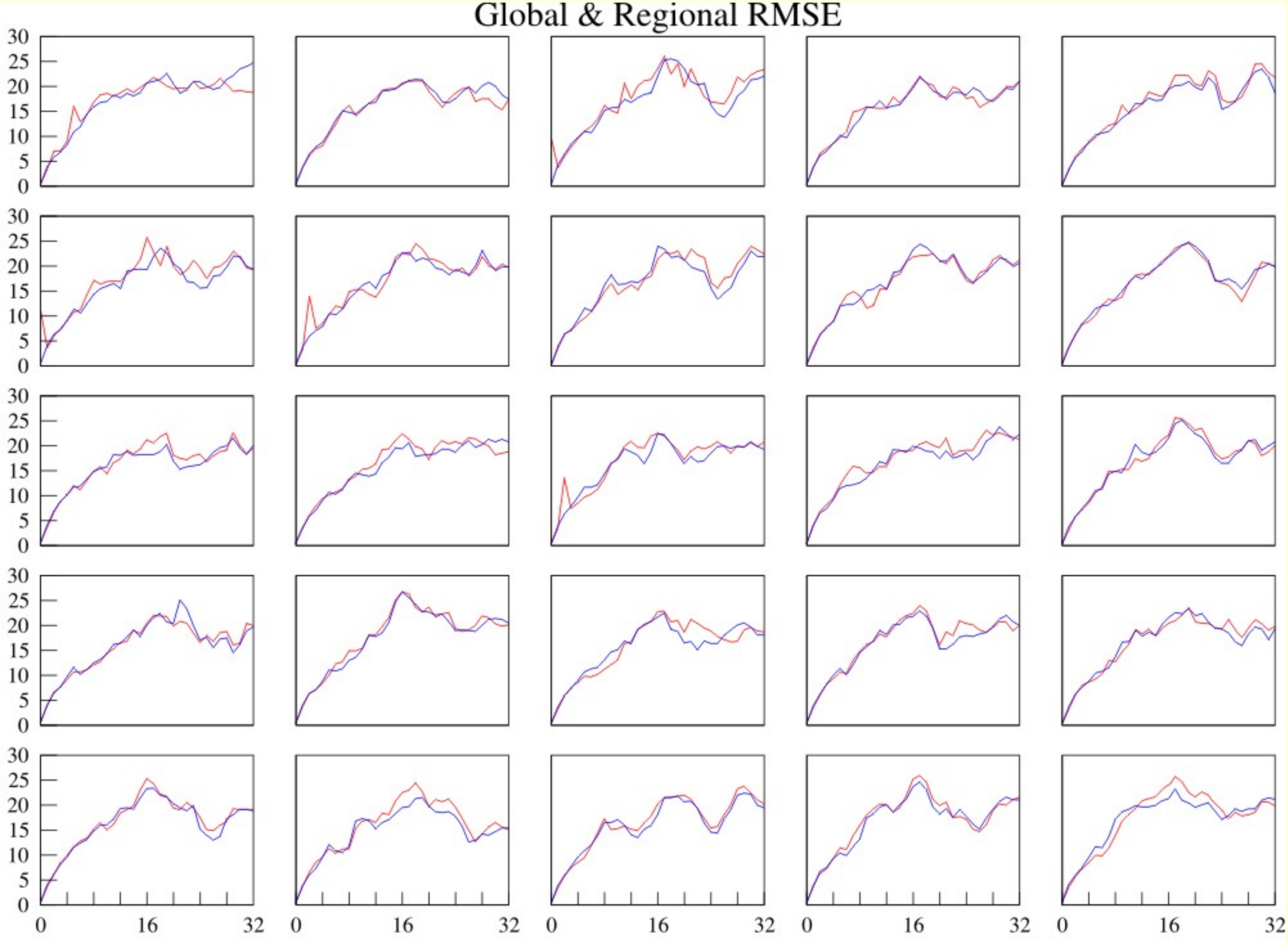
Results: 26 (25 members + control) 32-day forecasts:



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]

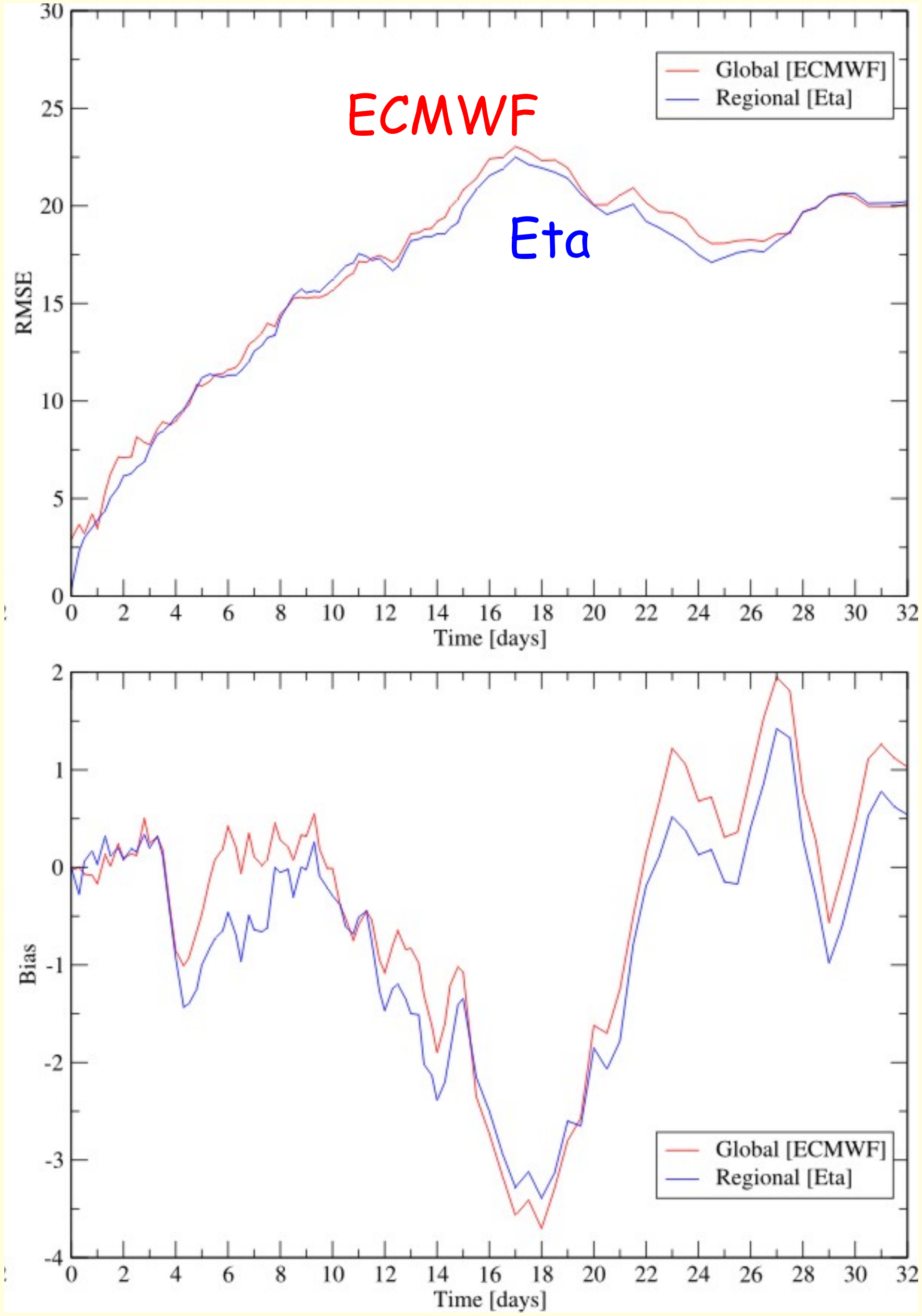
More traditional verification: **root mean square** 250 mb wind errors:



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 !!!!!

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!

What is/are the main advantage/
main advantages of the Eta making this
happen?

Work in progress

- "Cubed sphere" version (Rancic) running at CPTEC;
- RRTM radiation (running in Athens)
- . . . .

Collaboration with the Skiron (Eta group) efforts of the Univ. of Athens, George Kallos

Work in progress

- "Cubed sphere" version (Rancic) running at CPTEC;
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Geor

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