# Eta vs. sigma, an update: Gallus-Klemp test, and 250 hPa wind skill compared to ECMWF in ensemble experiments

Fedor Mesinger [1], Katarina Veljović [2]

1) Serbian Academy of Sciences and Arts, Belgrade, Serbia

2) Institute of Meteorology, Faculty of Physics, University of Belgrade, Belgrade, Serbia;

fedor.mesinger@gmail.com

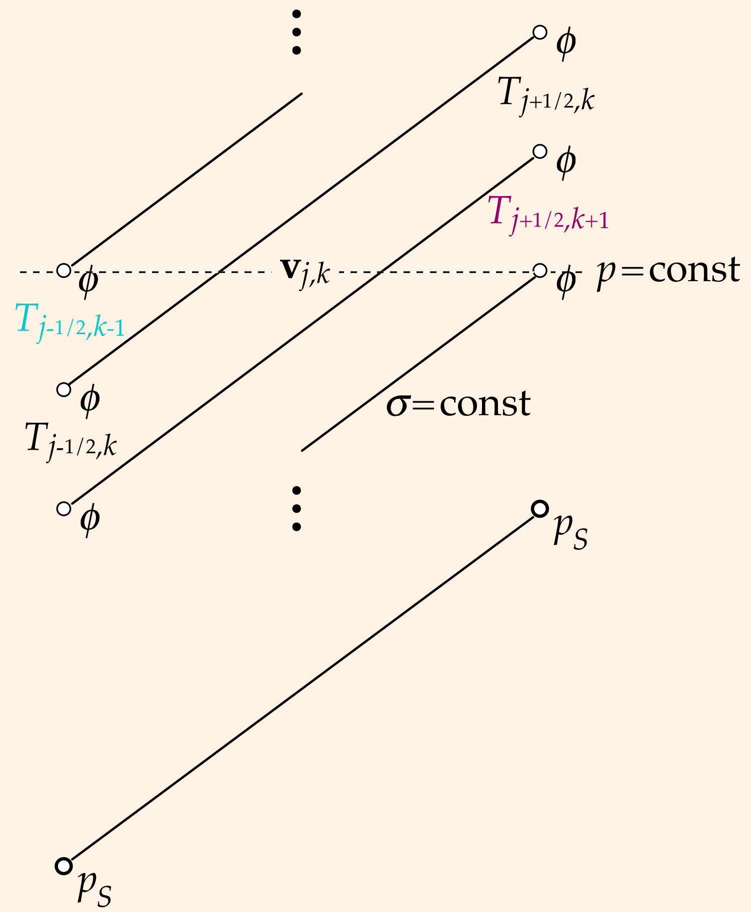
EGU Assembly, Vienna, 15 April 2015

# Contents

1) Introduction:
   - summary of various documented eta vs. sigma tests;
   - Eta topography
2) Gallus-Klemp / Witch of Agnesi test
3) Skill in 250 hPa winds vs. ECMWF in ensemble experiments
4) Concluding comments

1)

# 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 !

Over the years, five documented tests eta vs sigma:

- Mesinger et al. (MWR, 1988); **Noise with sigma !**
- Black ("The step-mountain ...: A documentation", NMC, 1988):

  Geopotential height errors, 14 consecutive forecasts, as a function of height and time: NGM, Eta, Eta/sigma;

- Mesinger, Black (Met. Atmos. Phys., 1992):

  Cases of lows in the lee of Rockies, precipitation scores;

- Mesinger, Black, Baldwin (André Robert Mem. Vol., 1997)

  Precipitation scores, a detailed synoptic study of a case;

- Chuang, in Mesinger et al. (AMS, Orlando 2002); also in

  Mesinger (2004, 50th Anniversary of Oper. NWP Symp., College Park, MD): the case of the Mesinger paper of the Potsdam Symp. book, 2001, run as sigma

#1

Sigma Eta

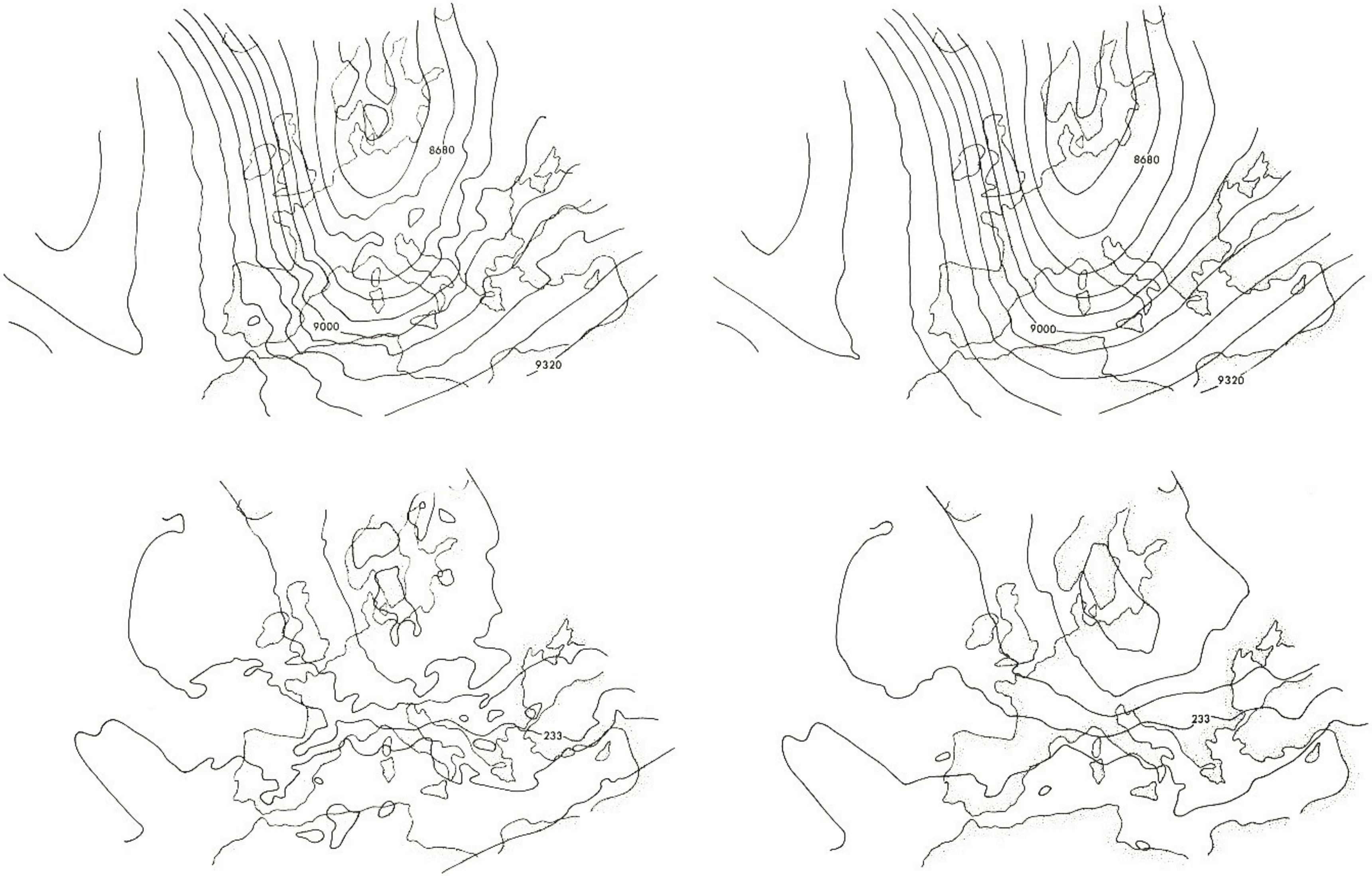
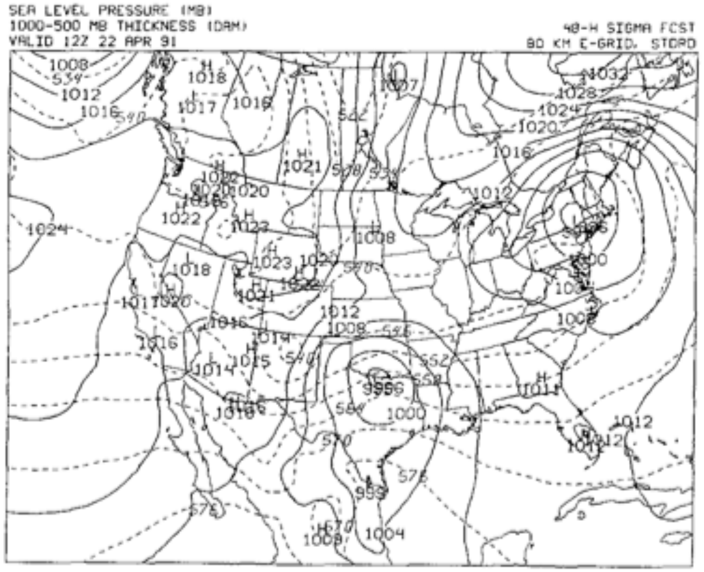



FIG. 6. 300 mb geopotential heights (upper panels) and temperatures (lower panels) obtained in 48 h simulations using the sigma system (left-hand panels) and the eta system (right-hand panels). Contour interval is 80 m for geopotential height and 2.5 K for temperature.

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

# #3

## Eta run as sigma, 48 h




Eta
48 h
(80 km / 16 lyrs)

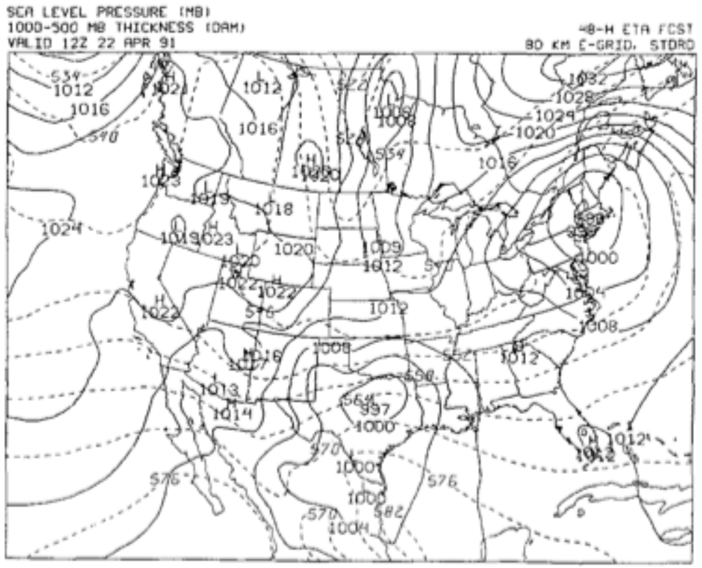
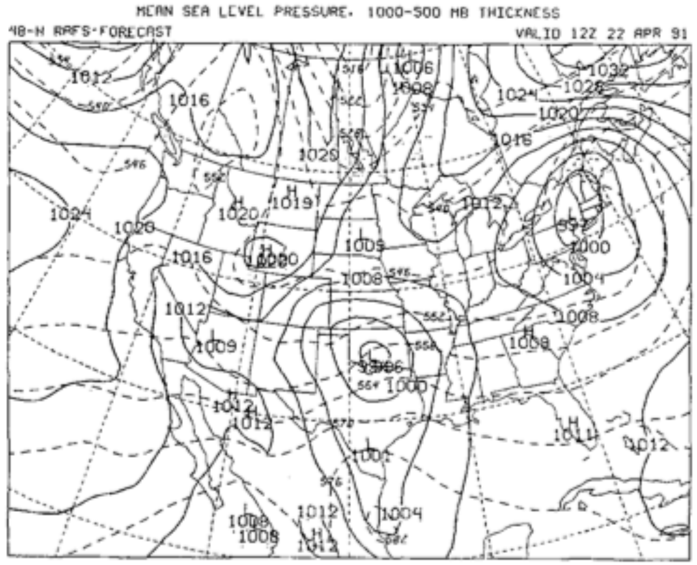



Fig. 7. As in Fig. 3 except for verifying at 1200 UTC 22 April 1991

NGM
48 h




NGM
36 h

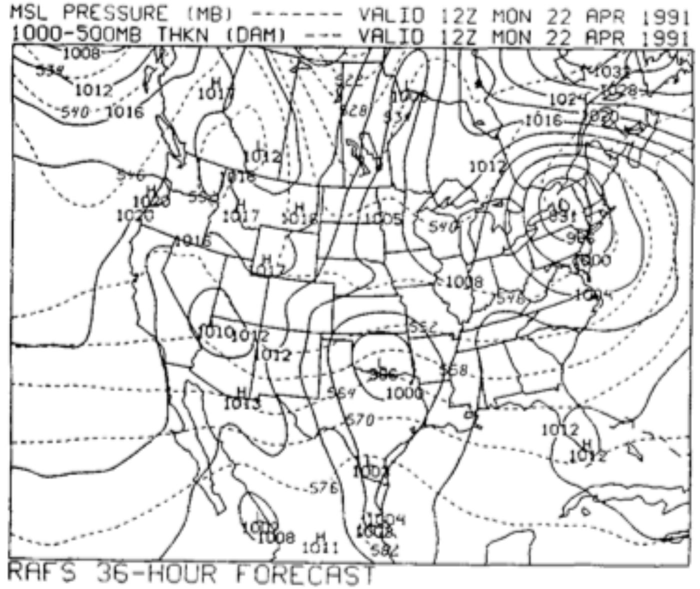
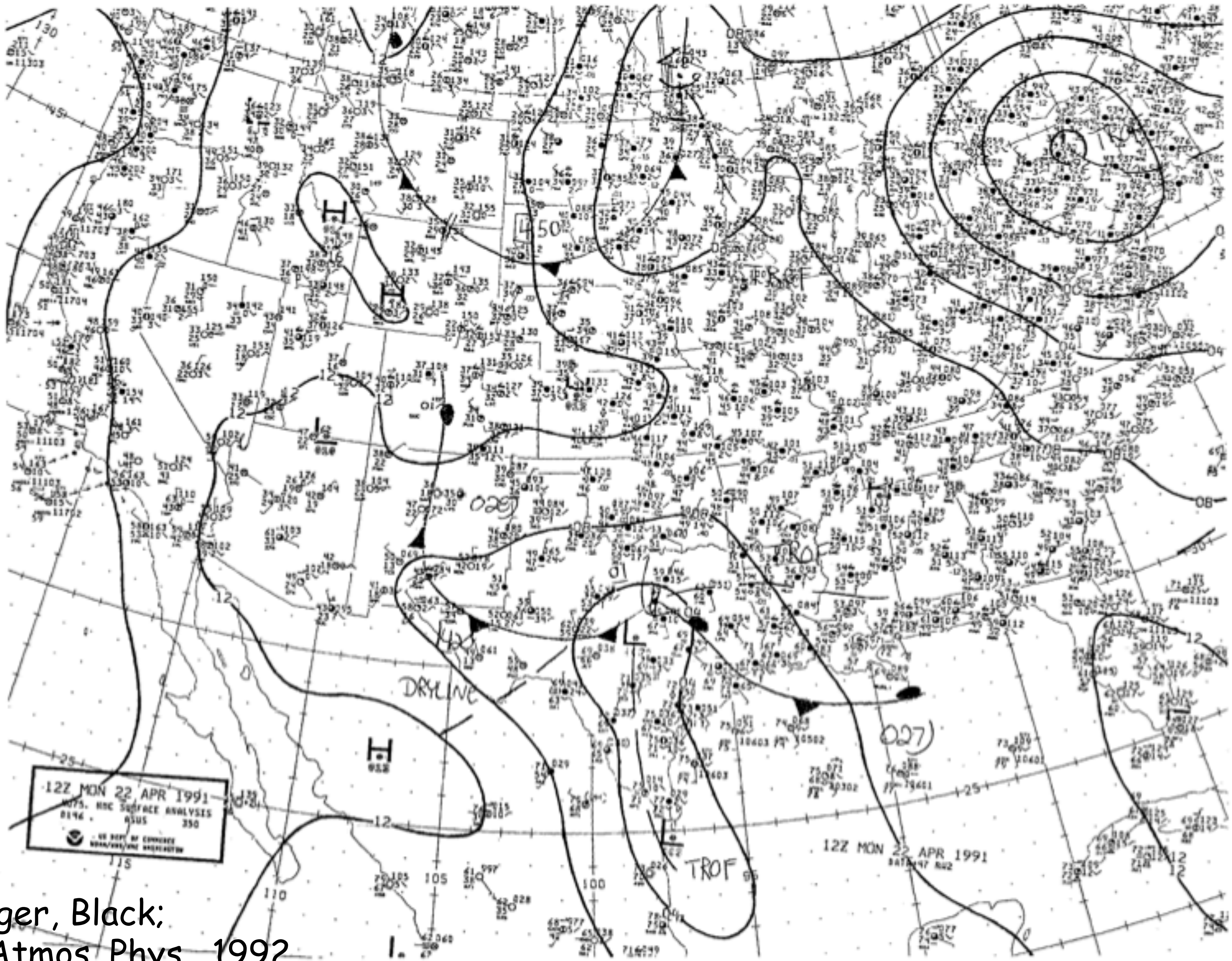


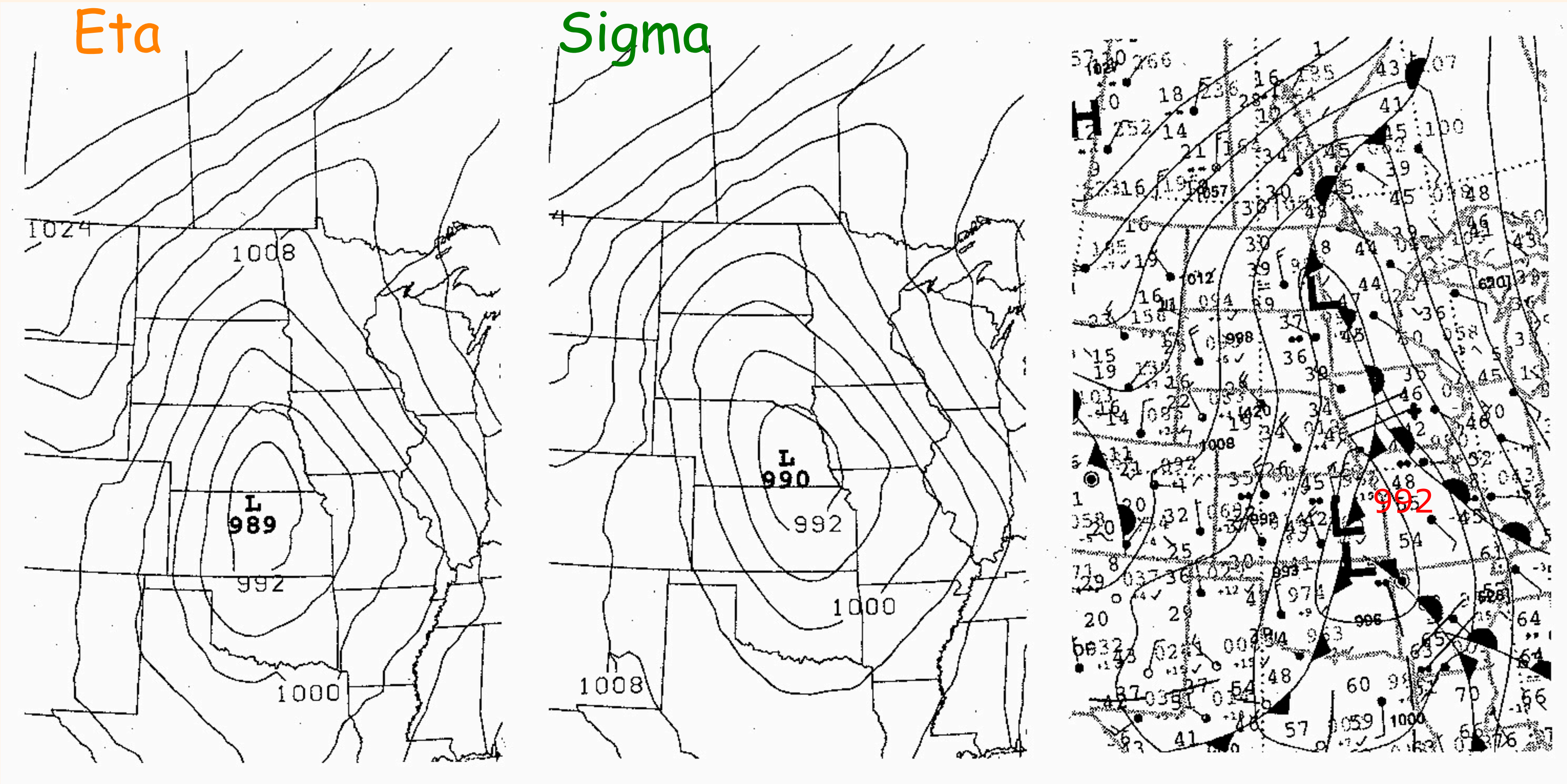

Fig. 8. U.S. operational regional model (NGM) forecasts of sea level pressure (mb, solid lines) and 1000–500 mb thickness (dam, dashed lines), verifying at 1200 UTC 22 April 1991. 48-h forecast is shown as the upper panel, and 36-h forecast as the lower panel




Mesinger, Black;
Met. Atmos. Phys., 1992

Fig. 6. A section of the NMC surface analysis for 1200 UTC 22 April 1991

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




Valid 6 Nov. 2000; similar to earlier experiments at lower resolution

Chosen because "Avn" / GFS, at 48 h, was forecasting a very deep low centered in North Dakota – favoring the more northerly center

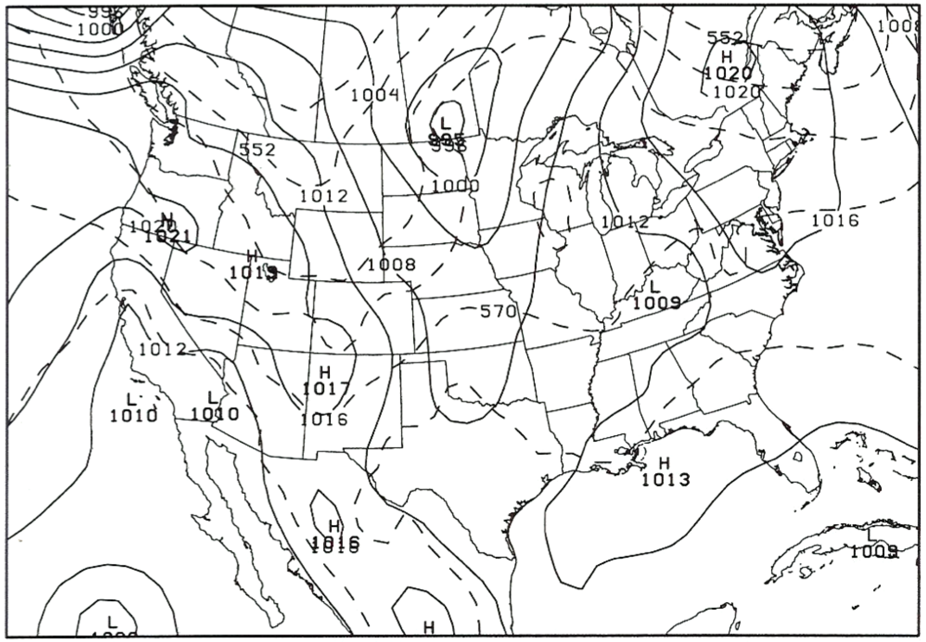
With increased resolution (22 km/50 lyr to 12 km/60 lyr) the Eta did better in forecasting the detail of the placement of centers

# The three low centers case

Valid at

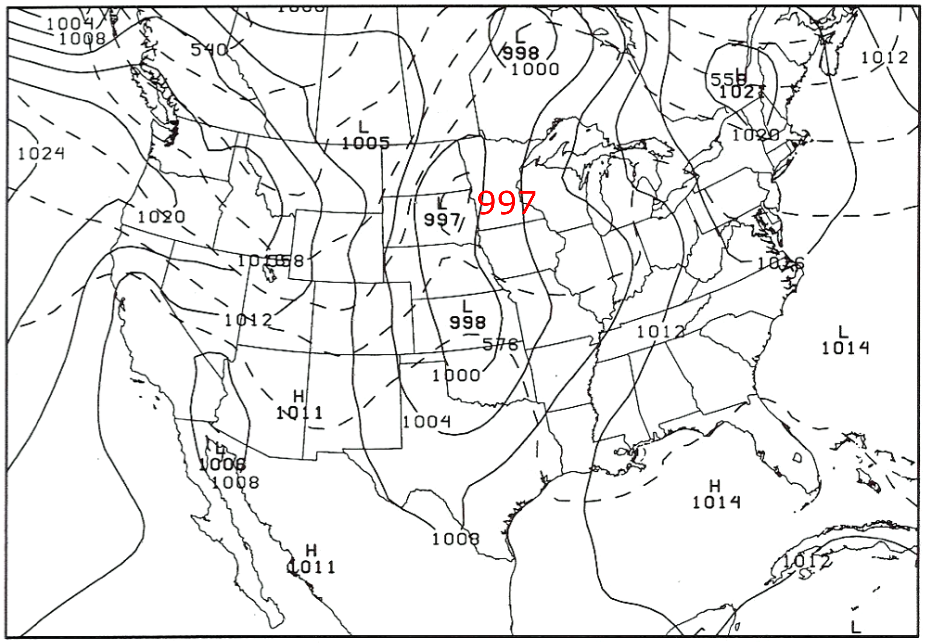
12z 18 September 2002

Avn




020918/1200V060 SFC MSLP & THCK -- AVN

Eta



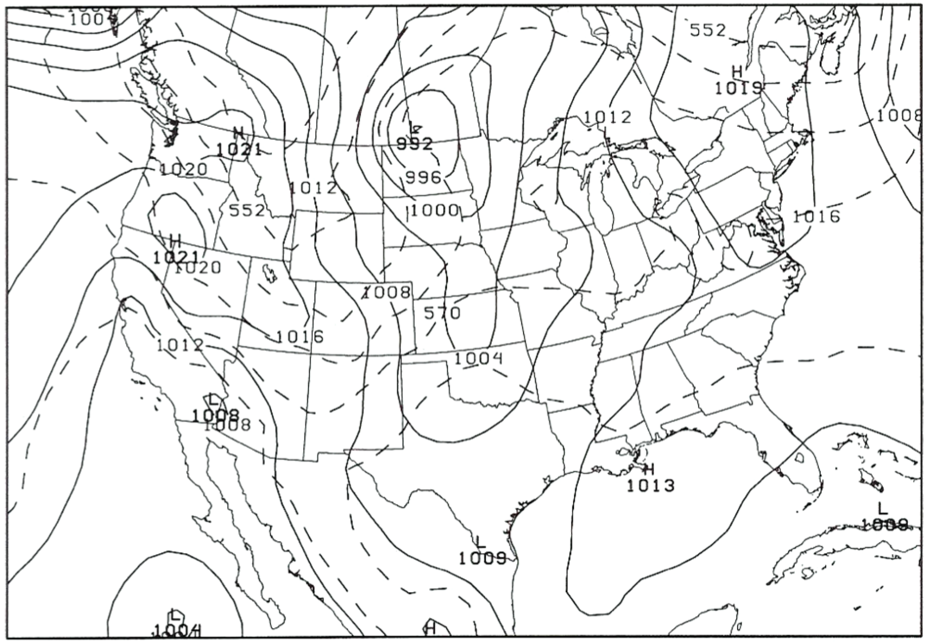

020918/1200V060 SFC MSLP & THCK -- ETA

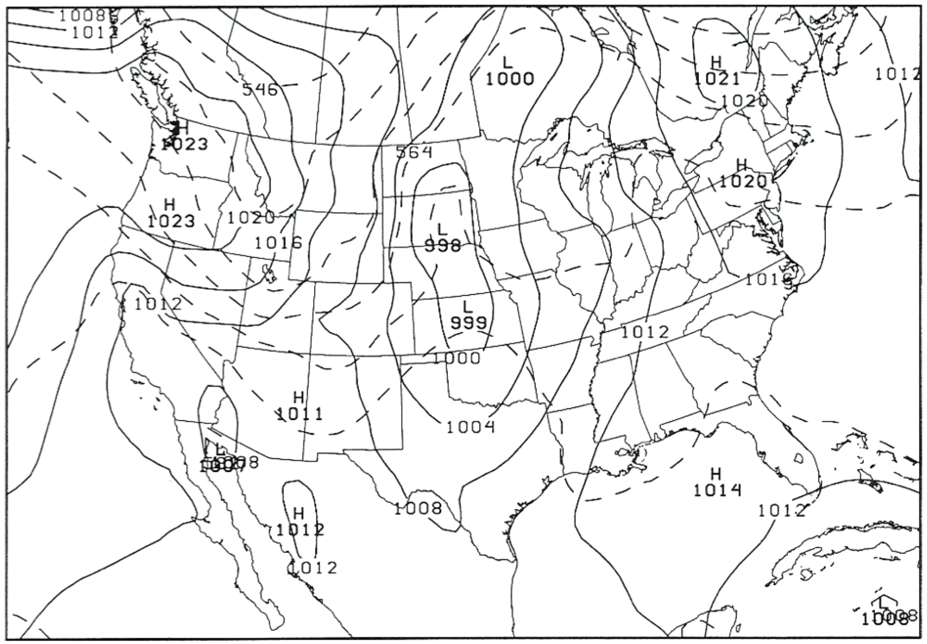
60 h fcsts

Avn

Eta

48 h fcsts

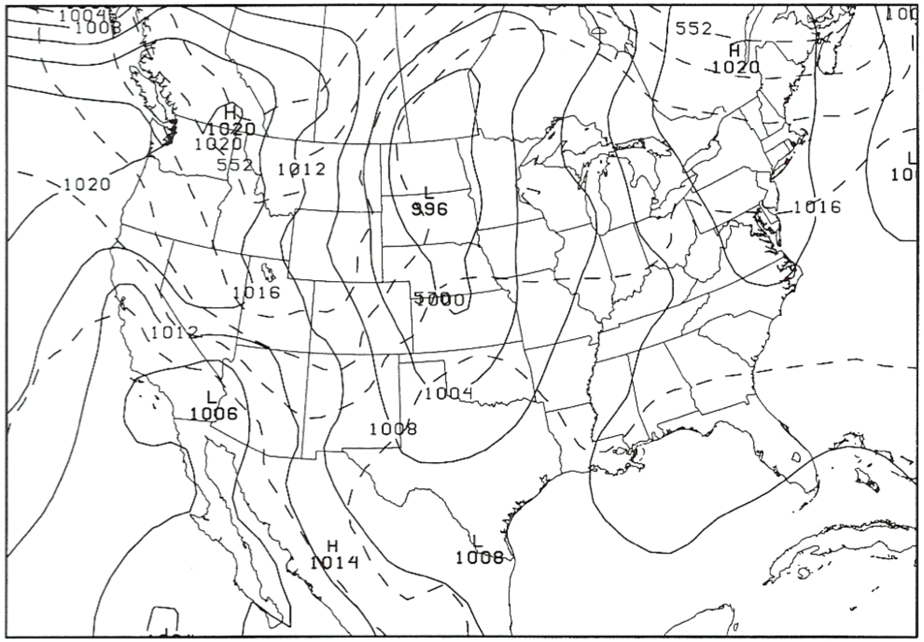


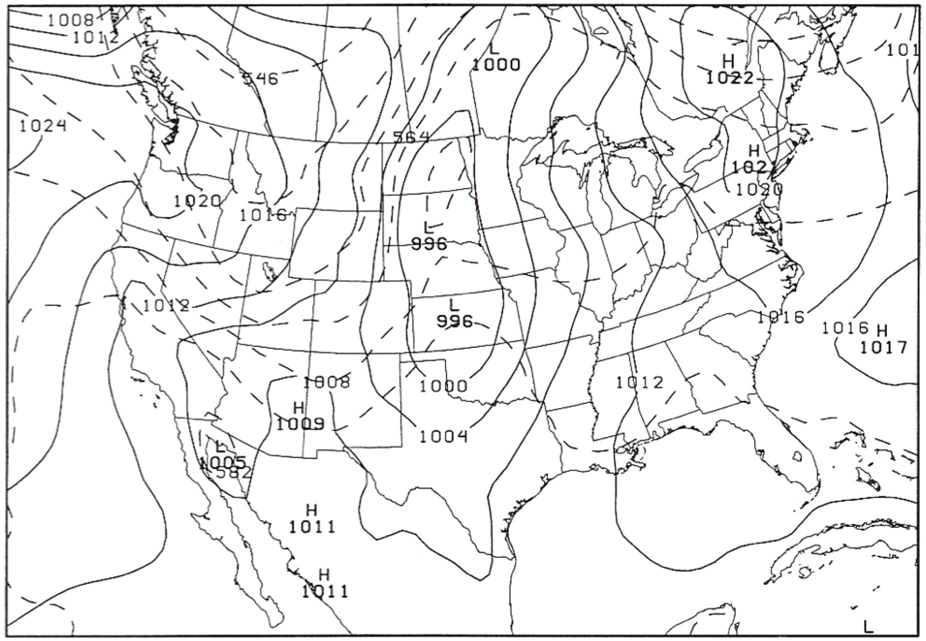
Avn

Eta

36 h fcsts

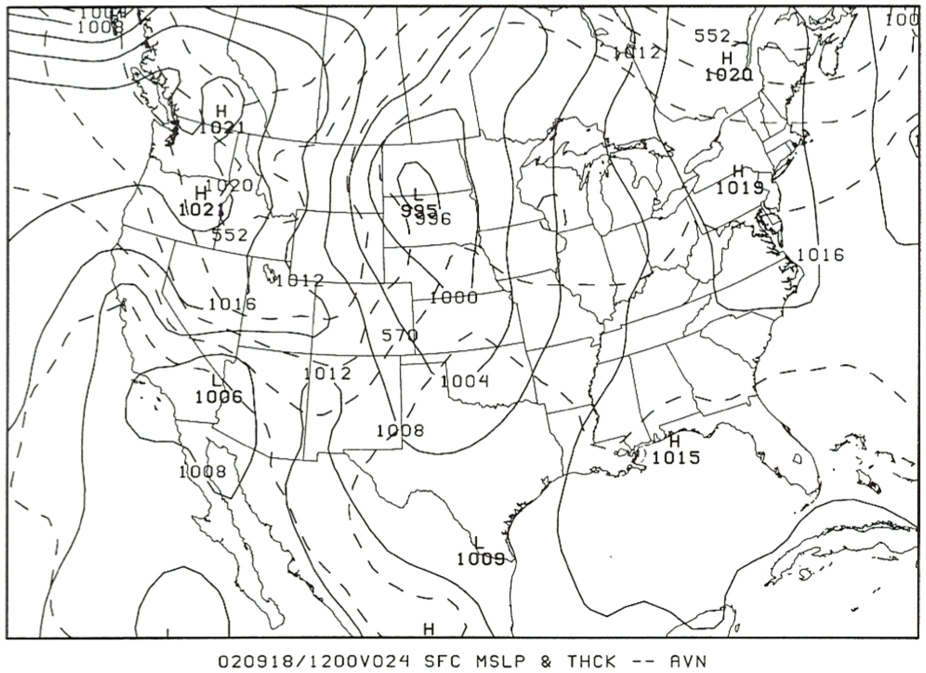


020918/1200V036 SFC MSLP & THCK -- AVN

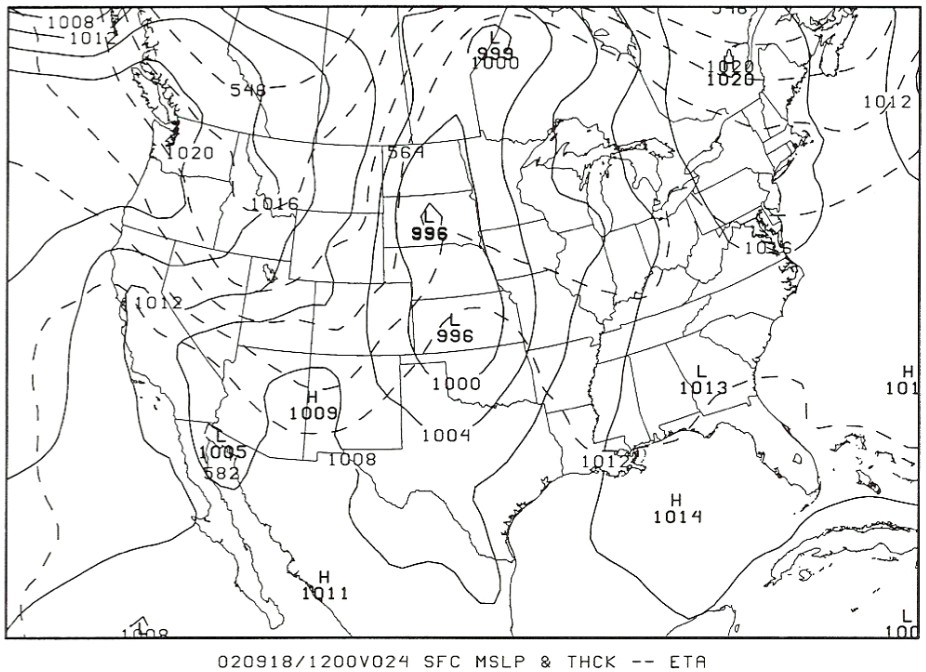


020918/1200V036 SFC MSLP & THCK -- ETA

Avn

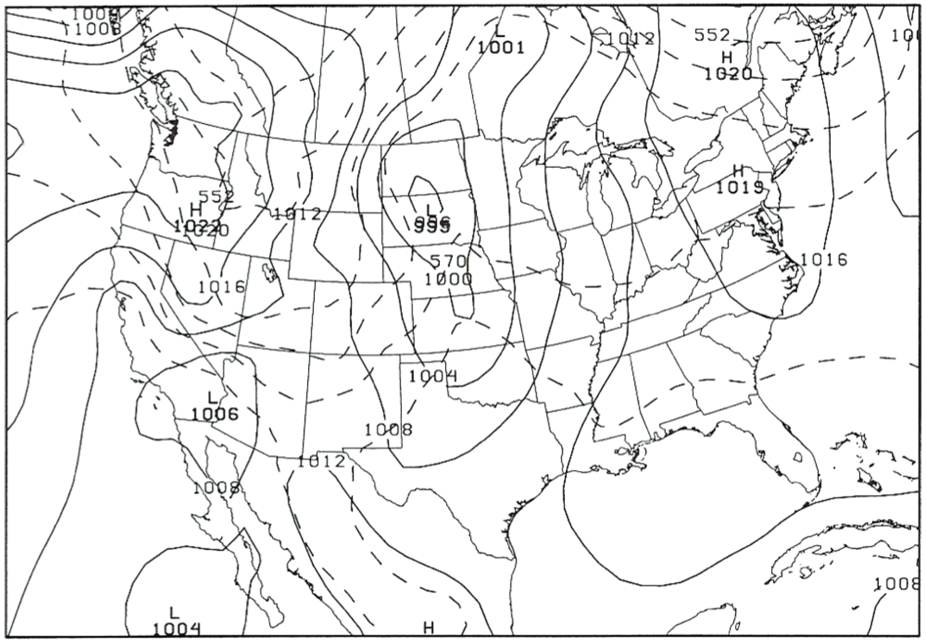



Eta



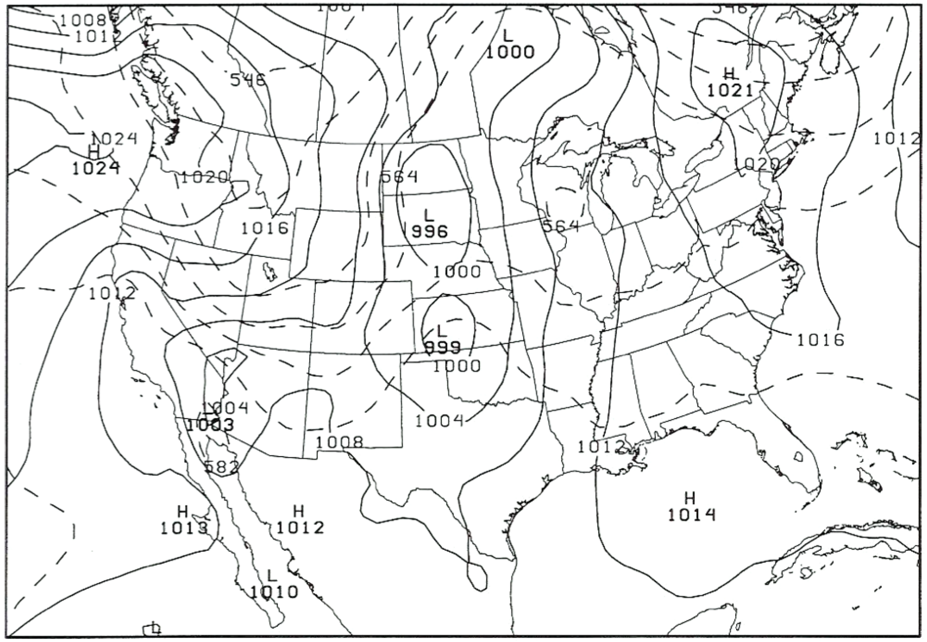

24 h fcsts

Avn



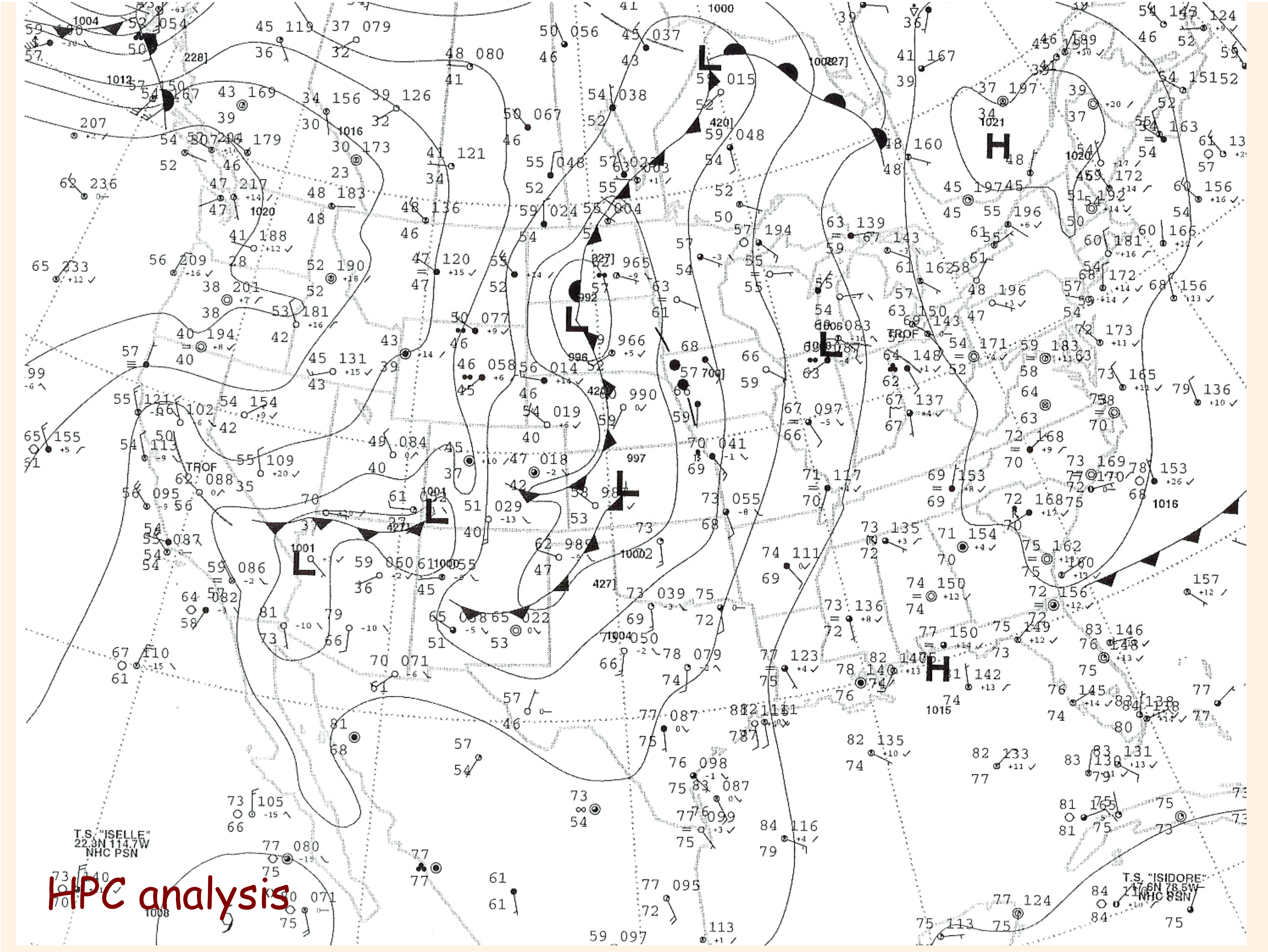
020918/1200V012 SFC MSLP & THCK -- AVN

Eta



020918/1200V012 SFC MSLP & THCK -- ETA

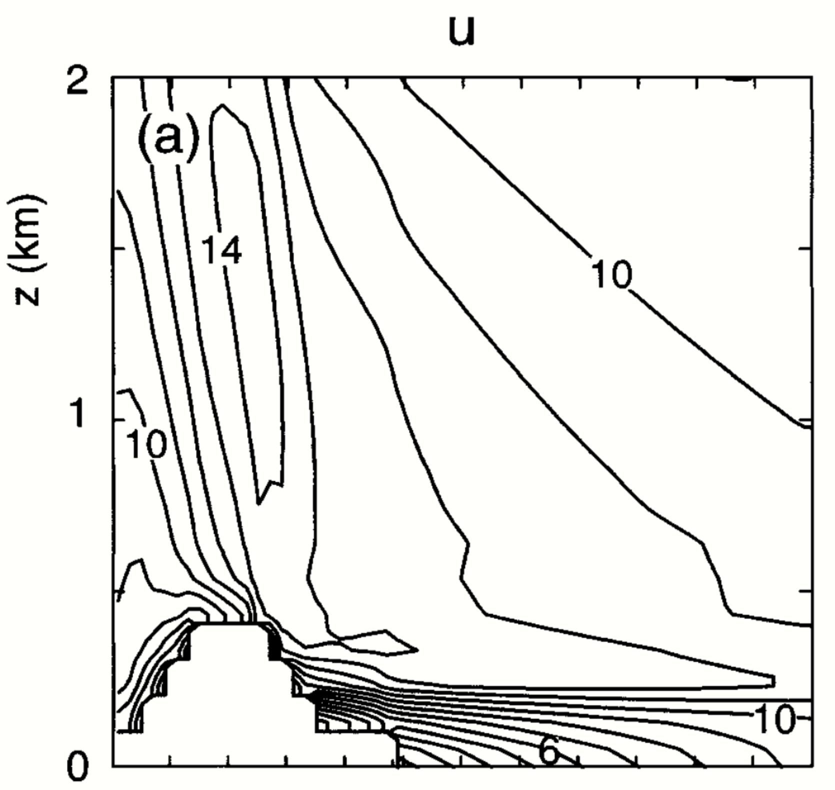
12 h fcsts

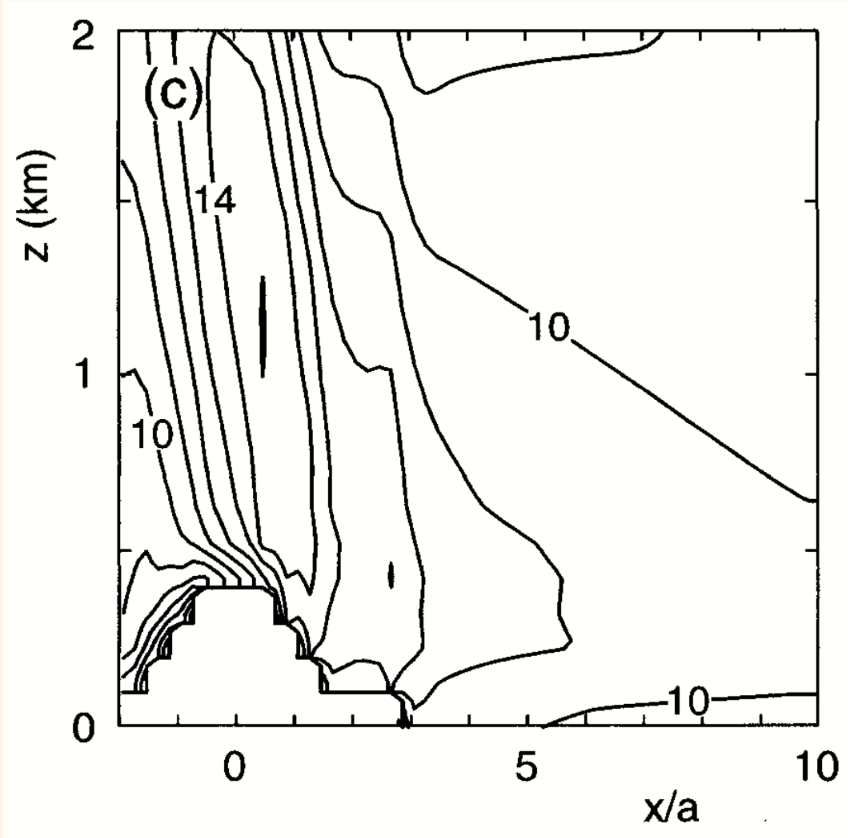



HPC analysis

# 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

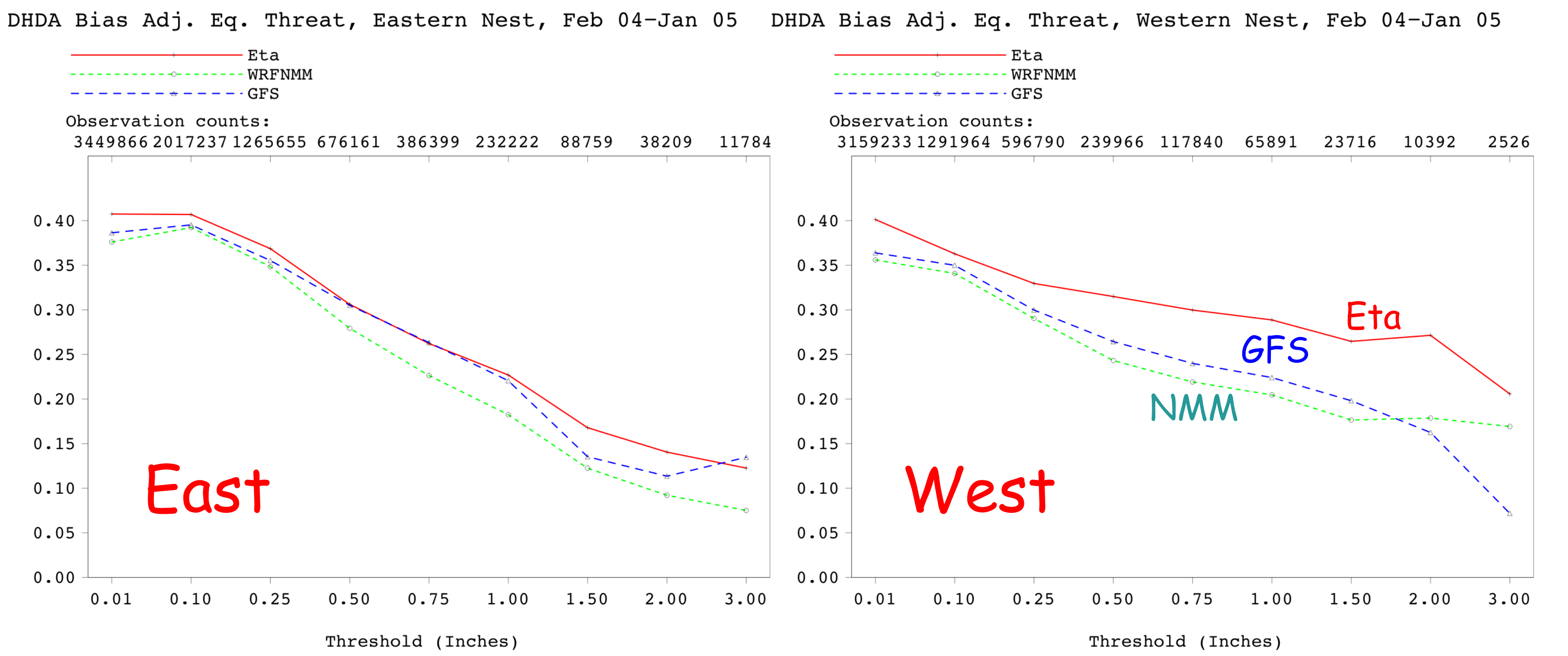
Also: poor Eta performance for a case of a downslope windstorm

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

Eta "frozen" (single implementation after summer of 2003 in land-surface, and cloud/radiation)

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

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



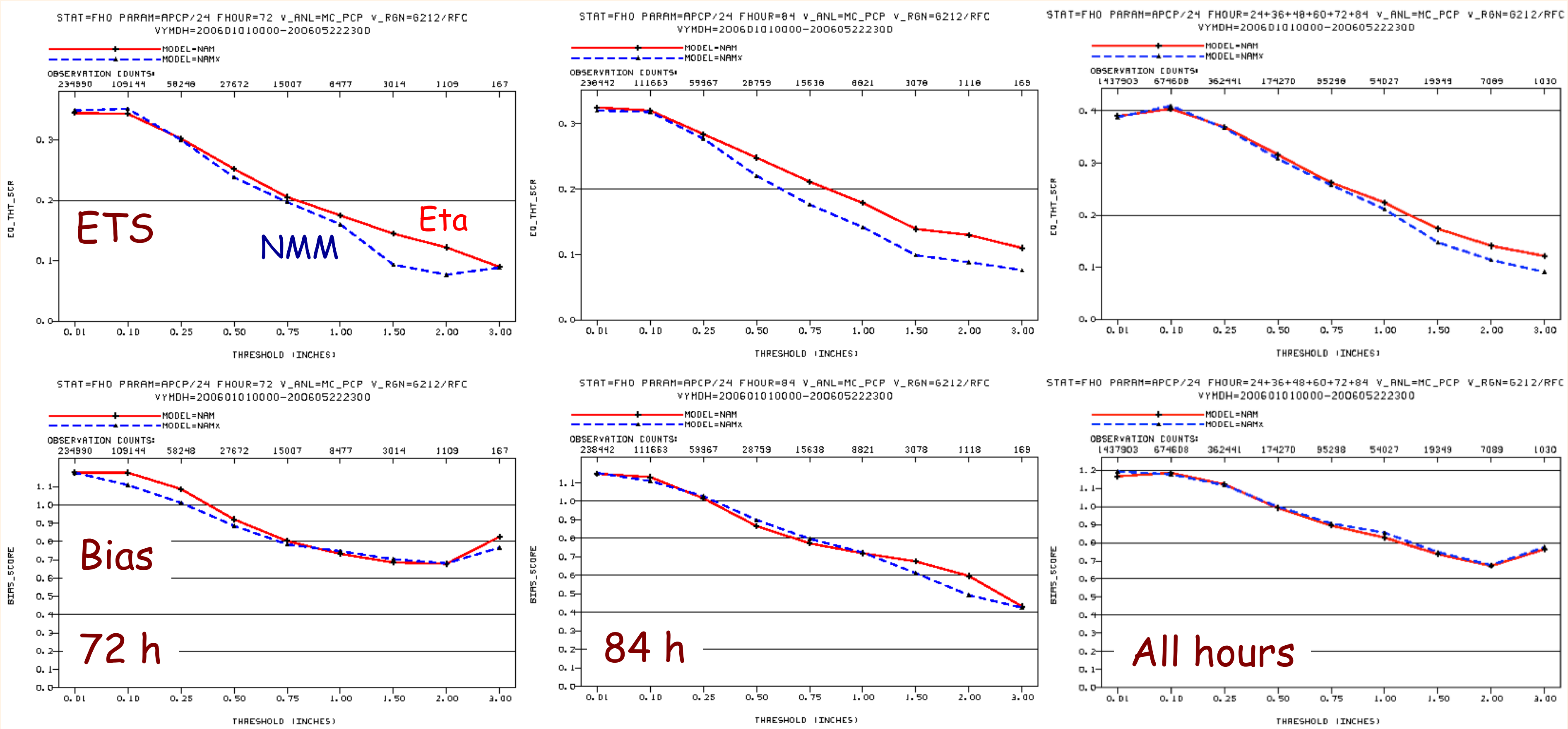

Eta 12-km, NMM 8-km; correction for bias: Mesinger (Adv. Geosci. 2008): In order to obtain score that verifies placement of precipitation !

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).

# Eta developments subsequent to its NCEP "Workstation version":

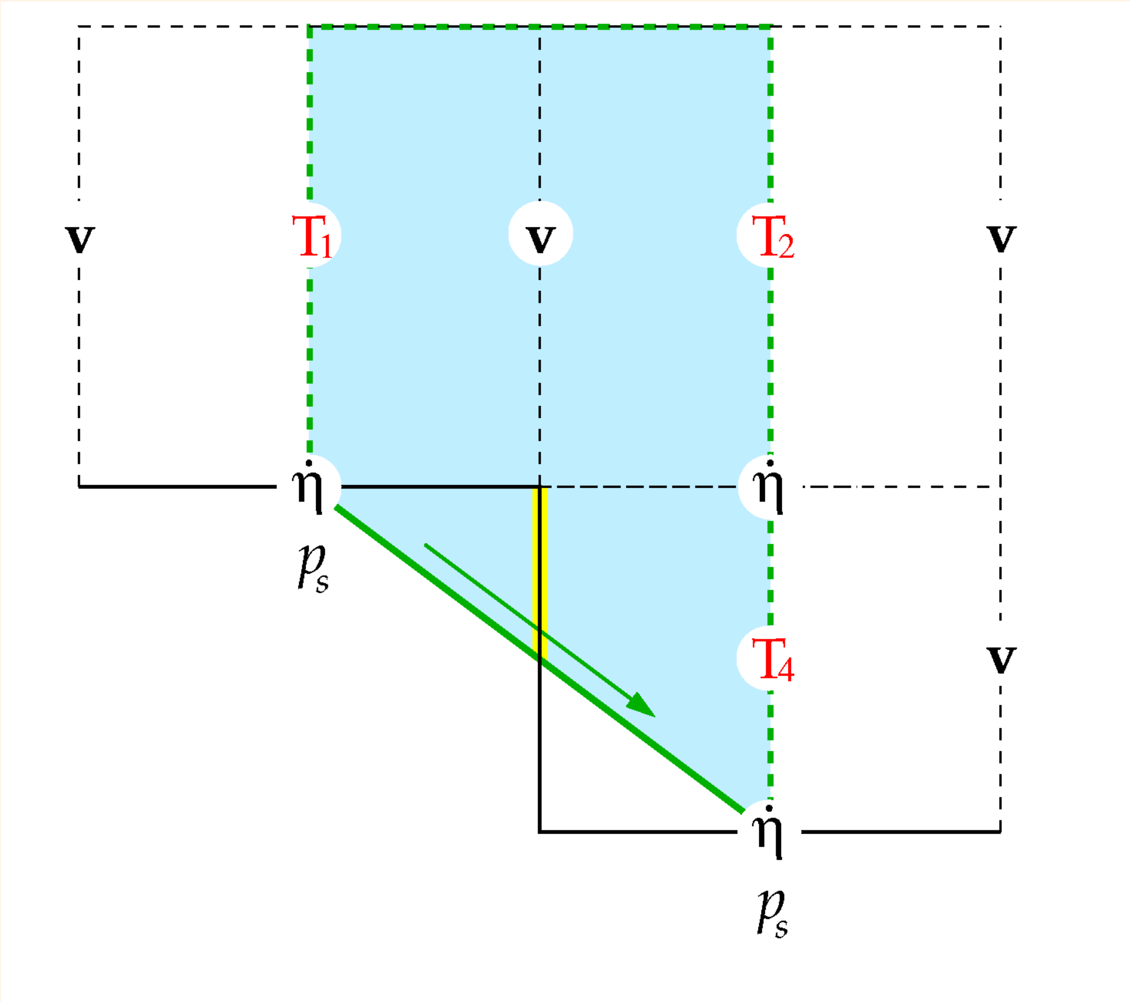
Mesinger, F., S. C. Chou, J. Gomes, D. Jovic, P. Bastos, J. F. Bustamante, L. Lazic, A. A. Lyra, S. Morelli, I. Ristic, and K. Veljovic, 2012: An upgraded version of the Eta model. *Meteor. Atmos. Phys.*, **116**, 63-79.

Major new feature: "sloping steps"

(Mesinger and Jovic, NCEP ON 439)

## 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
(EGU 2013):

A real data downslope windstorm test:

Zonda case of
11-12 July 2006



Acknowledgement:
. . .

# 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:

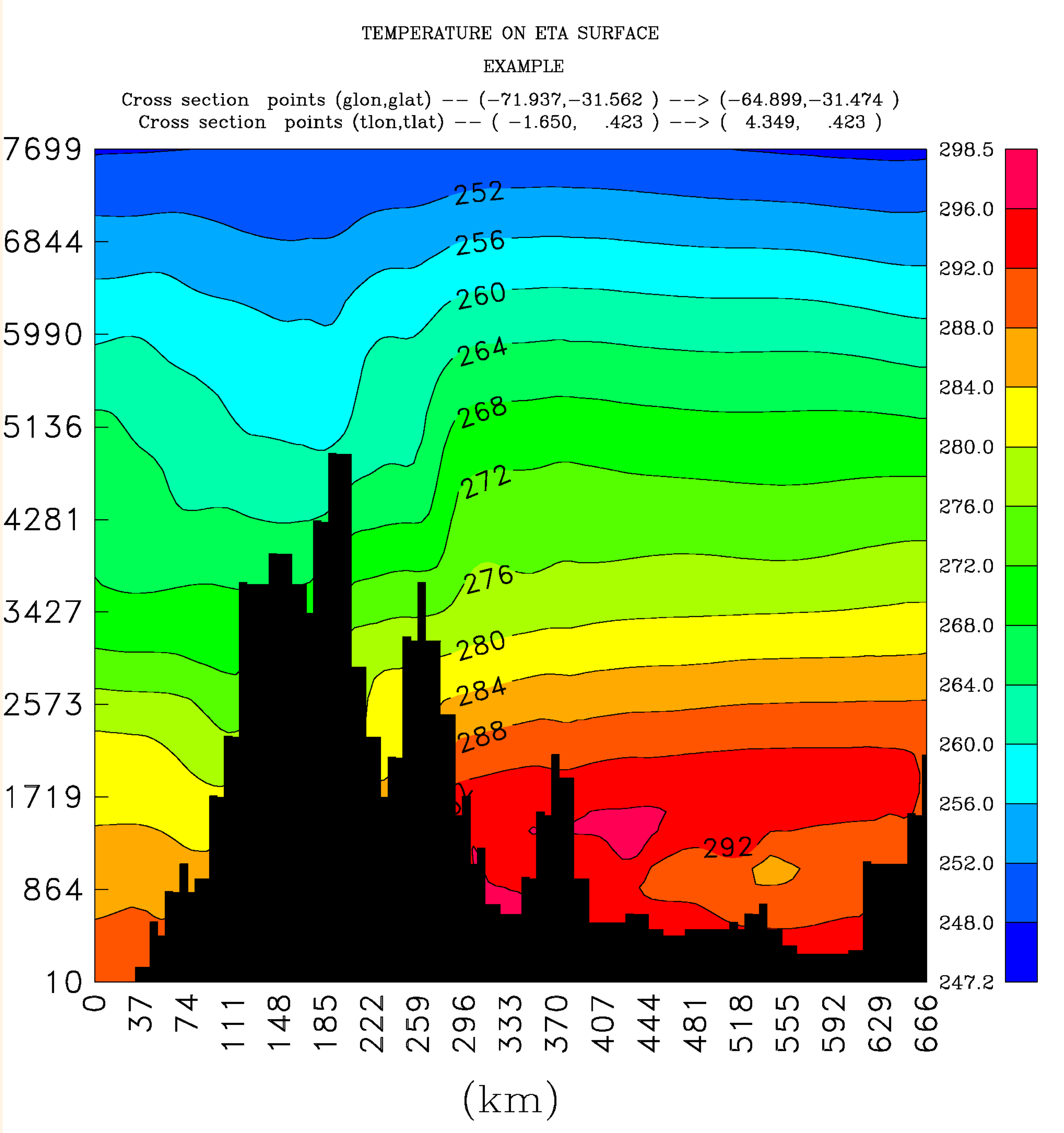
ABSTRACT

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"


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
0
37
74
111
148
185
222
259
296
333
370
407
444
481
518
555
592
629
666
(km)
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

## 2) 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

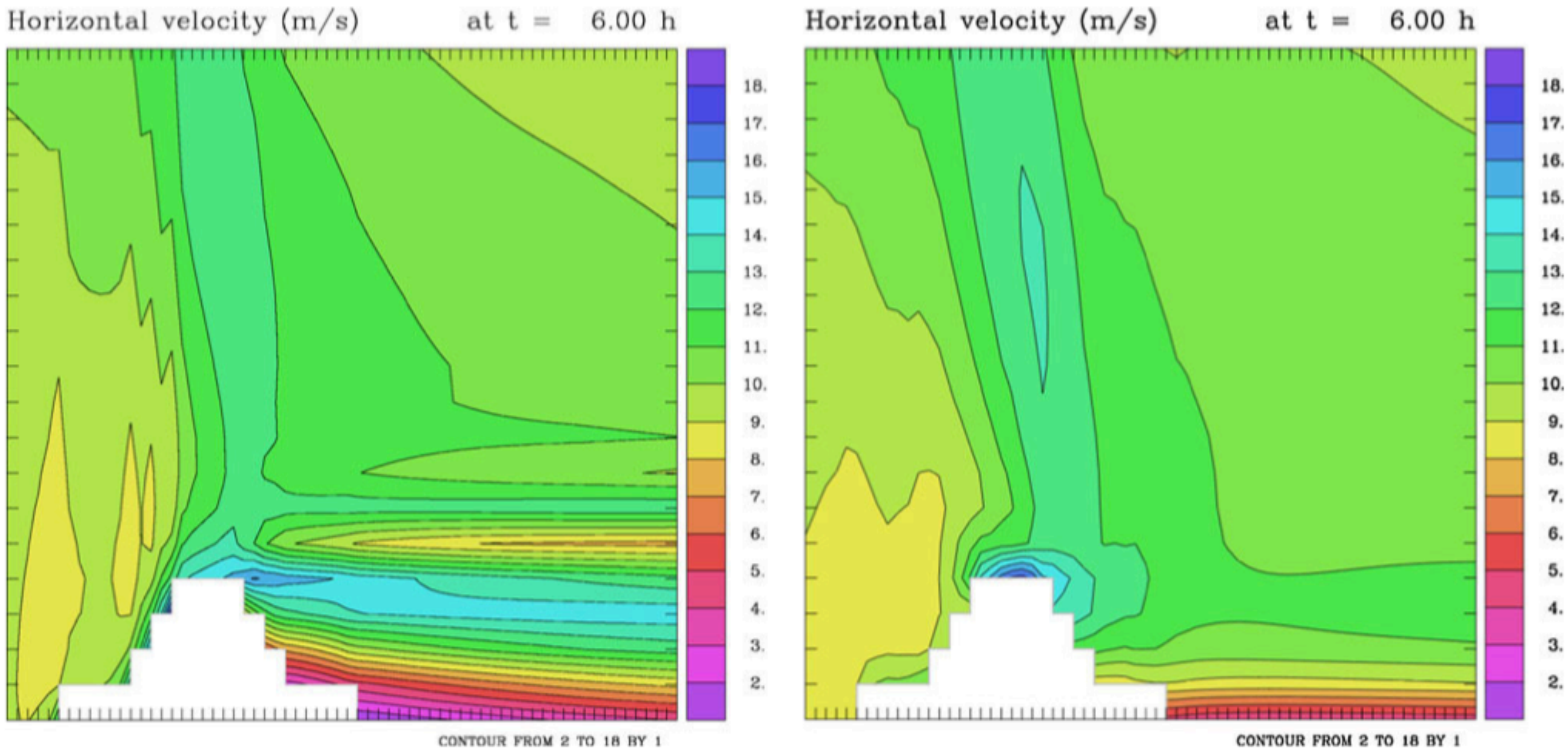
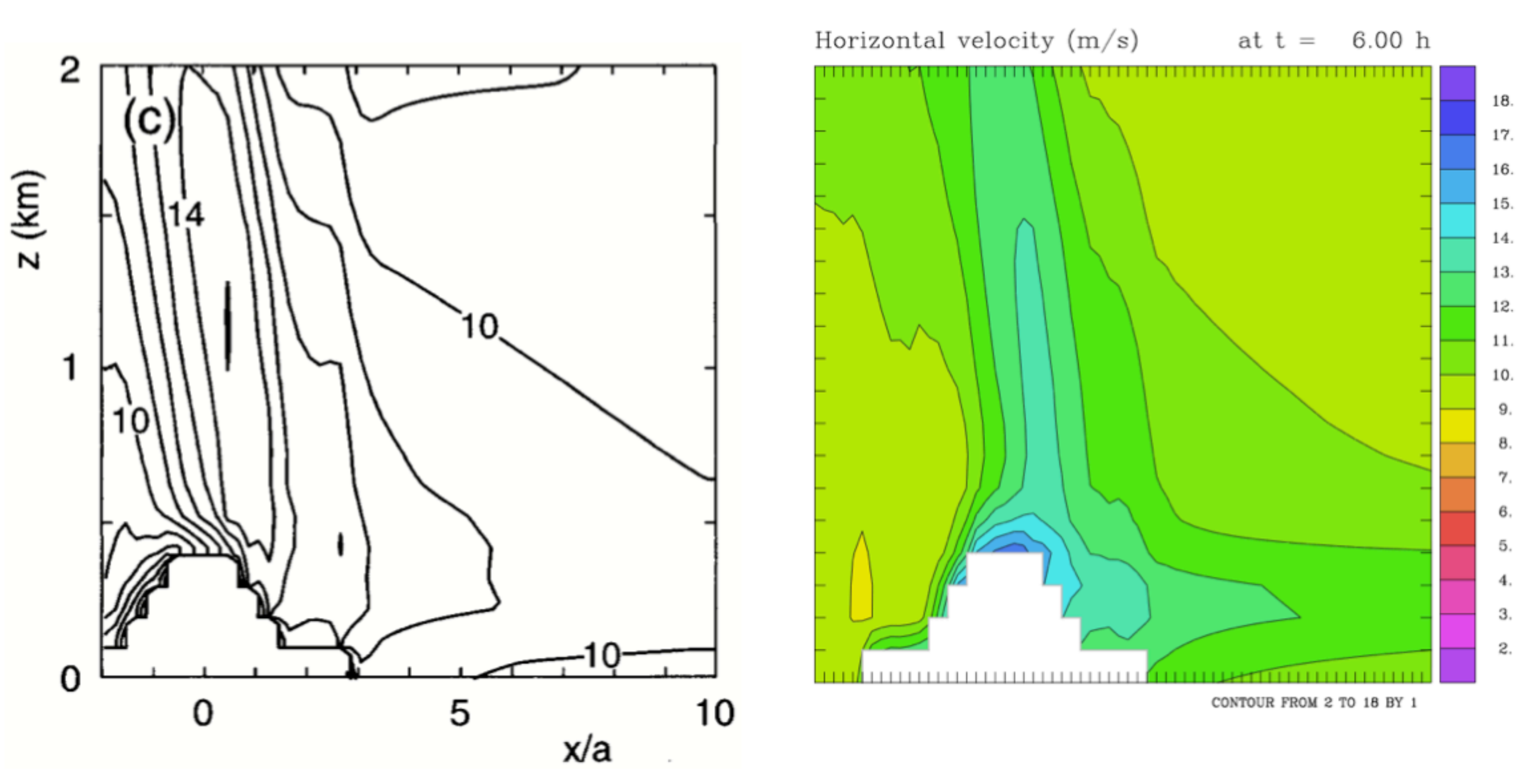



**Fig. 3** Gallus–Klemp experiment, with parameters chosen so as to mimic the results shown in Gallus–Klemp (2000) Fig. 6. Control, *left panel*; code using sloping steps eta discretization, *right panel*

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.

# 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 #1 asked:

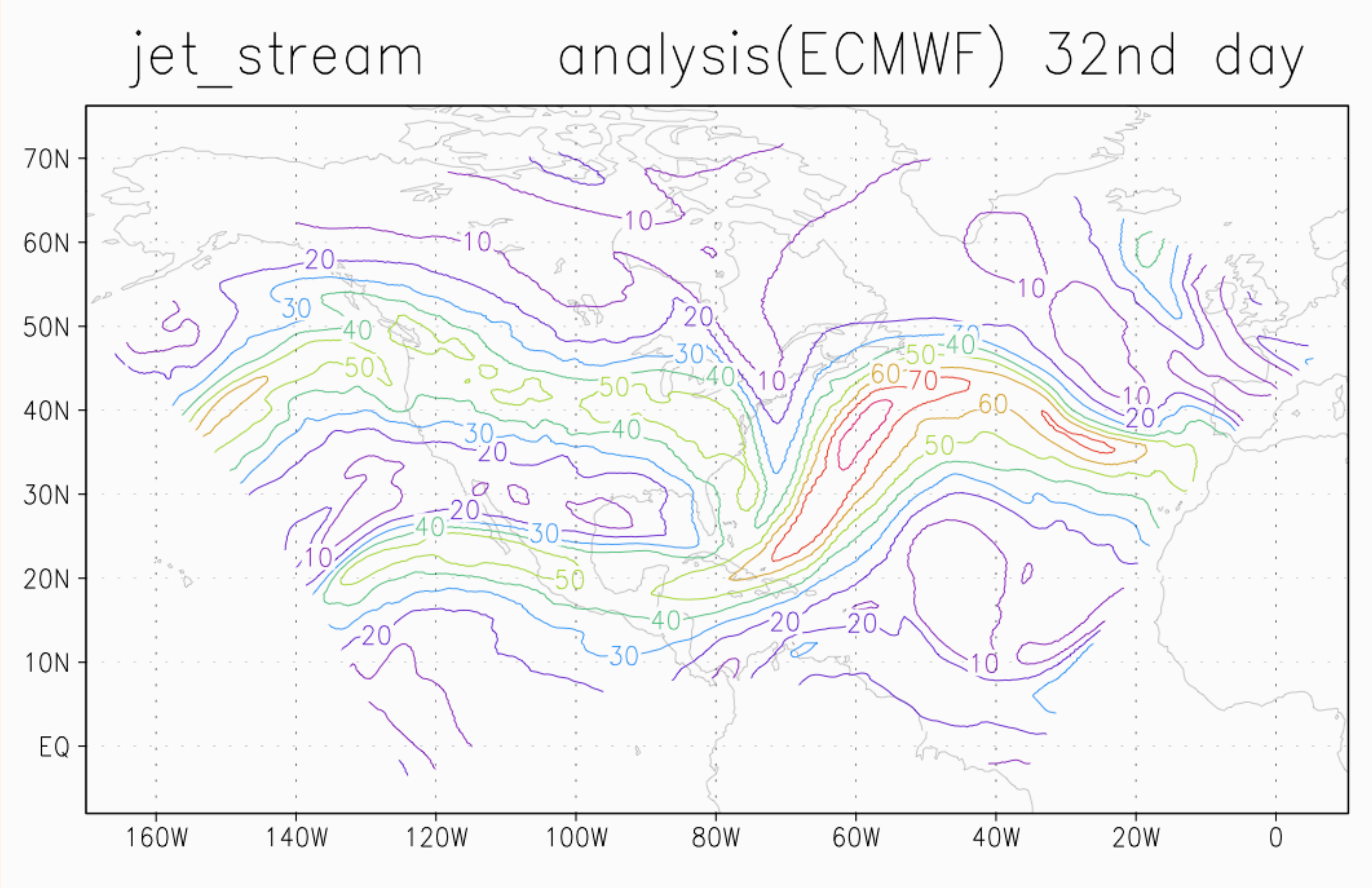
**Can a nested model improve on large scales ?**

How do we look at "large scales" ?

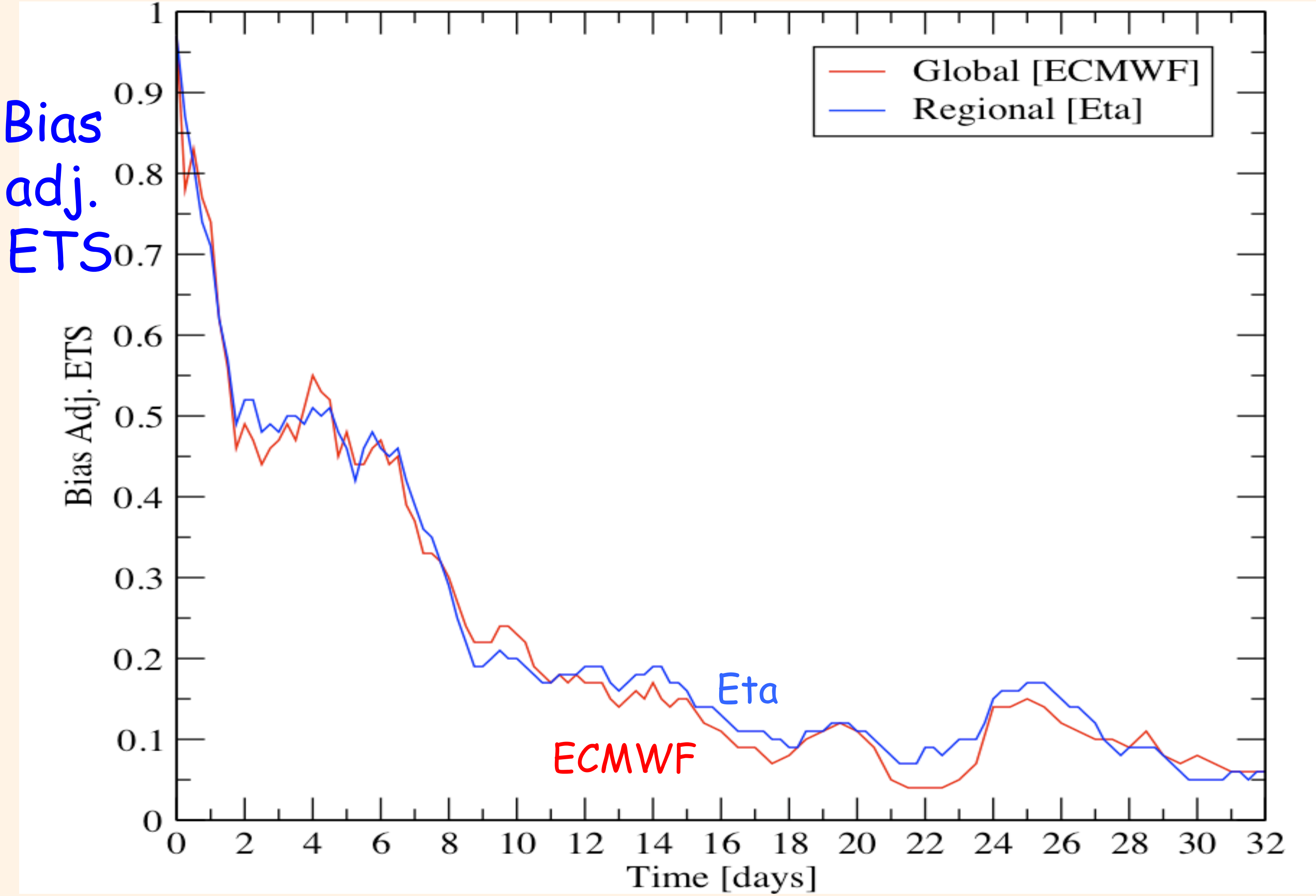
Winds at 250 hPa, position of the jet stream !

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

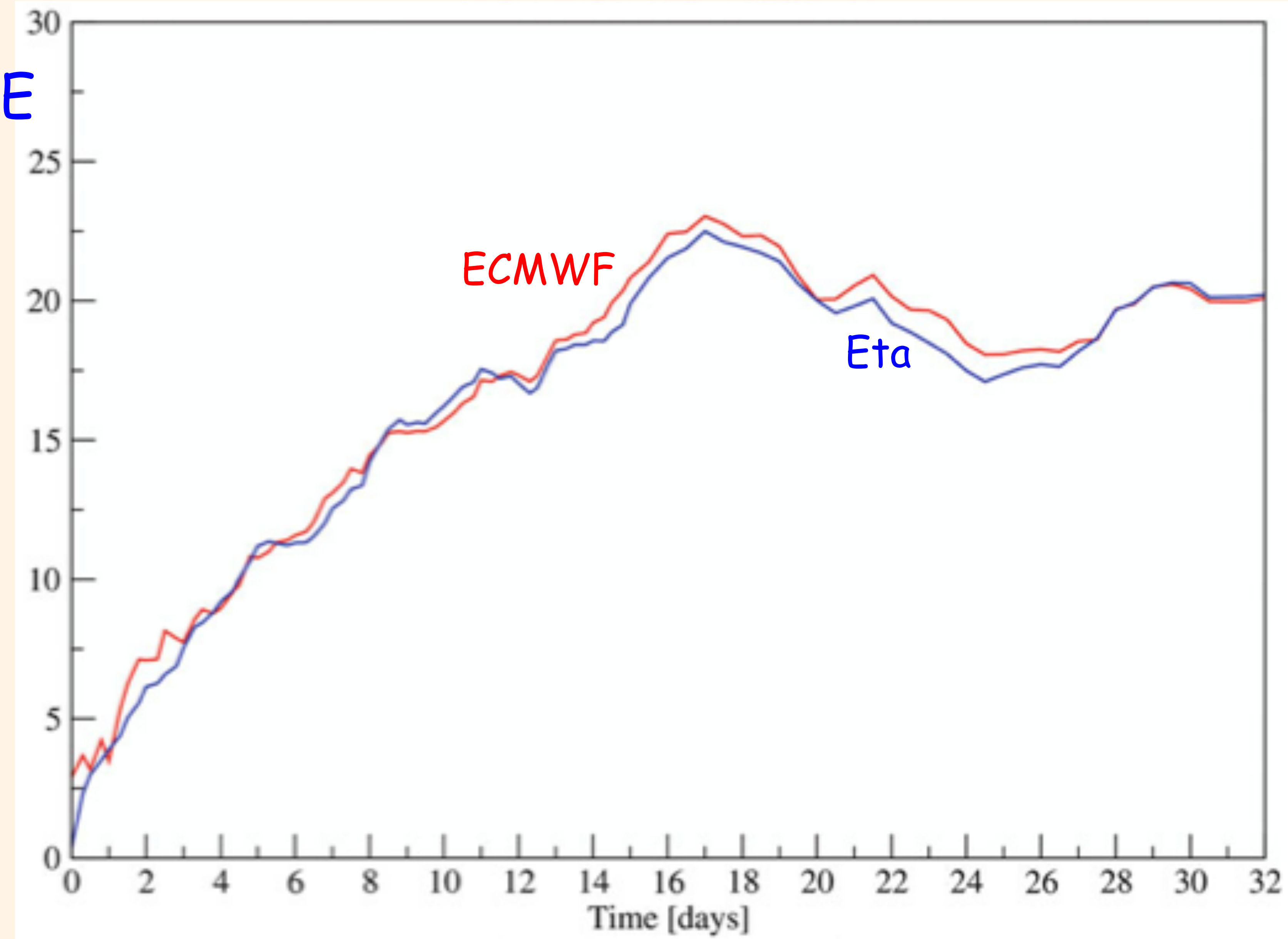

jet_stream analysis(ECMWF) 32nd day
70N
60N
50N
40N
30N
20N
10N
EQ
160W
140W
120W
100W
80W
60W
40W
20W
0

Results: 26 members 32-day forecasts, winds > 45 m/s:



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

RMSE



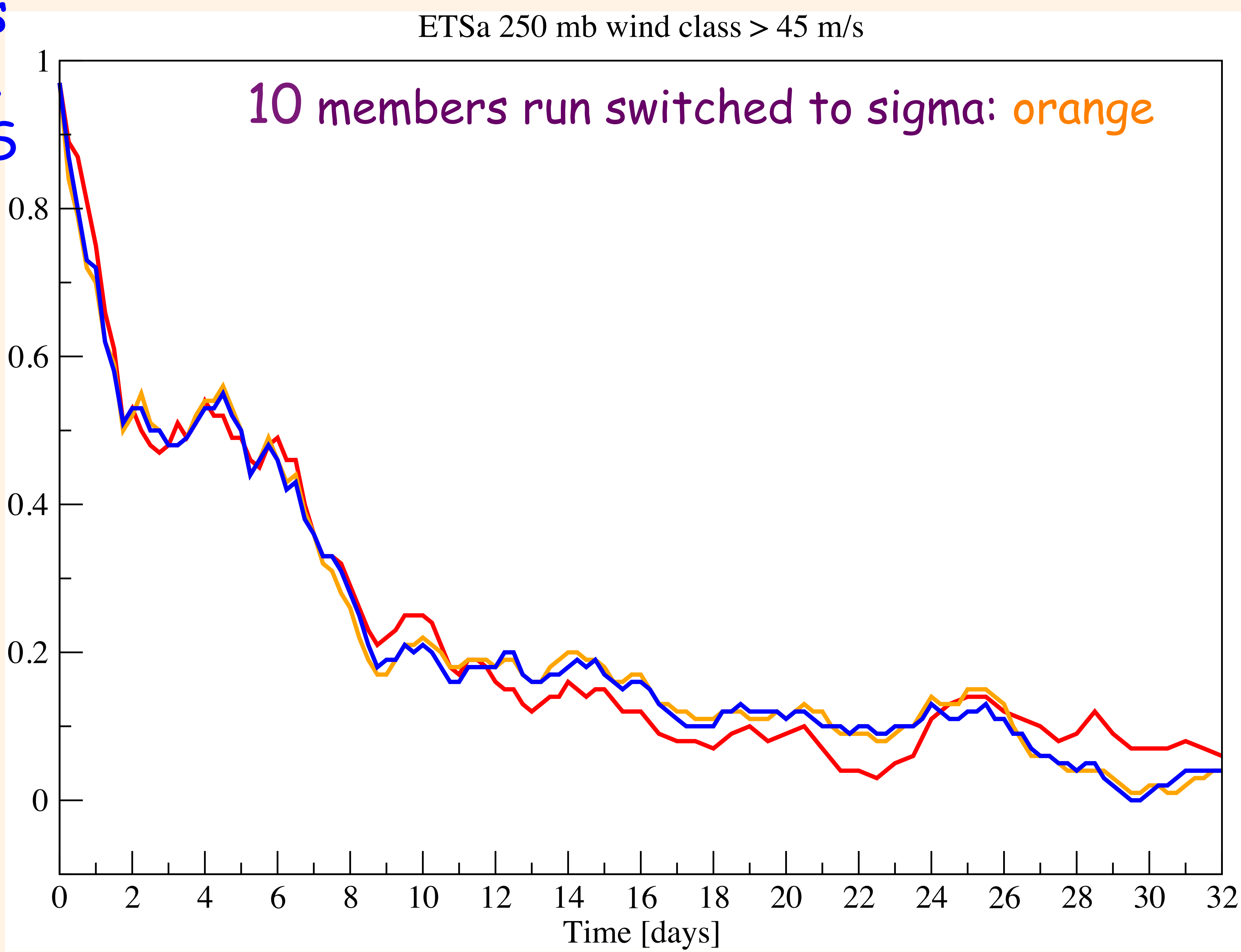
## What made this possible / main reason(s) ?

## 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

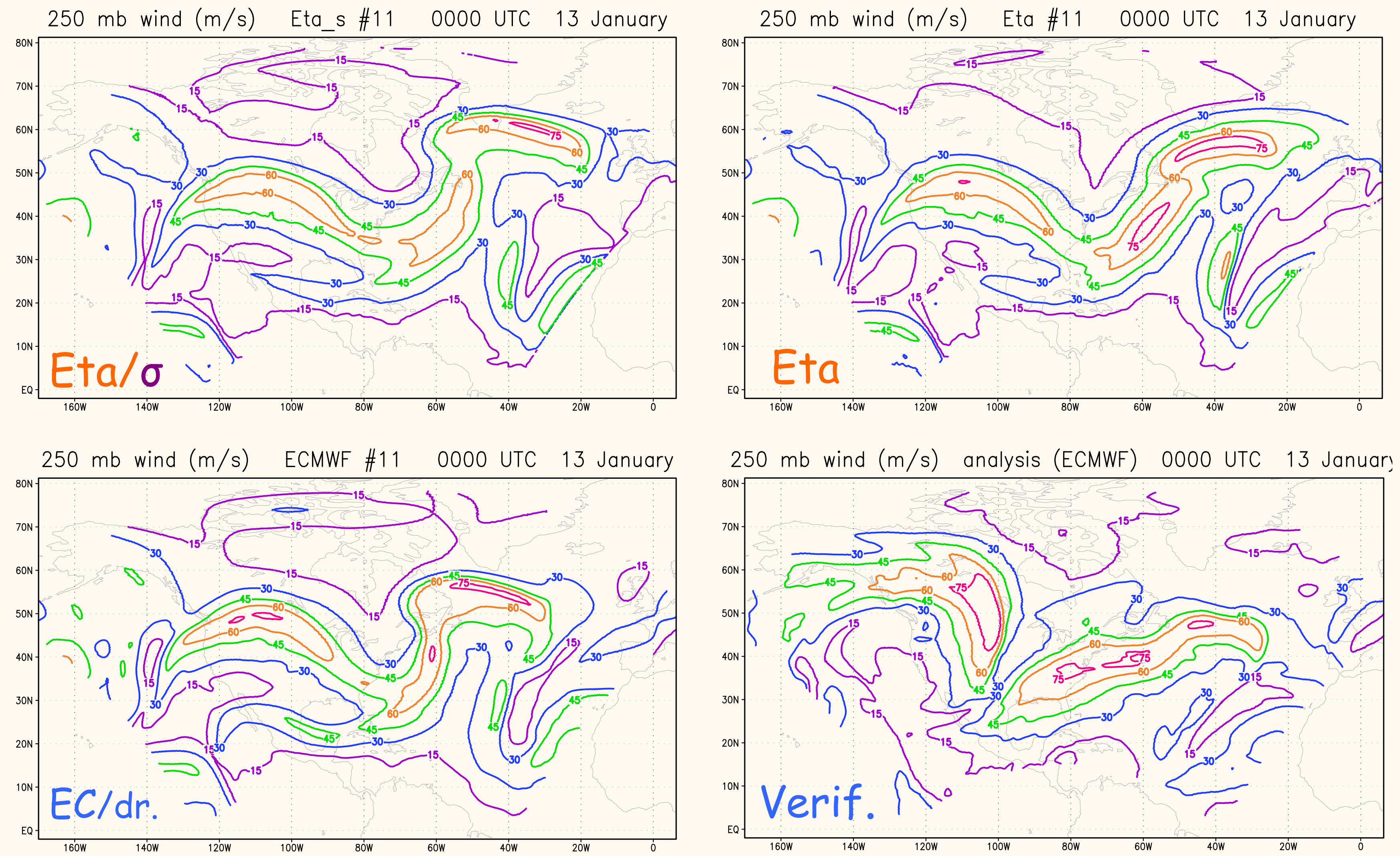
Bias adj. ETS



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.

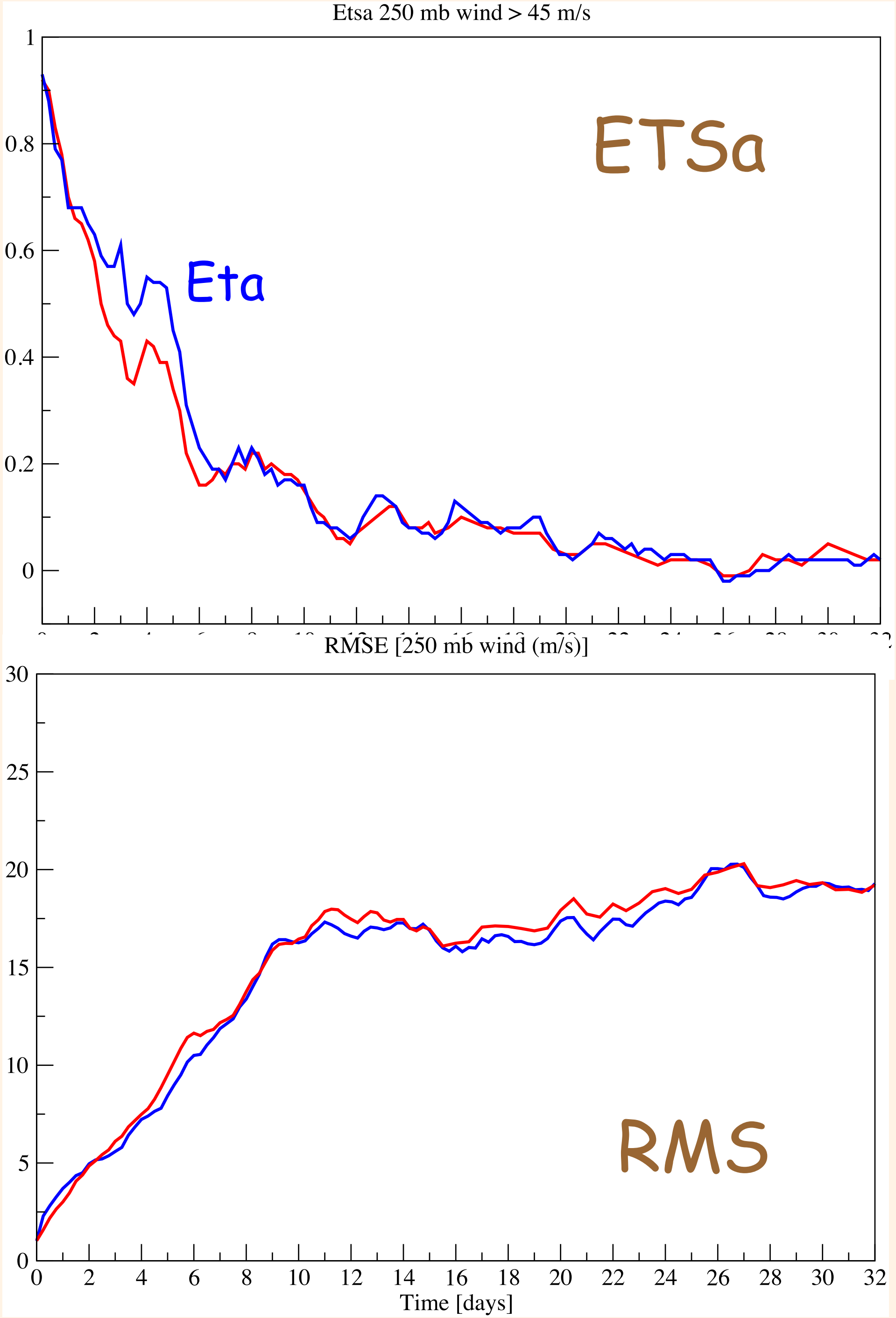
**This kind of an advantage for Eta in 3 out of 10 members. In one member sigma had a more accurate tilt.**

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

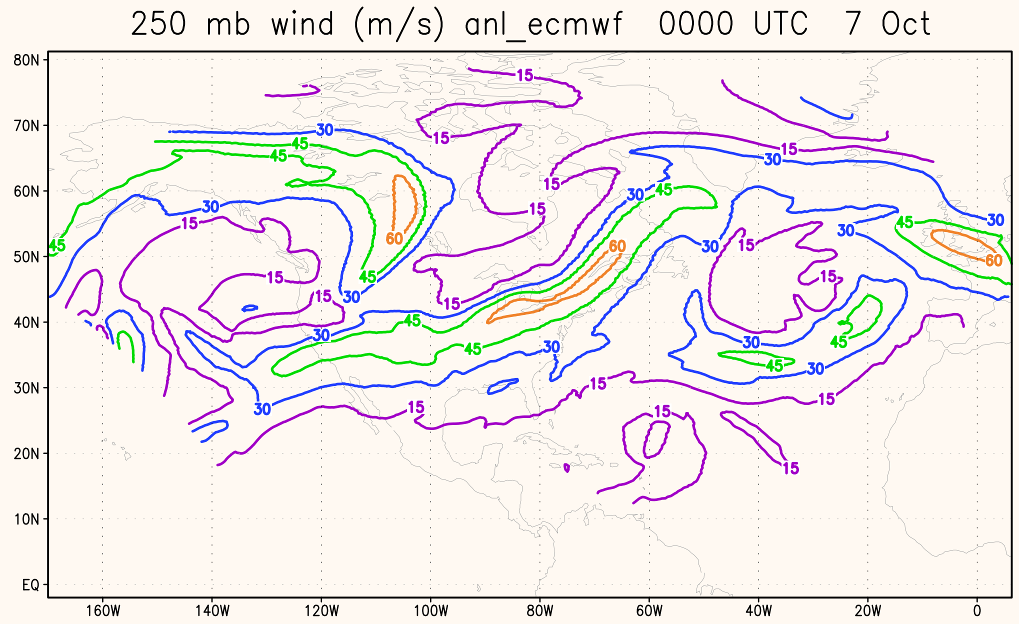
Bias adjusted ETS scores of wind speeds greater than 45 m $s^{-1}$, upper panel, and RMS wind difference, lower panel, of the driver ECMWF ensemble members (red) and Eta members (blue), both at 250 hPa and with respect to ECMWF analyses.

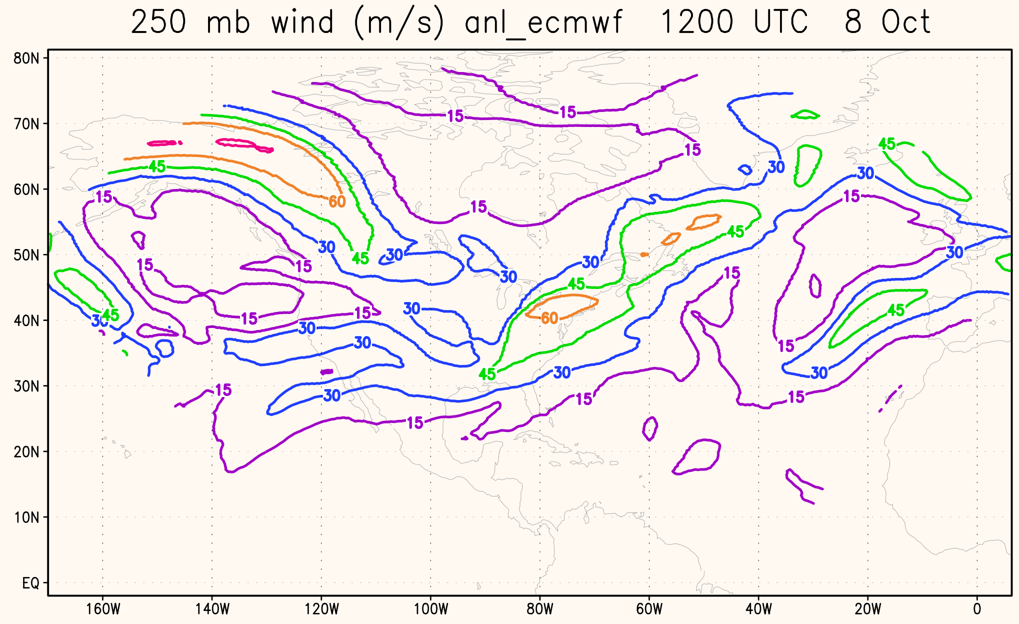
Initial time is 0000 UTC 4 October 2012



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

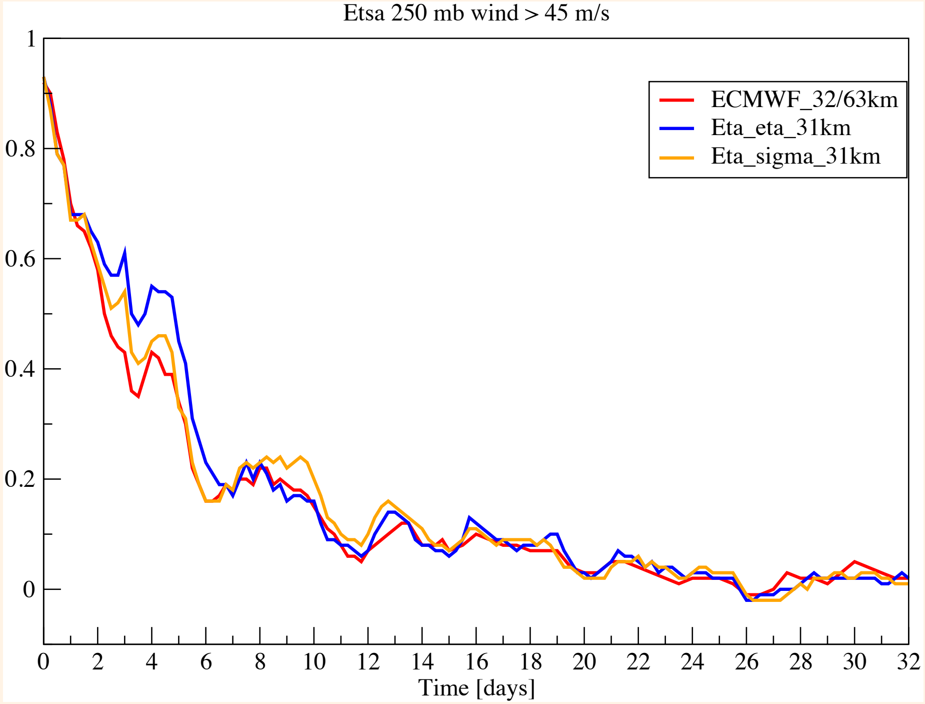
The plot times correspond to day 3.0, and 4.5, respectively, of the plots of the preceding slide

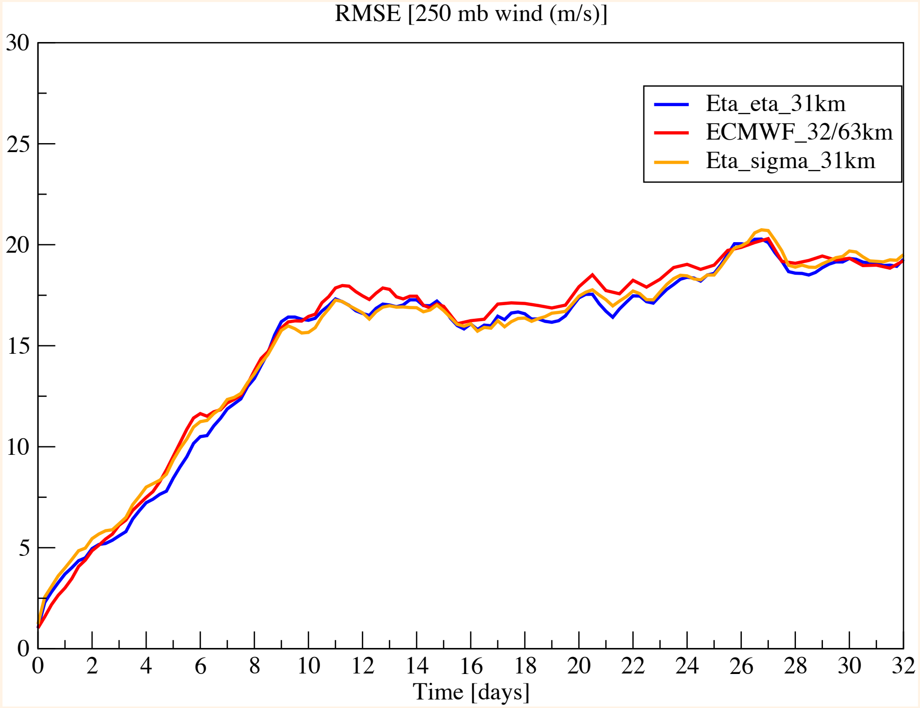


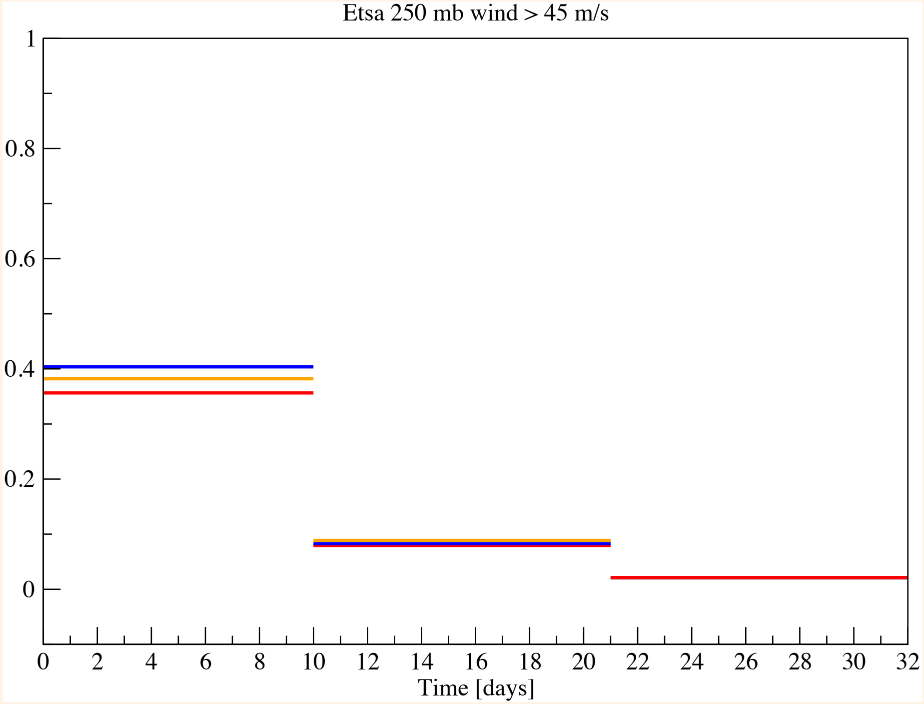
# Eta coordinate ?

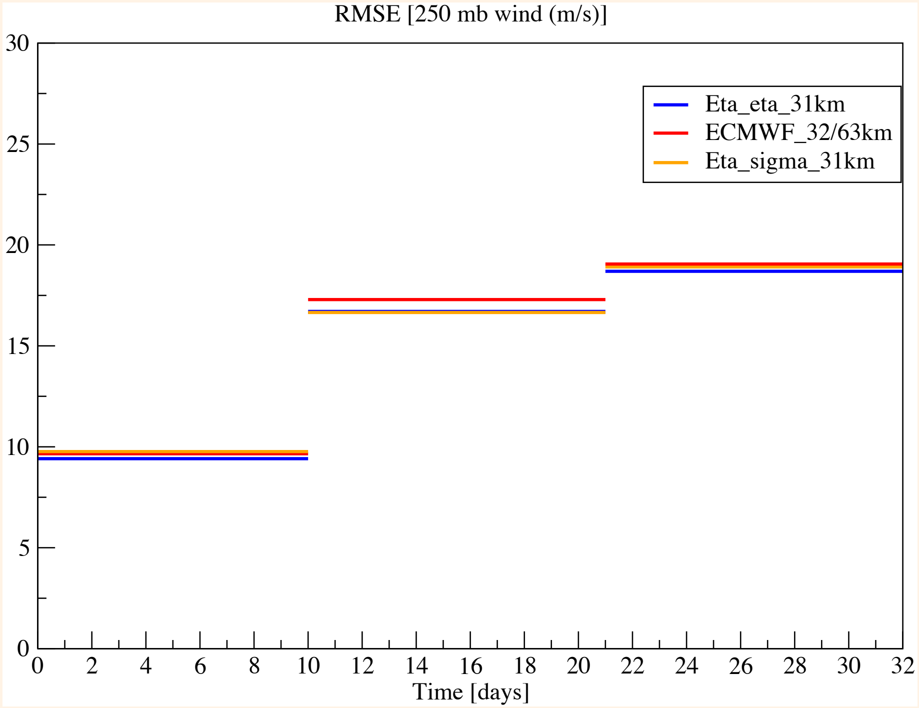
## Eta switched to use sigma:



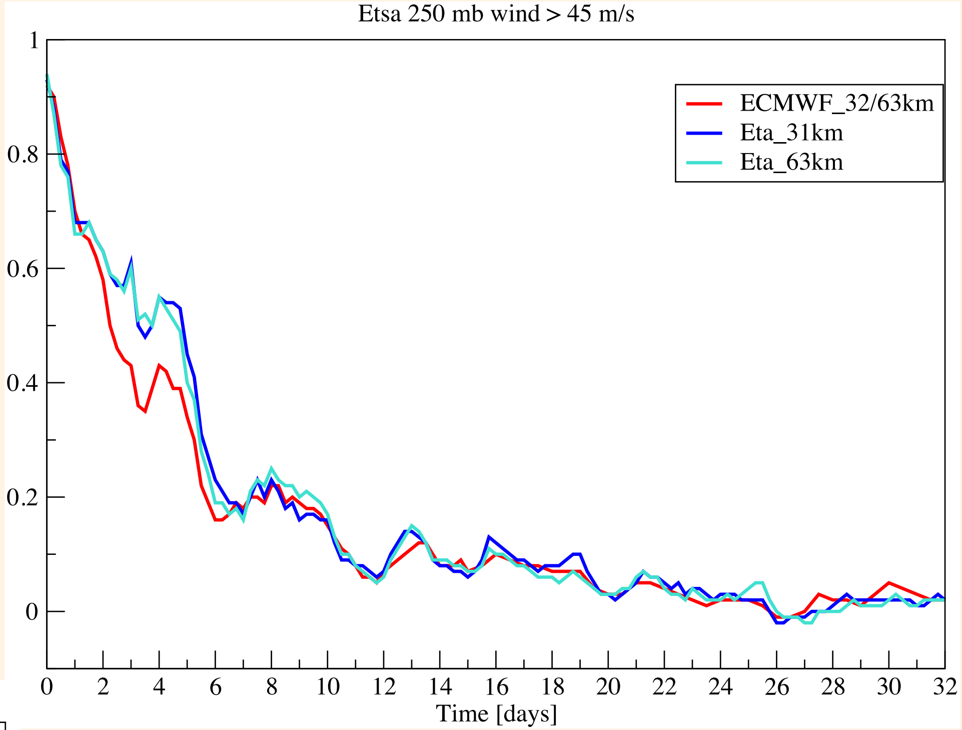



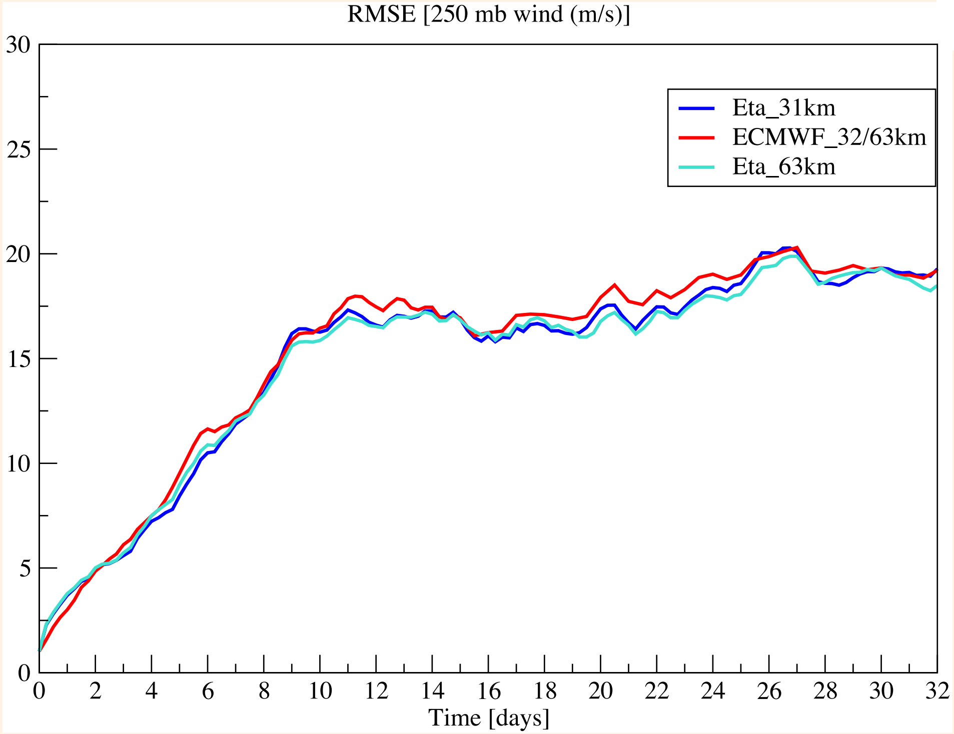
# 10, 11, 11 day averages:



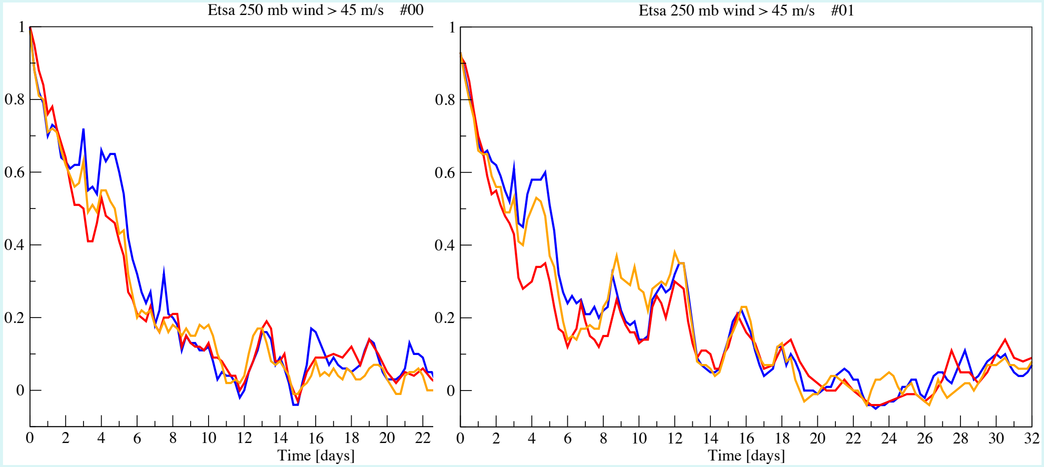
# Resolution ?

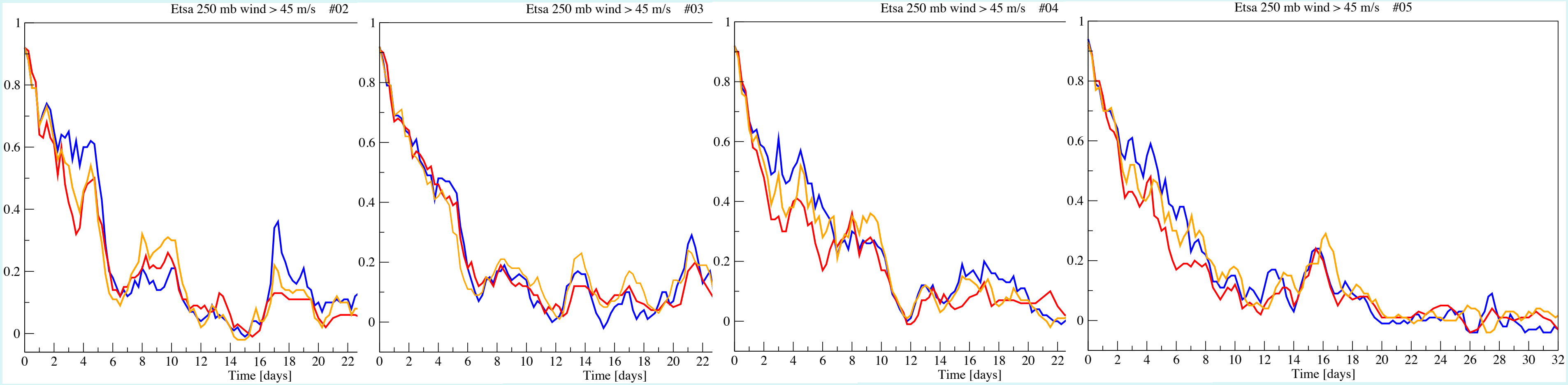


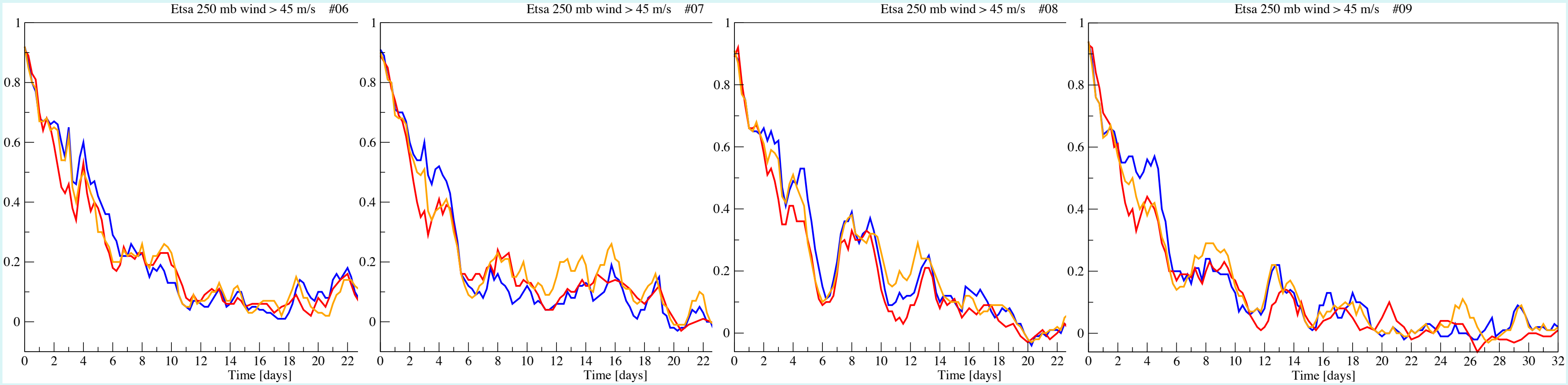




# No visible impact !!

# 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

# 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.

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 . . .

# 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.

*Acknowledgments*. It was under the directorship of Eugenia Kalnay of the Development Division of the then National Meteorological Center in the early nineties that critical steps took place enabling the Eta model to achieve its prominence, this having been made possible by Eugenia's respect for results – as opposed to a pre-established plan as to what should happen. Attention to the horizontal diffusion of the Eta was prompted by comments from Sandra Morelli, of the University of Modena, Italy; and experiments that led to the discovery of the problem at 1-km resolution were carried out by Jorge Luis Gomes, and Gustavo Sueiro, of the Center for Weather Prediction and Climate Studies (CPTEC), Cachoeira Paulista-SP, Brazil. Fedor Mesinger's work on the development of the "sloping steps" discretization of the Eta dynamical core has been partially funded by NCEP/EMC via grants to ESSIC, University of Maryland, College Park, MD, awarded by Stephen Lord, then EMC Director. Subsequent work on the Gallus-Klemp problem reported on here was done within a visit of Fedor Mesinger to CPTEC, hosted by Sin Chan Chou, under a grant awarded by the National Council for Scientific and Technological Development (CNPq), Brazil. Our work has been partially supported by the Serbian Academy of Sciences and Arts, via grant F-147, and that of Katarina Veljovic by the Ministry of Science and Technological Development of the Republic of Serbia, under Grant No. 176013.

# Some of the references that might have been used:


Black, T. L., 1988: *The step-mountain eta coordinate regional model: A documentation*. NOAA/NWS National Meteorological Center, April 1988, with revisions later. 47 pp. Available from NCEP Environmental Modeling Center, 5830 University Research Court, College Park, MD 20740.

Chao, W. C., 2012: Correction of excessive precipitation over steep and high mountains in a GCM. *J. Atmos. Sci.*, **69**, 1547-1561.

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

McAfee, S. A., J. L. Russell; P. J. Goodman, 2011: Evaluating IPCC AR4 cool-season precipitation simulations and projections for impacts assessment over North America. *Climate Dyn.*, **37**, 2271-2287.

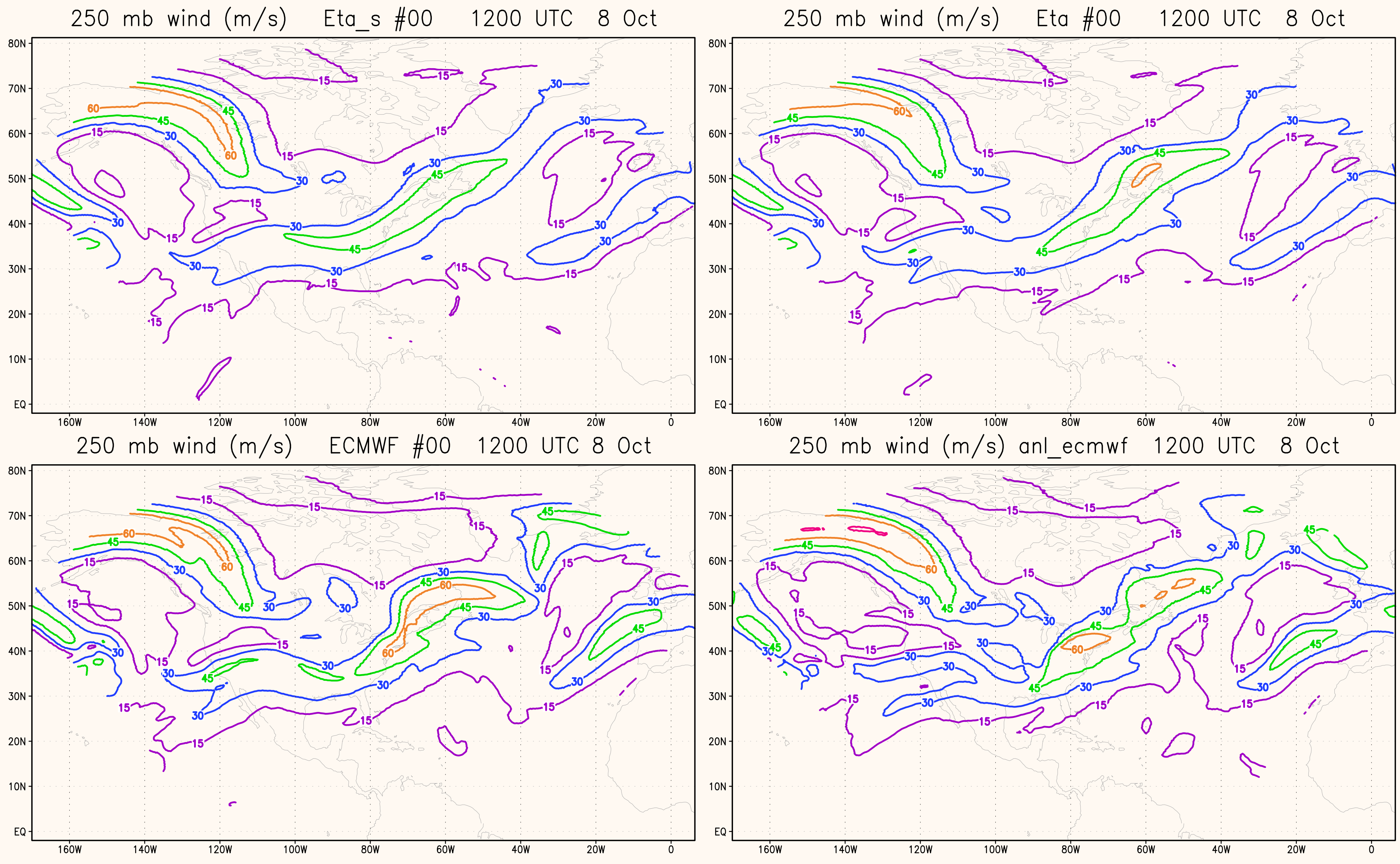
Mesinger, F., 2008: Bias adjusted precipitation threat scores. *Adv. Geosciences*, **16**, 137-143. [Available at http://www.adv-geosci.net/16/index.html.]

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.

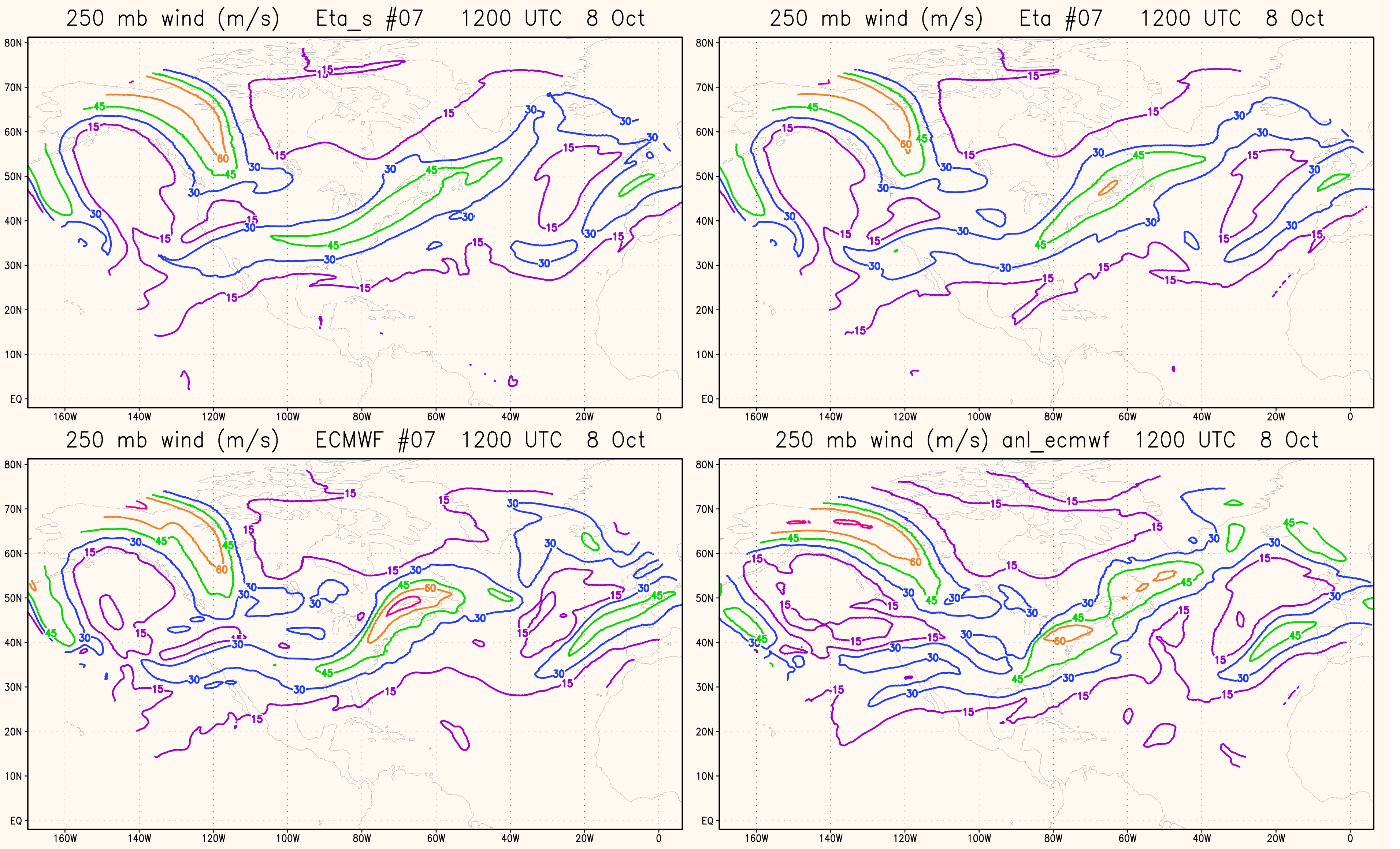
Mesinger, F., S. C. Chou, J. Gomes, D. Jovic, P. Bastos, J. F. Bustamante, L. Lazic, A. A. Lyra, S. Morelli, I. Ristic, and K. Veljovic, 2012: An upgraded version of the Eta model. *Meteor. Atmos. Phys.*, **116**, 63-79 [Available at http://www.springerlink.com/content/0177-7971/116/3-4/.]

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.

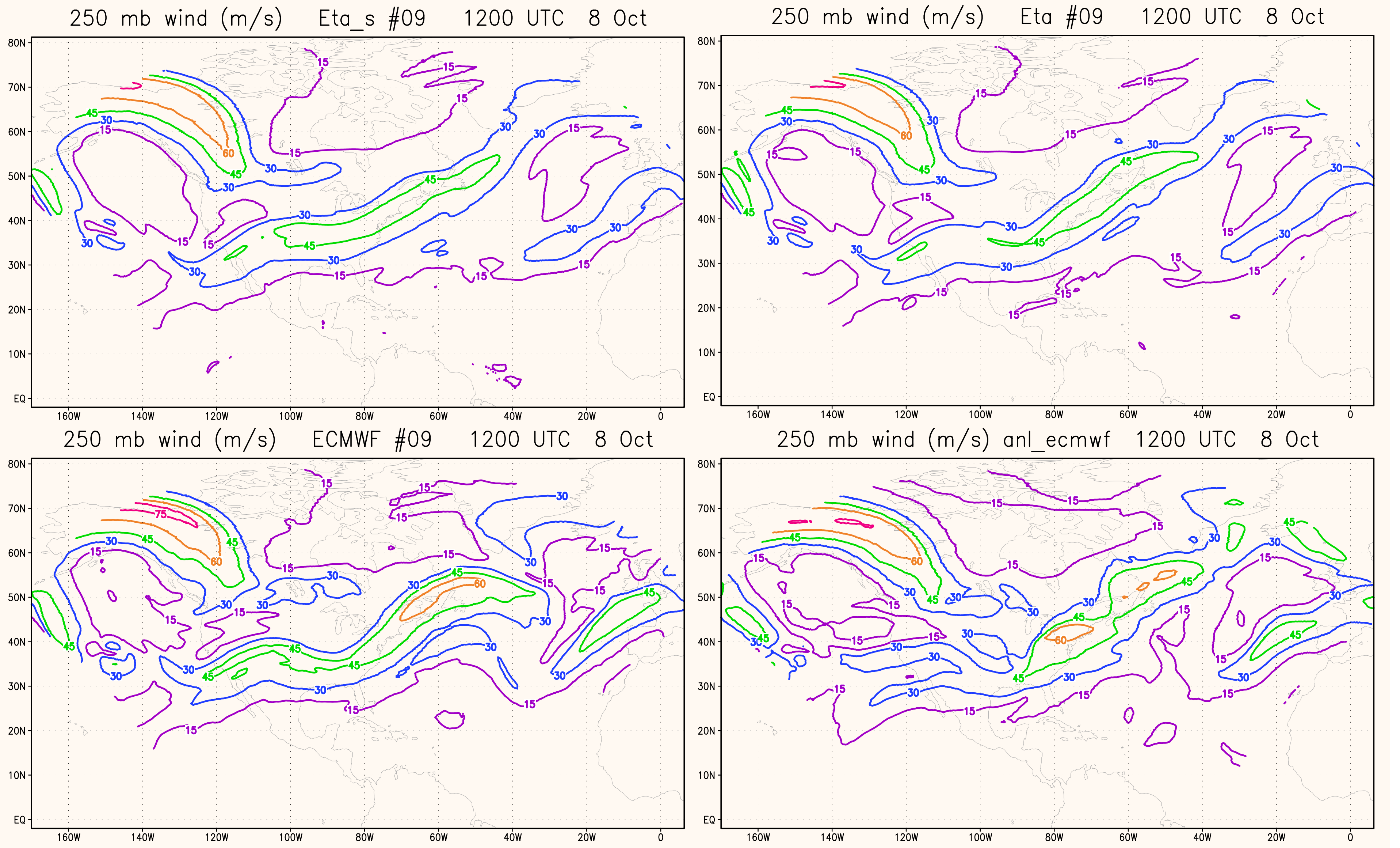
Steppeler, J., H. W. Bitzer, Z. Janjic, U. Schättler, P. Prohl, U. Gjertsen, L. Torrisi, J. Parfinievicz, E. Avgoustoglou, and U. Damrath, 2006: Prediction of clouds and rain using a *z*-coordinate nonhydrostatic model. *Mon. Wea. Rev.*, **134**, 3625–3643.




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




Ensemble members 07 at 4.5 day time: Eta/sigma top left, Eta top right, EC driver bottom left, EC verification analysis bottom right.




Ensemble members 09 at 4.5 day time: Eta/sigma top left, Eta top right, EC driver bottom left, EC verification analysis bottom right.