Regional Climate Modeling: Challenges and Issues

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Entrenamiento en Modelado Numérico de Escenarios de Cambio Climático

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Contents

- RCM role in the climate change effort
- Issues

    René Laprise et al.'s menu of tenets

    Added value?

    Lateral boundary conditions: the problem, schemes, "spectral nudging"

    More on added value: can one (should one try to) add value at large scales?

    Why does it matter? Resolution vs domain size

    . . . . .

- Sample applications

    South America: present climate, projections

    Mediterranean: same, coupled atmosphere/ocean RCM

- The future

RCMs: obtain improved regional climate information. Why?

IPCC AR4 MMD (multi-model data set) used results of 21 global models;

atmospheric components resolution: 400 to 125 km

Met Office "Centennial Model" 2009 (G. Pankiewicz, Workshop I):

135 km/ 38 L

Regional information ?

Dynamical downscaling

Variable resolution AGCMs

Nested regional climate models

Empirical and statistical downscaling methods

Some history

- Dickinson et al. (1989): Enhanced MM4 (radiation, land surface), but ran a sequence of short (few days) integrations;
- Giorgi and Bates (1989): "perfect" boundary conditions, month long integrations;
- Giorgi (1990): GCM-driven experiments

. . . multi-year, decadal, . . .

Resolution: 50-125 km initially, nowadays ~50 and ~25 km, and less . .

Coupled RCMs (regional ocean, ocean/ice, chemistry, . . .)

Recent reviews:

Giorgi, *J. Phys. IV France* 139 (2006);

Christensen, Hewitson, et al., *Climate Change 2007,* Ch. 11;

Laprise et al., *Meteorol. Atmos. Phys.* 100 (2008)

Issues: added value

How/ for what features can one "add value"?

(Higher resolution ! Additional processes also…)

- Fine scale topographic features

  (e.g., precipitation over Great Britain, GCM vs RCM)

- Extreme events;
- Complex coastlines;
- Mesoscale circulations driven by surface heterogeneity
- . . . . .

Example:

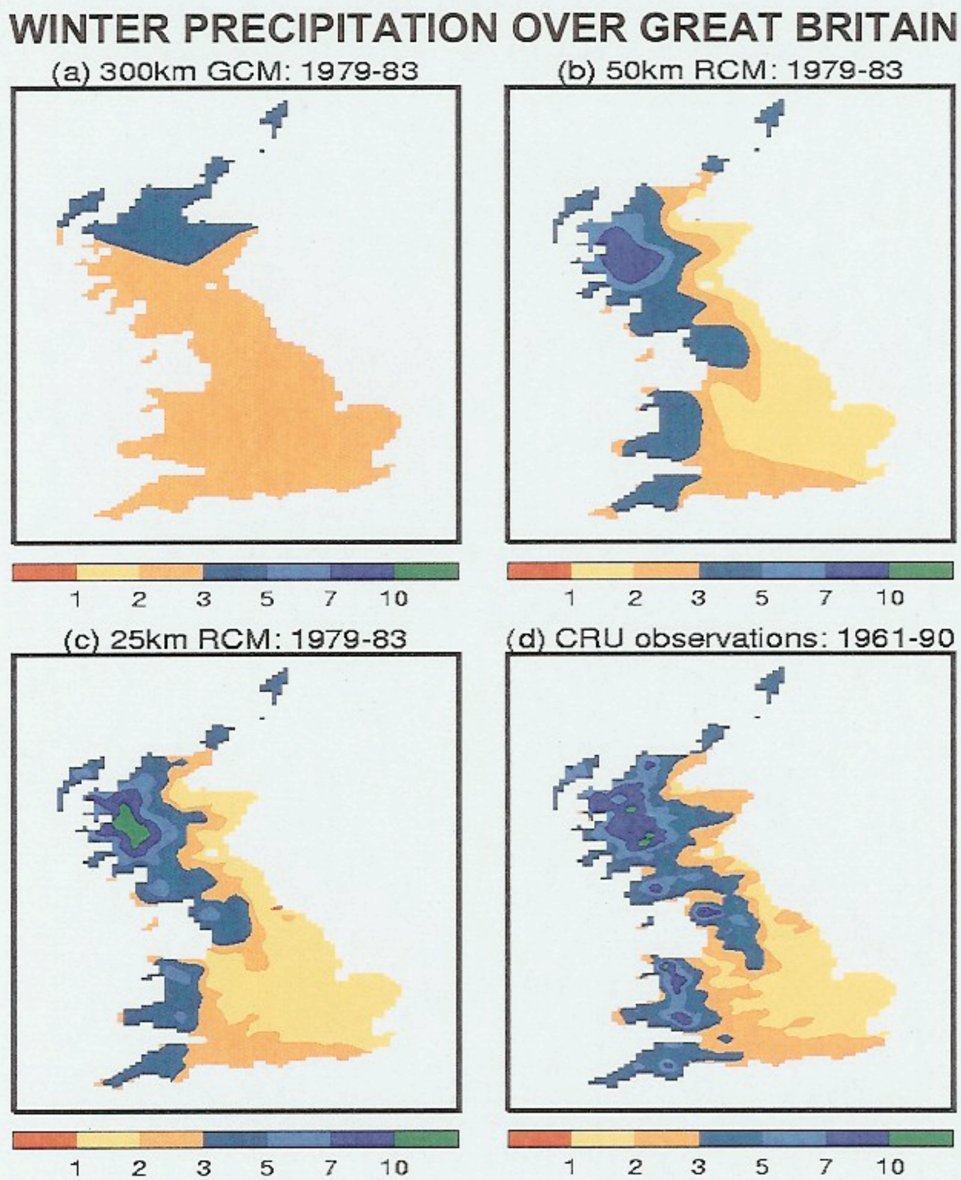

Figure 2. Winter precipitation (mm/day) over Great Britain as simulated by a GCM (a) and an RCM at 50 km (b) and 25 km (c) grid spacing. Corresponding observations are shown in (d). The improved agreement with observations at the higher RCM resolutions is evident. (Courtesy of R.G. Jones).

From:
Giorgi (2006)

Issues: added value, cont'd

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Laprise et al. (Met. Atmos. Ph., 2008) tenets:

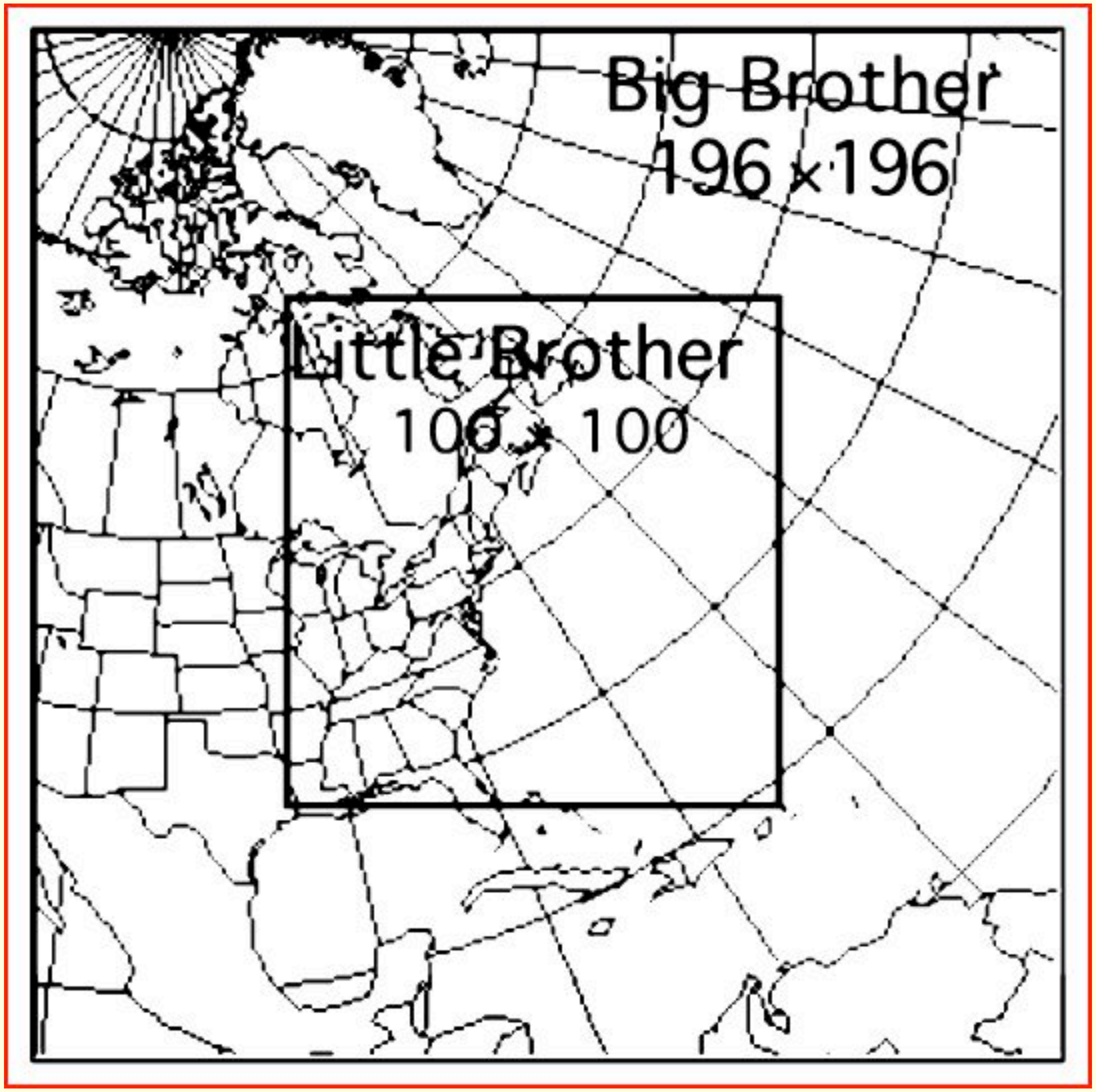
- Tenet 1: RCMs are capable of generating small scale features absent in the driving fields supplied as lateral boundary conditions (LBC);

- Tenet 2: The small scales that are generated have the appropriate amplitudes and climate statistics;

- Tenet 3: The generated small scales accurately represent those that would be present in the driving data if it were not limited by resolution;

- Tenet 4: In performing dynamical downscaling, RCM generated small scales are uniquely defined for a given set of LBC.

"Big Brother Experiments"



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Right location, time: No

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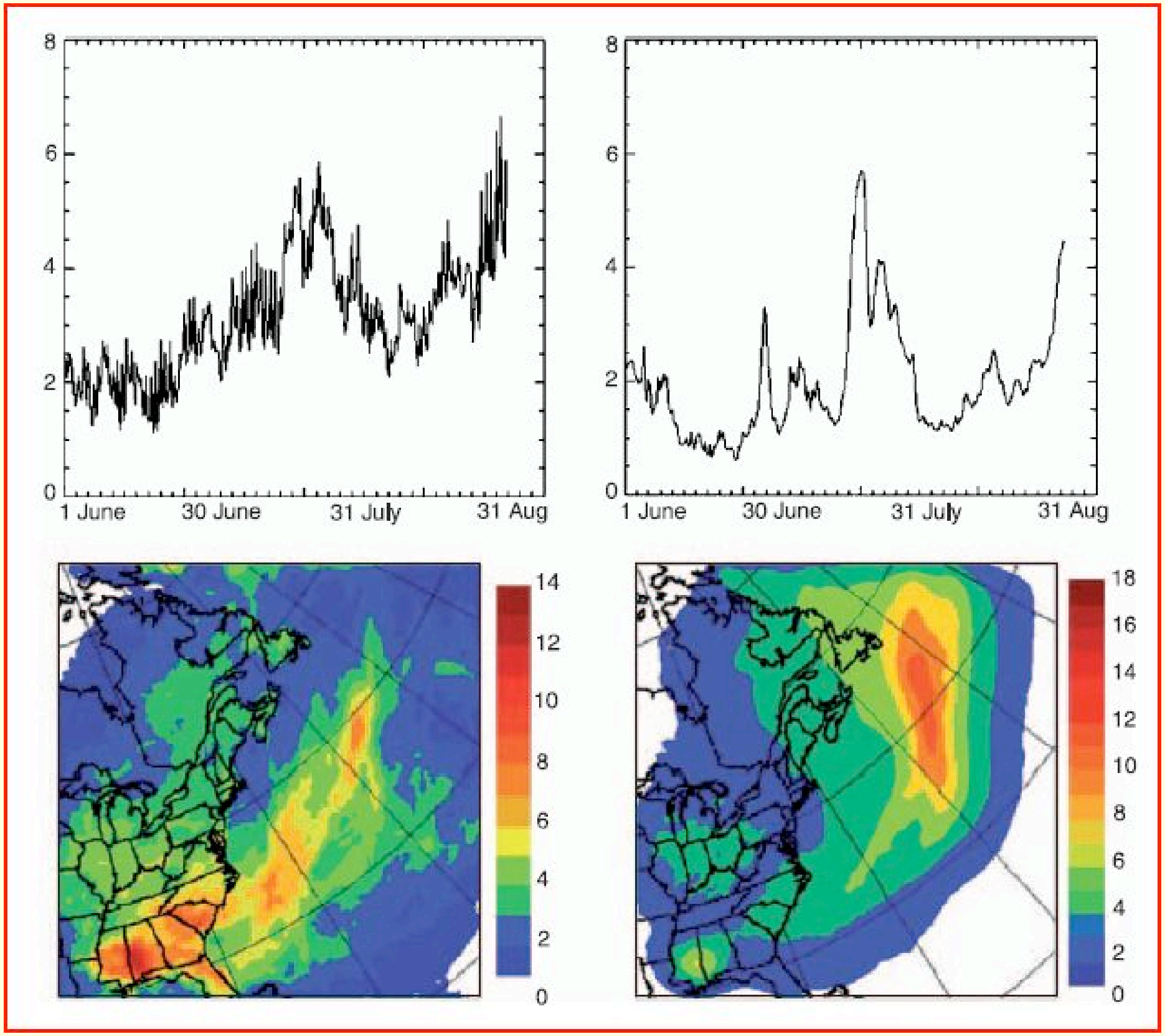

Time evolution of the domain-average inter-member spread (top row) and spatial distribution of the time average inter-member spread (bottom row), for precipitation (left column, in mm da_1) and 850-hPa geopotential (right column, in m). The inter-member spread is defined as the rms difference between the individual members and the ensemble mean (Laprise et al. Fig. 7)

"Internal variability" (IV)

smaller than natural, depending on domain size; additional to differences between ens. members resulting from model changes, or choice of models

Laprise et al. "Tenet 5":

- Tenet 5a: The large scales are unaffected within the RCM domain;

- Tenet 5b: The large scales may be improved owing to reduced truncation and explicit treatment of some mesoscale processes with increased resolution within the RCM domain;

- Tenet 5c: The scales larger than or comparable to the RCM domain are degraded because the limited domain is too small to handle these adequately

If you believe in 5c, or if this is "your religion":

"spectral (or, large scale) nudging" inside the domain !

Motivation:

"An fundamental assumption in using RCM states that the large-scale atmospheric circulation in the driving data and in the RCM should remain the same at all time" (Lucas-Picher et al., 2004)

Denis et al. (2002): "the ineffectiveness of the nesting for controlling the large scales over the whole domain"

Thus, "spectral nudging" (Kida et al., 1991, Waldron et al. 1996; von Storch et al. 2000): provide large scale forcing to the model fields throughout the entire model domain

A lot of discussion at:

http://cires.colorado.edu/science/groups/pielke/links/Downscale/

Castro, C. L., R. A. Pielke, Sr., and G. Leoncini: 2005: Dynamical downscaling: Assessment of value retained and added using the Regional Atmospheric Modeling System (RAMS). *J. Geophys. Res.*, 110, D05108, doi: 10.1029/2004JD004721

Castro et al., 4 types of downscaling:

Type 1: NWP (results depends on initial condition);

Type 2: "Perfect" LBCs (=reanalysis) *

Type 3: GCM (=predicted) LBCs, but still specified SSTs inside

Type 4: Fully predicted, both LBCs and inside the RCM domain

* In the paper as published, GCM also included within Type 2

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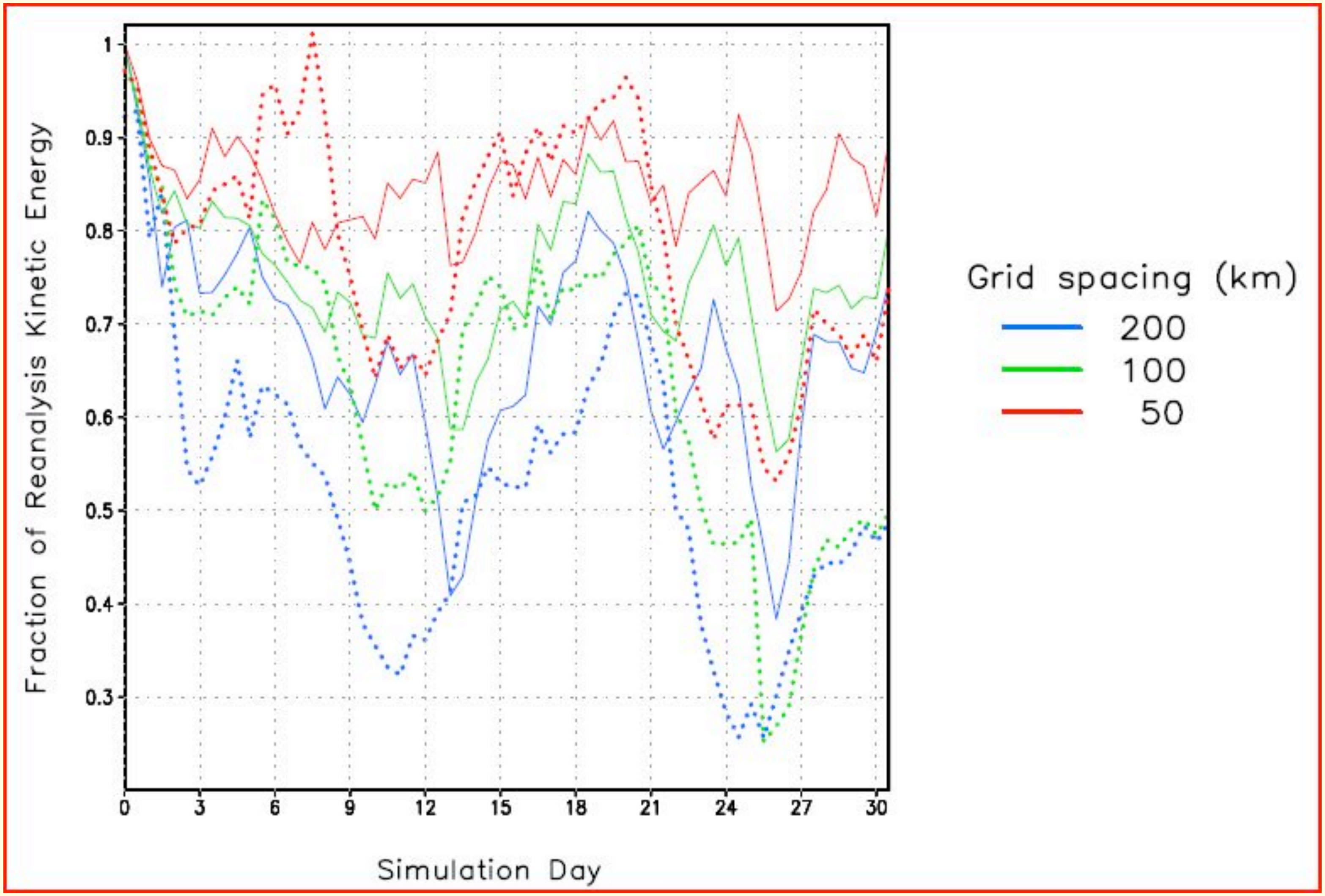
Castro et al.: Type 2, conclusions:

"Absent interior nudging . . . . failure of the RCM to correctly retain value of the large scale . . ."

". . . underestimation of kinetic energy …" "The results here and past studies suggest the only solution to alleviate this problem is to constrain the RCM with the large-scale model (or reanalysis) values."



Time evolution of the fraction of model simulated to reanalysis regridded domain-averaged total kinetic energy for the six basic experiments on equivalent grids. The small domain is indicated by a solid curve, and the large domain is indicated by a dashed curve. (Castro et al., Fig. 6)

The discussion: 35 very small font pages of e-mails …

One e-mail:

Hi Barry

I do not see how a regional model can reproduce realistic long wave patterns, as these are hemispheric features.

Roger

fm:

- We are solving our RCM model equations as an initial-boundary value problem. Doing things inside the domain beyond what RCM equations tell us is in conflict with our basic principles.

Alternative formulation of the same idea: an air parcel inside the RCM knows about forces acting on it, heating it undergoes, etc. It has no allegiance to a given scale !! (It has no idea what goes on on the opposite side of the globe!)

- If the RCM is not doing well the large scales inside the domain, there must be a reason for it;

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fm, cont'd:

- Type 2 experiments in which reanalysis is declared truth and an RCM's performance is assessed according to how close to the reanalysis it gets are not appropriate to answer this question. The purpose of an RCM is to *improve* upon what we have !

  Note that in a "thought experiment" a perfect RCM, one that by definition would behave exactly as the real atmosphere, in a Type 2 experiment would depart from reanalysis more and more as the domain gets bigger! (LBCs are not perfect !!)

- There are results claiming or showing improvements in large scales, and at least one Type 3 - albeit somewhat dated - in which improvement in large scales can hardly be questioned !

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Giorgi et al., Climatic Change, 1998, 40, 457-493;

Mitchell, Fennessy, et al., GEWEX News, 2001, No. 1, 3-6;

Gustafson and Leung, BAMS 2007

Fennessy and Altshuler, 2002:

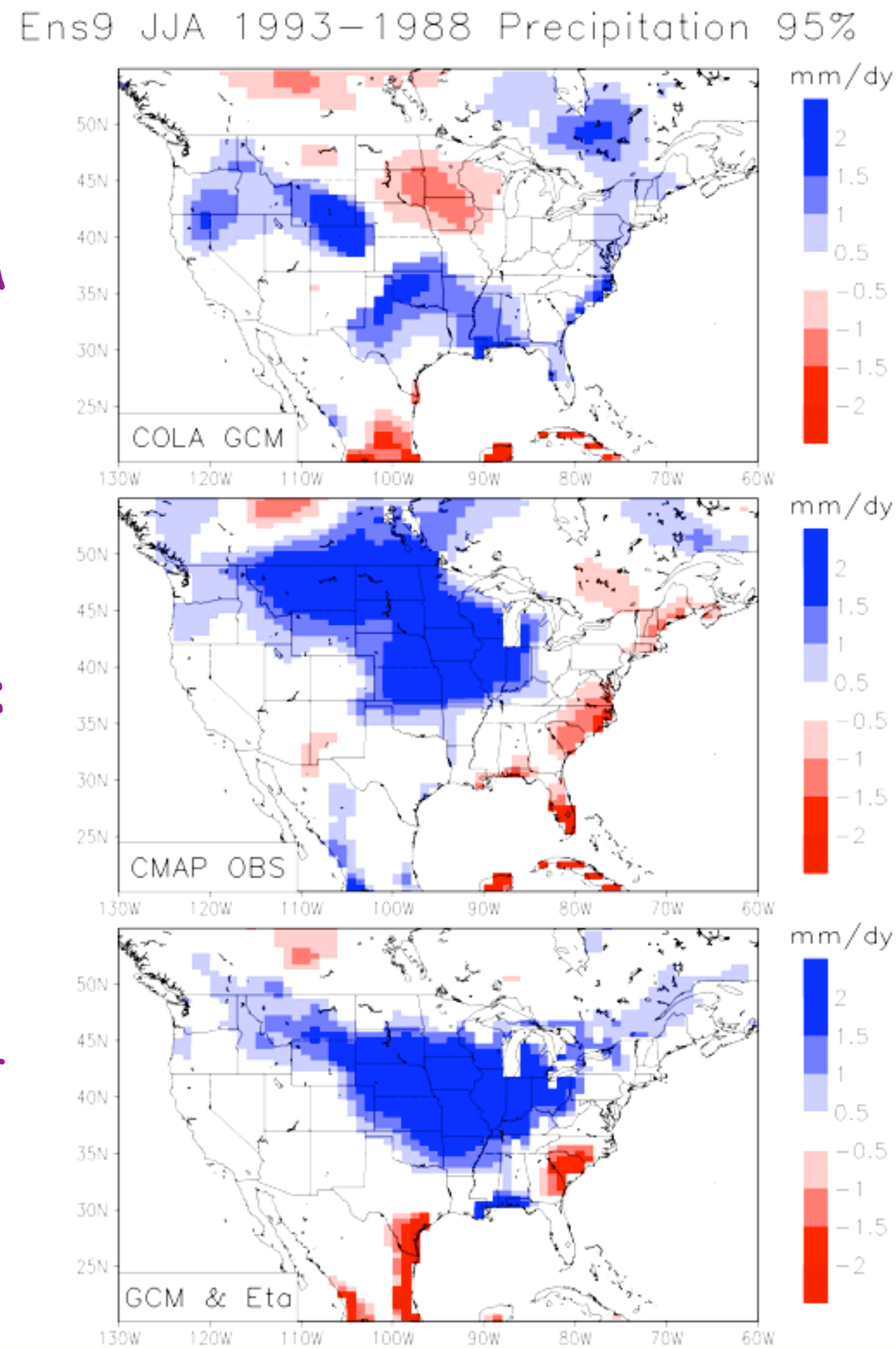
9 ensemble members

precip difference 1993-1988

COLA GCM:

Obs.:

GCM+ Eta:



- Lateral boundary condition scheme(s)

The problem:
Considered already in Charney (1962):

Linearized shallow-water eqs., one space dimension, characteristics;

“at least two conditions have to be specified at inflow points and one condition at outflow”.

Charney (1962) (Tokyo NWP Symp.)

tives. We next observe that the specification of u' at a boundary determines $\partial v'/\partial t + U\partial v'/\partial x$ by (2.6) and the specification of q' dertermines v' by elimination of h' and u' from (2.7) with the aid of (2.6) and (2.8). Elimination of u' and h' from equations (2.5)-(2.7) gives

$$\left(\frac{\partial}{\partial t}+U\frac{\partial}{\partial x}\right)\left[\left(\frac{\partial}{\partial t}+U\frac{\partial}{\partial x}\right)^2-gH\frac{\partial^2}{\partial x^2}\right]v' + f^2\frac{\partial v'}{\partial t}=0\,, \tag{2.9}$$

It follows from the theory of characteristics that the domain of dependency of this equation is determined by the coefficients of the highest order terms. Since we are concerned only with the establishment of the boundary conditions, it is sufficient to consider the solution of the equation obtained by omitting the first order time term:

$$v'=\sum_{i=1}^{3} V_i(x-c_i t)\,, \tag{2.10}$$

where the V_i's are arbitrary functions to be determined, and

$$c_1=U\,,\quad c_2=U+\sqrt{gH}\,,\quad c_3=U-\sqrt{gH}\,. \tag{2.11}$$

The specification of v', $\partial v'/\partial t$ and $\partial^2 v'/\partial t^2$ at $t=0$ determines $\sum^3 V_i$ and linear combinations of the first and second x-derivatives of the V_i and therefore the V_i them-

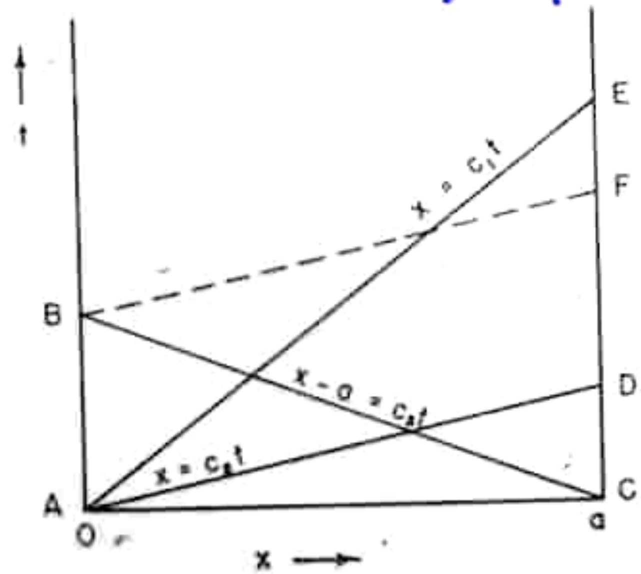


Fig. 1. Domains of dependence of the solutions of the perturbation equation (2.9) in the $x-t$ plane.

tion at $x=a$, determines V_3 along DF. Hence all the V_i's are determined along CF. It is now obvious how by continuation of the above reasoning one may show that the V_i's are determined for all t at the boundaries $x=0$ and $x=a$, and consequently that they are determined for all $0\leq x\leq a$ and $t\geq 0$. Thus the initial and boundary conditions are sufficient to determine the motion. It is also clear that they are necessary in the sense that at least two conditions have to be specified at inflow points and one condition at outflow.

We have tacitly assumed that the Froude

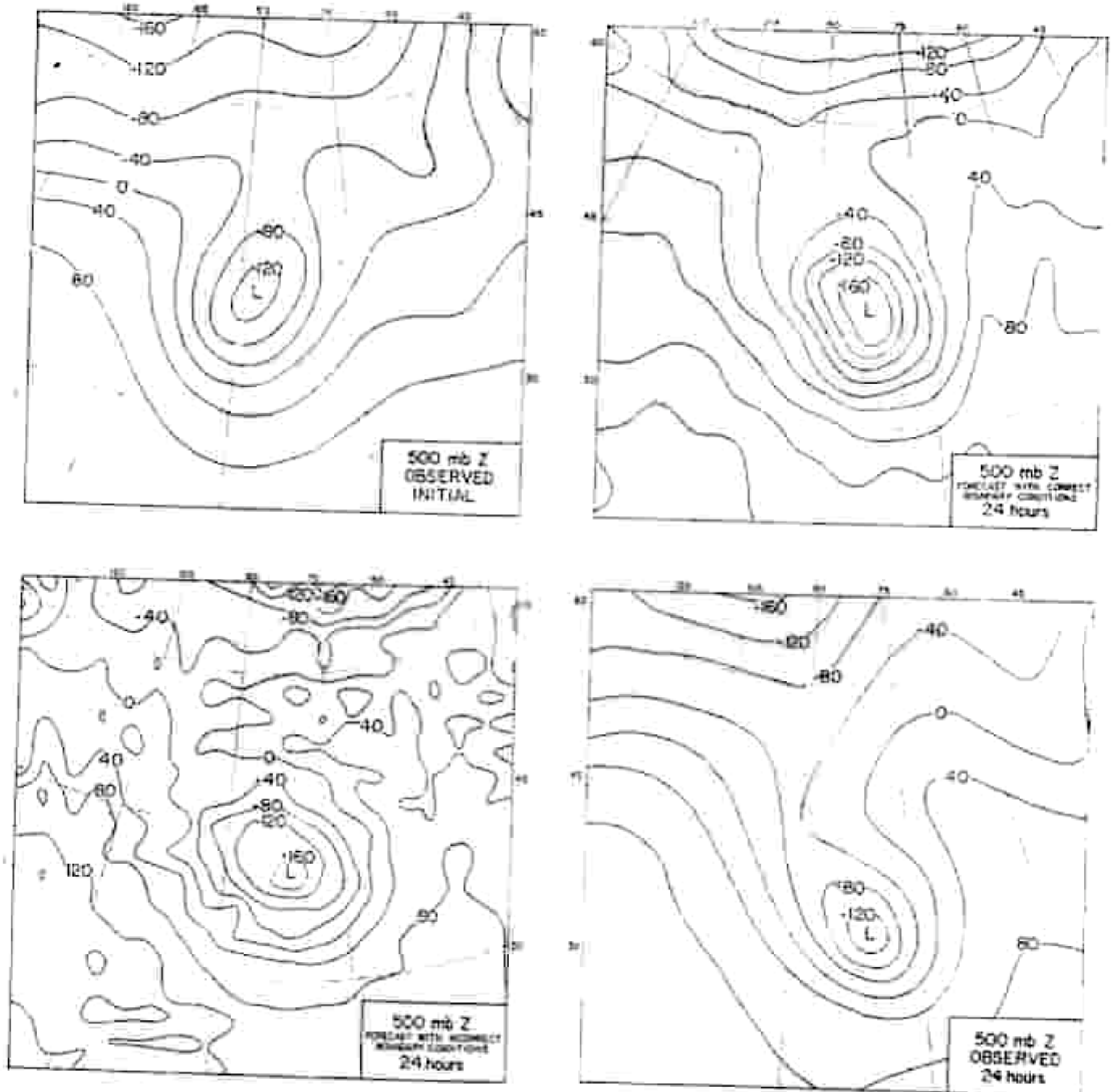


Fig. 2. A comparison of the 24-hour 500 mb predictions made from the primitive equations for a single-layer barotropic atmosphere with both correct and incorrect boundary conditins. The initial time is 24 November, 1950, 1500 G.M.T. The unit of z is 10 feet.

Subsequently:

Sundström (1973)

However:

Davies (1976): "boundary relaxation scheme"

Almost all LA models:

Davies ("relaxation LBCs"):

Outside row: specify all variables

Row 1 grid line inside: specify, e.g.,

$$0.875 * Y_{DM} + 0.125 * Y_{LAM}$$

Row 2 grid lines inside:

$$0.750 * Y_{DM} + 0.250 * Y_{LAM}$$

. . .

Res. Activities ..., 1999:

A TEST OF THE ETA LATERAL

Thomas L. Black, Geoffrey
U.S. National Centers for Environme

Over the years considerable degree of concern has been expressed by various investigators regarding the non well-posedness of the one-way boundary conditions of hydrostatic limited-area models. To aggravate the feelings, it is perhaps universally considered that "A common and essential ingredient of limited-area strategies is the introduction of an adjustment region immediately adjacent to the lateral boundaries, where one or both of the techniques of blending and diffusion, either explicit or implicit, are applied" (Côté et al. 1998). As a summary, Côté et al. cite as many as ten papers stating that they "all indicate that lateral boundary condition error can, depending upon the meteorological situation, importantly contribute to the total error." This assessment seems to have played a crucial role in their favoring a global variable resolution as opposed to a limited-area strategy.

Warner, T. T., R. A. Peterson, and R. E. Treadon, 1997: A tutorial on lateral boundary conditions as a basic and potentially serious limitation to regional numerical weather prediction. Bull. Amer. Meteor. Soc., **78**, 2599-2617.

(Emphasis FM)

The Eta LBC scheme:

LBCs needed along
a single outer bndry line
of grid points

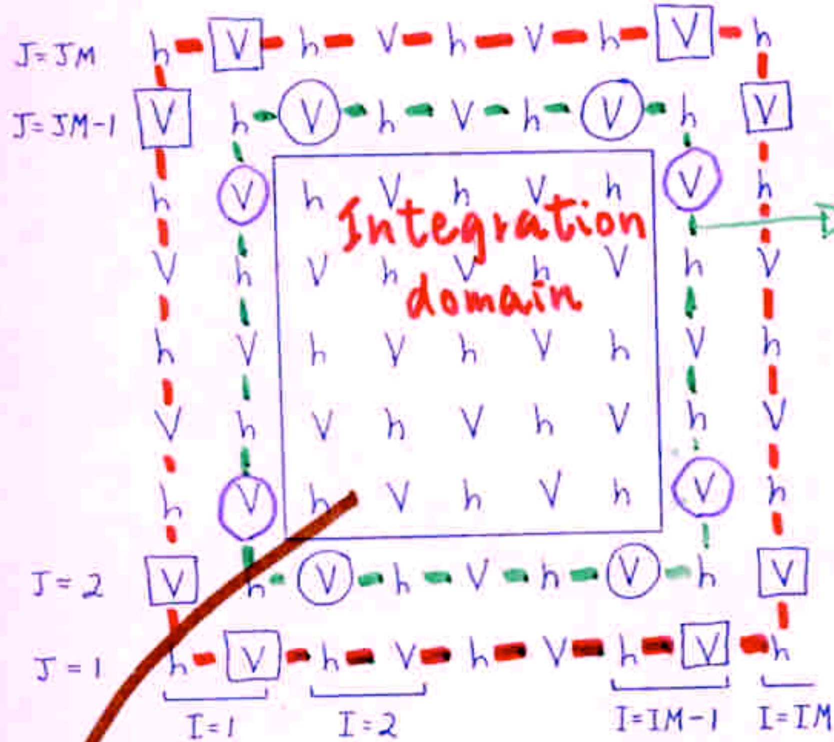
(as required by the mathematical nature of the initial-boundary value problem we are solving)

The scheme

- At the inflow boundary points, all variables prescribed;
- At the outflow boundary points, tangential velocity extrapolated from the inside (characteristics!);
- The row of grid points next to the boundary row, "buffer row"; variables four-point averaged (this couples the gravity waves on two C-subgrids of the E-grid)

Thus: No "boundary relaxation" !

Semi-Lagrangian advection the three outermost rows of the integration domain



"Buffer line": 4-point averaging

Three rows of upstream advection

No "boundary relaxation"!

Fig. 7. The eta model's E grid with solid line enclosing the integration domain. Boxed and circled V's are handled differently than others in boundary region, see text.

In flow: u, v, T, p_s prescribed

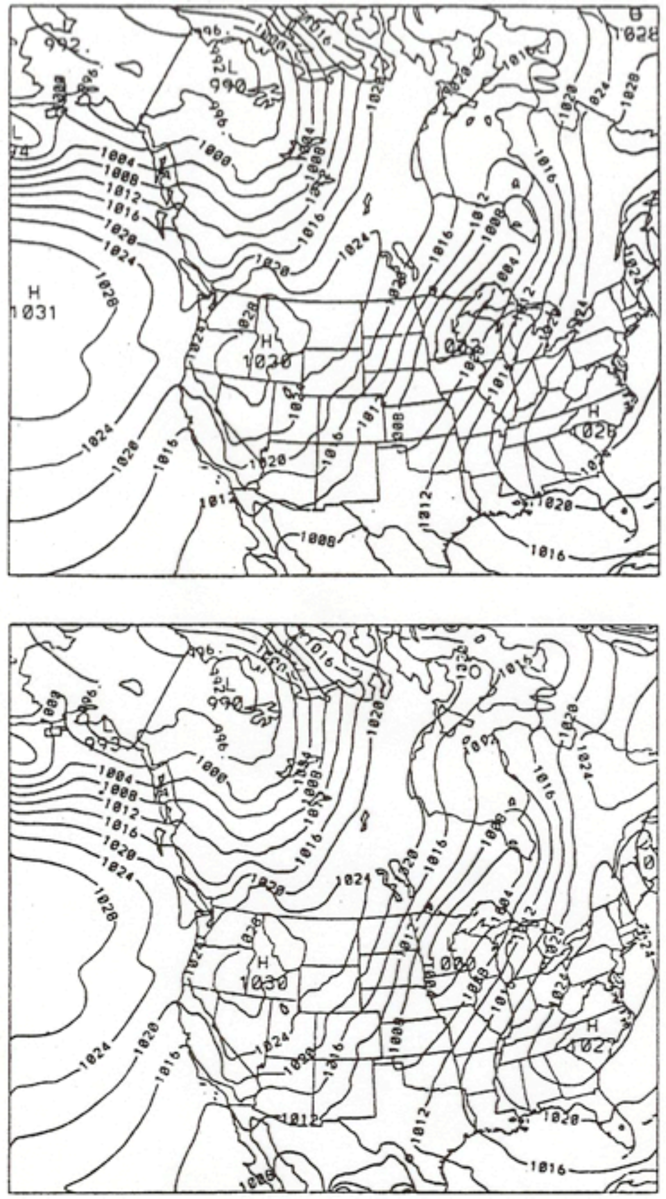
Out flow: v_{normal}, T, p_s prescribed, $v_{tang.}$ extrapolated

Mesinger 1977

"Control"

No space interpolation errors at the lateral boundary

Black at al., RAAOM, '99; 50th Anniv. of NWP, 2001



Driven using the "control" for lateral bnd. condition

Figure 4: A section of the then operational 32-km Eta 48-h sea level pressure forecast, valid at 1200 UTC 17 October 1998, top panel; same except for a run over a smaller domain, done using the operational forecast to supply its boundary conditions, bottom panel. Boundaries of the plots shown are the outermost boundaries of the smaller domain, thus, in the bottom panel, all of the forecast domain of the nested run is shown.

"limitation":

Near inflow boundaries, LA model cannot do better - it can only do worse - that its driver model

Thus: have boundaries as far as affordable !

McDonald, A, 1997: Lateral boundary conditions for operational regional forecast models; a review. HIRLAM Tech. Rep. 32:

1. Introduction;
2. Well posed boundary conditions;
3. Scheme which over-specify the boundary
   - 3a. Diffusive damping in a boundary zone;
   - 3b. Pseudo-radiation schemes;
   - 3c. Tendency modifications scheme;
   - 3d. Flow relaxation scheme;
   - 3e. Two 'fairly well-posed' schemes

The Eta scheme one

...

Work in progress:

Compare the Eta LBC scheme, against Davies':

Use GCM (ECMWF) LBCs and drive the Eta using one and the other, look at the difference

(Katarina Veljović, Un. Belgrade)

Also: Does the Eta RCM "retain value of the large scale"?

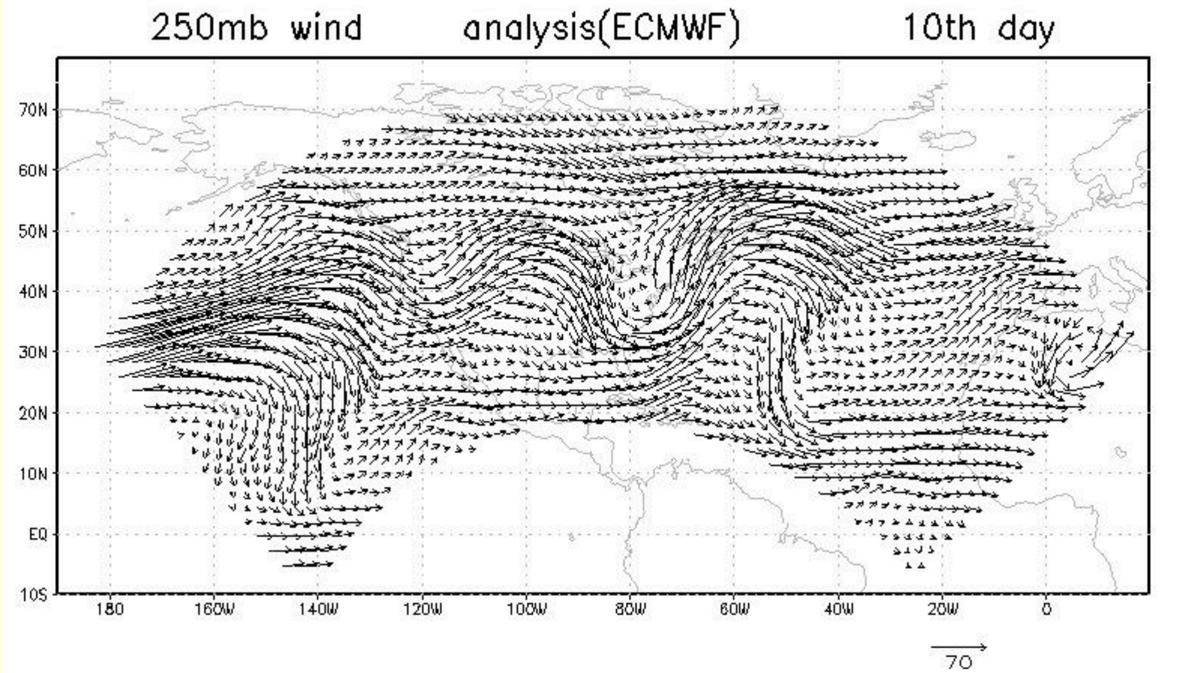
(Castro, Pielke and Leoncini, 2005)

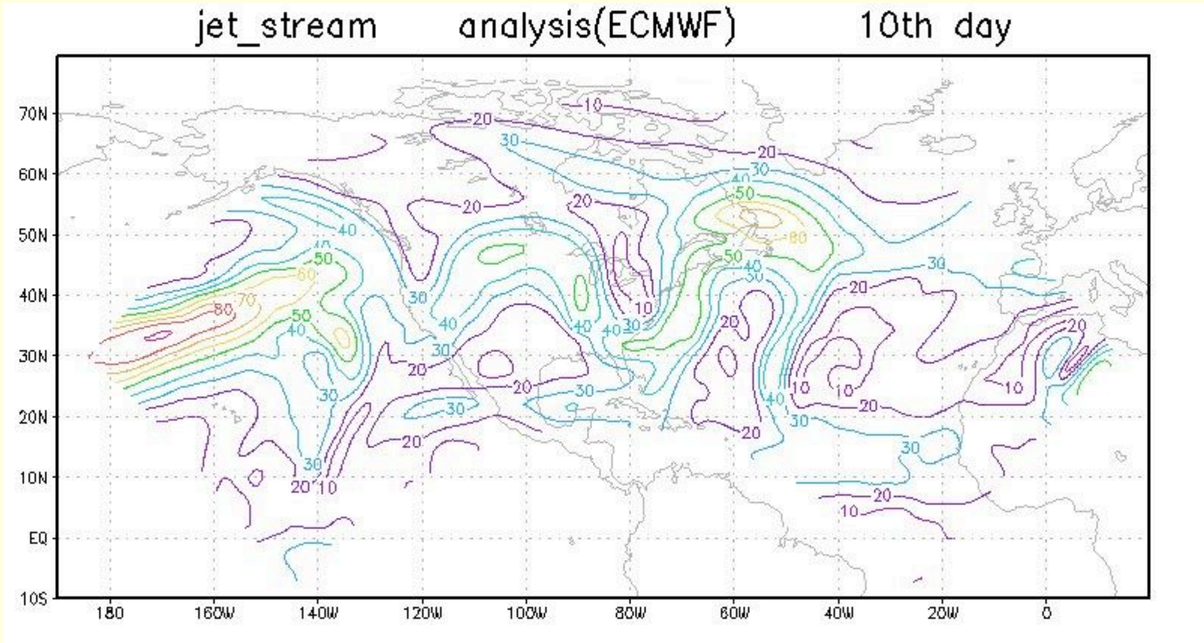
(Large scale skill in regional climate modeling and the lateral boundary condition scheme,

Veljović, Rajković, Mesinger, in preparation)

How can we identify "the skill in large scales"?

Standard method: "Direct-Cosine Transform" (DCT, Denis et al. 2002)





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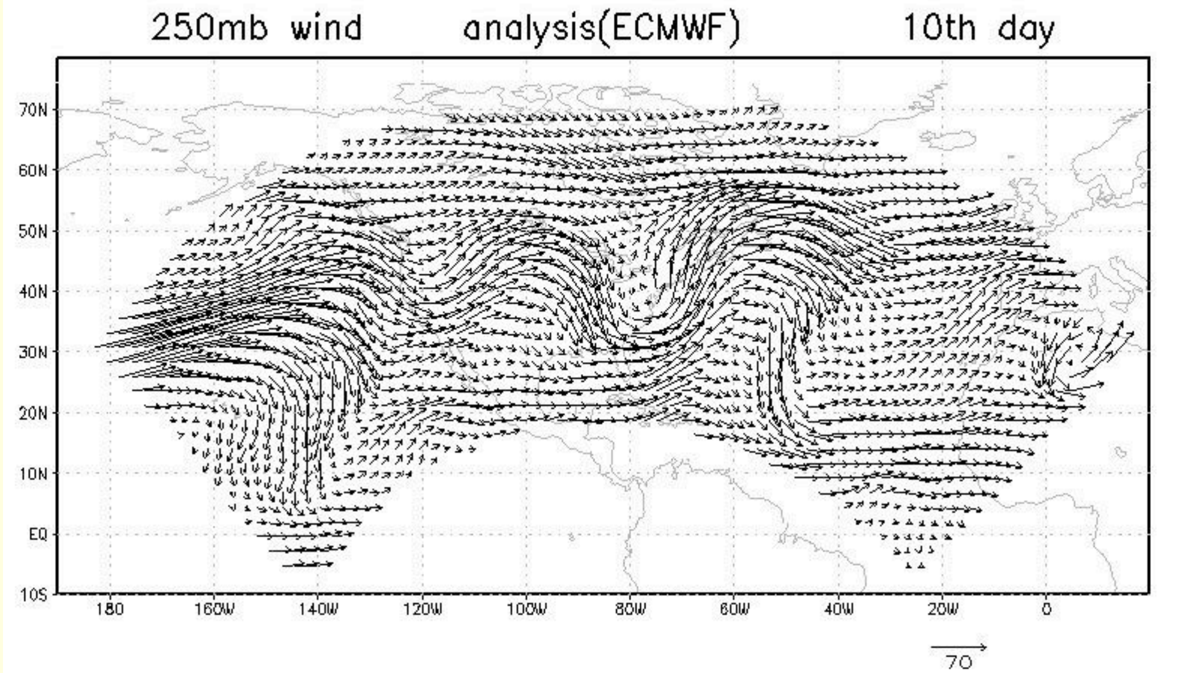
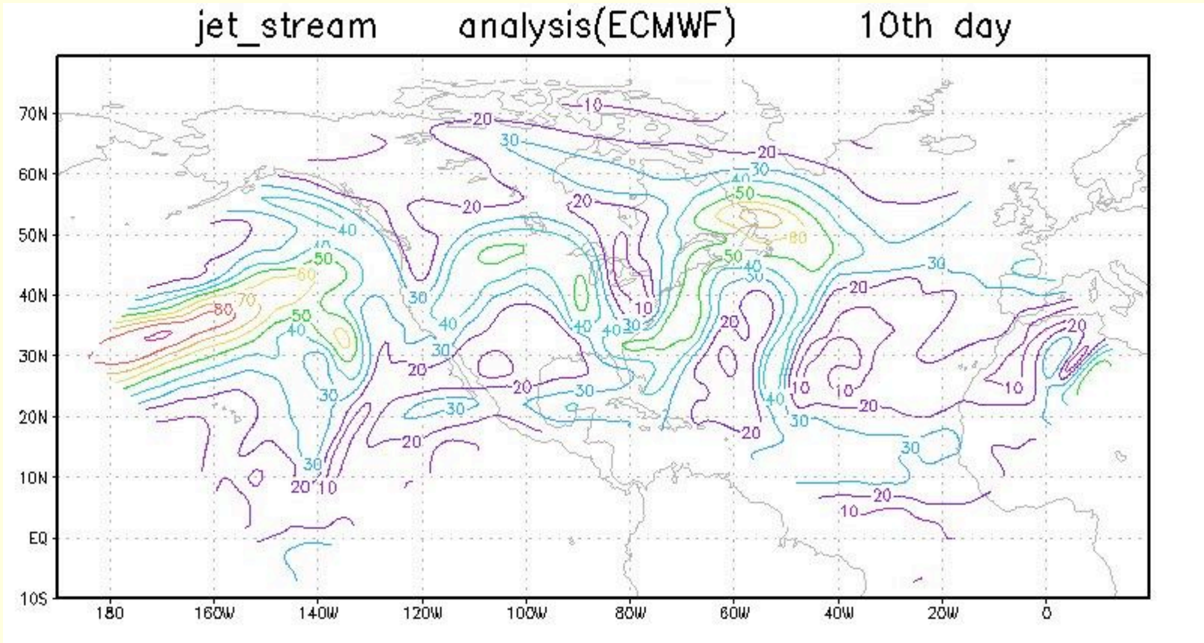
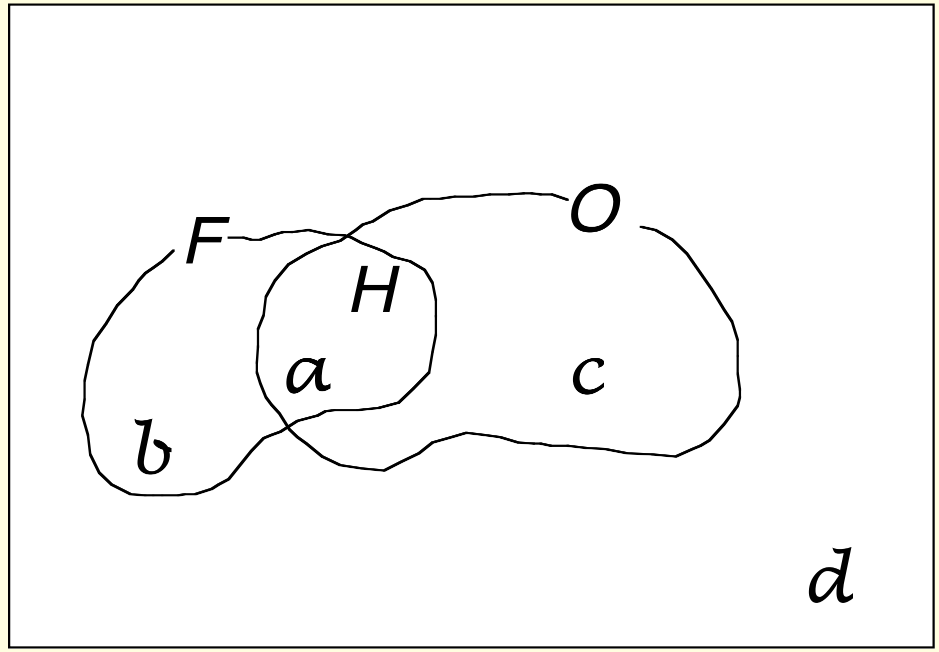
Veljović et al. instead: verification of the placement of the area of wind speeds > a chosen value (50 m/s?)





"dHdA" method:

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



Assume as F is increased by dF, ratio of the infinitesimal increase in H, dH, and that in false alarms $dA=dF-dH$, is proportional to the yet unhit area:

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

(*dA*=*dF*-*dH*)

One obtains

$$H(F) = O - \frac{1}{b}\mathrm{lambertw}\left(bO\,e^{b(O-F)}\right)$$

(Lambertw, or ProductLog in *Mathematica*,

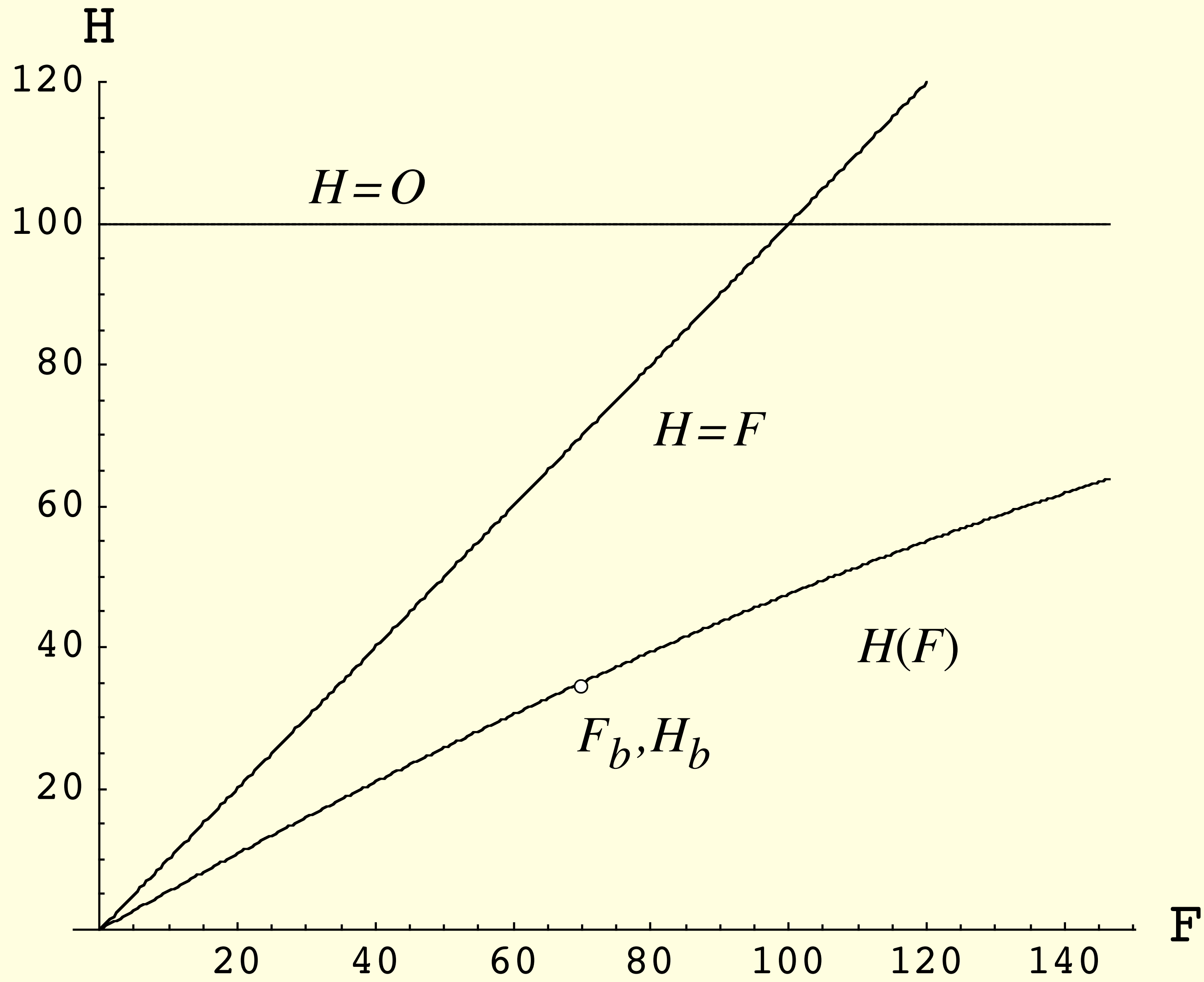
is the inverse function of

$$z = we^{w} \;)$$

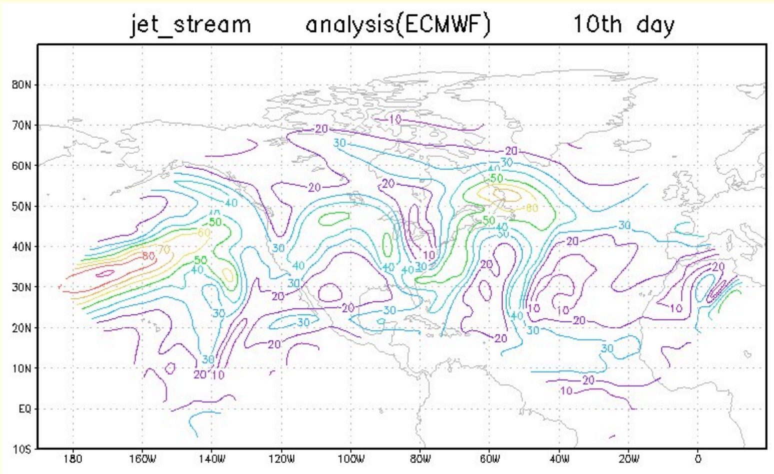
H (*F*) now satisfies an additional requirement compared to the scheme in Mesinger and Brill:

d*H*/d*F* never > 1

dHdA method



Large scale skill in LAM (LBC)

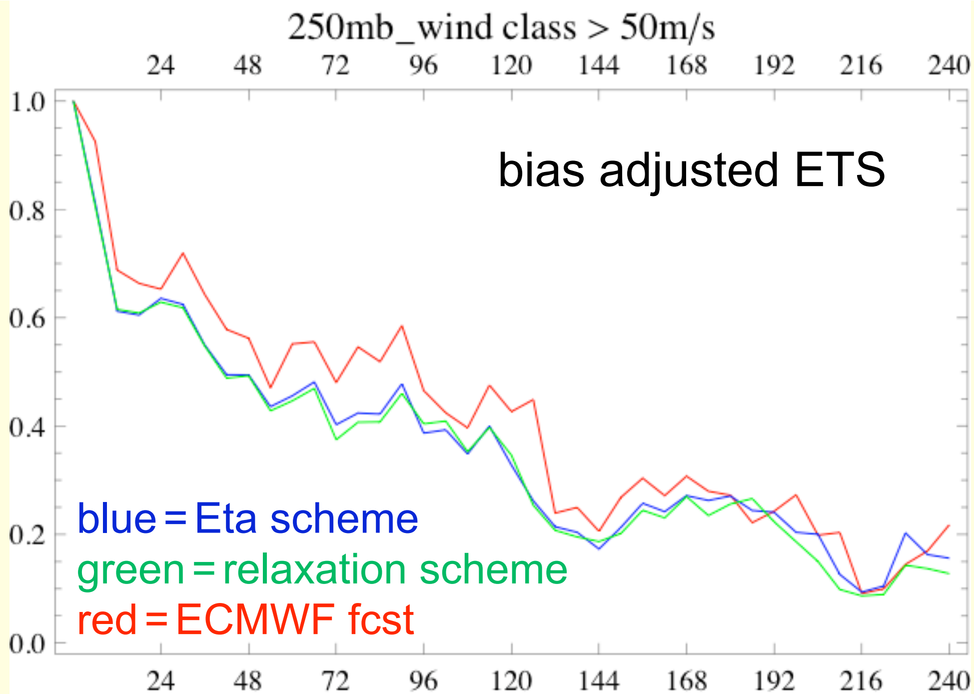


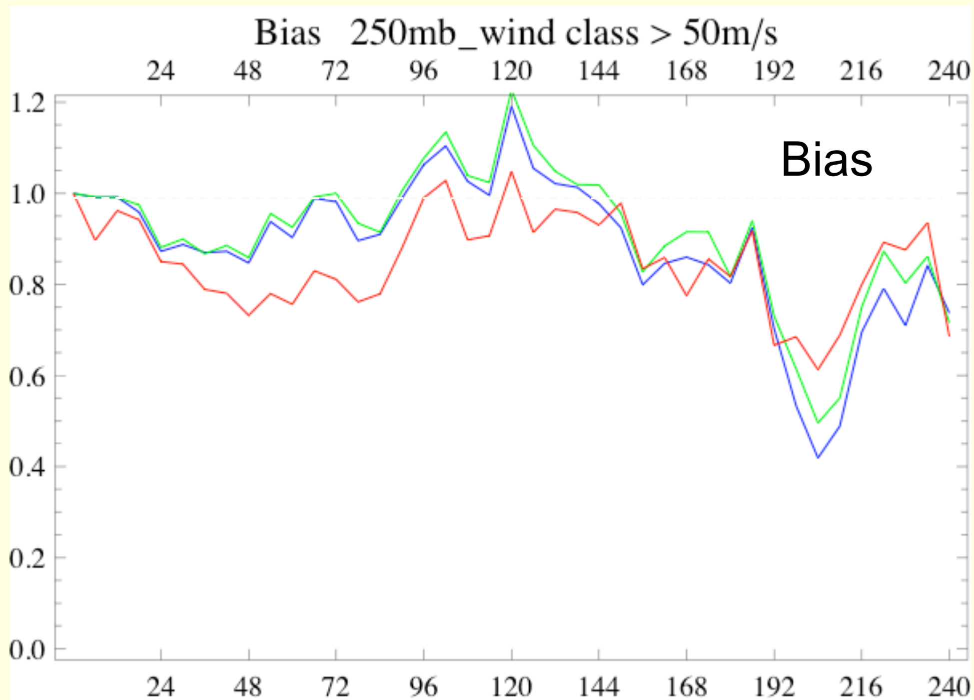
Two LBC schemes:

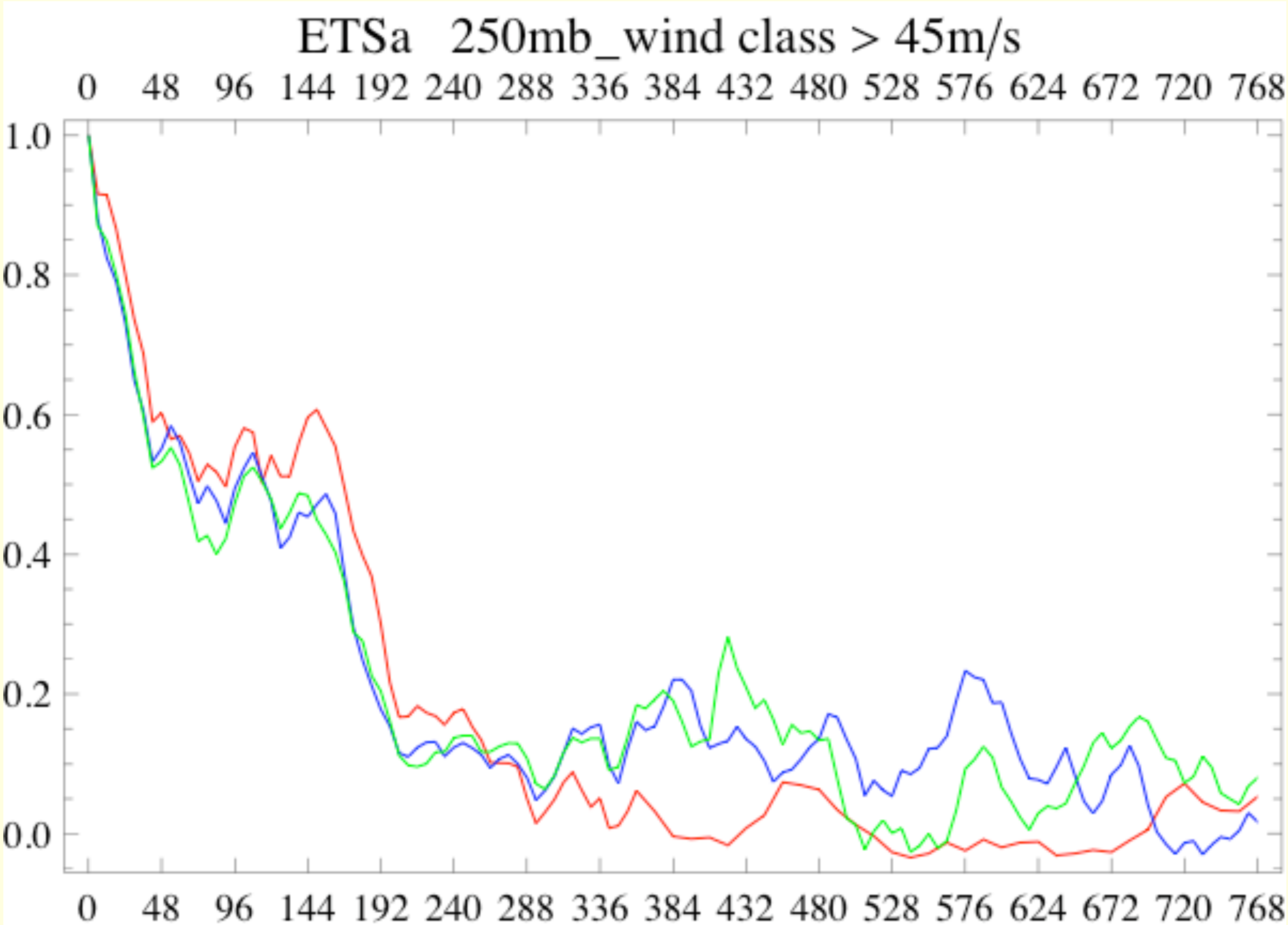
Eta scheme vs Davies relaxation scheme

No loss of "value of the large scale"

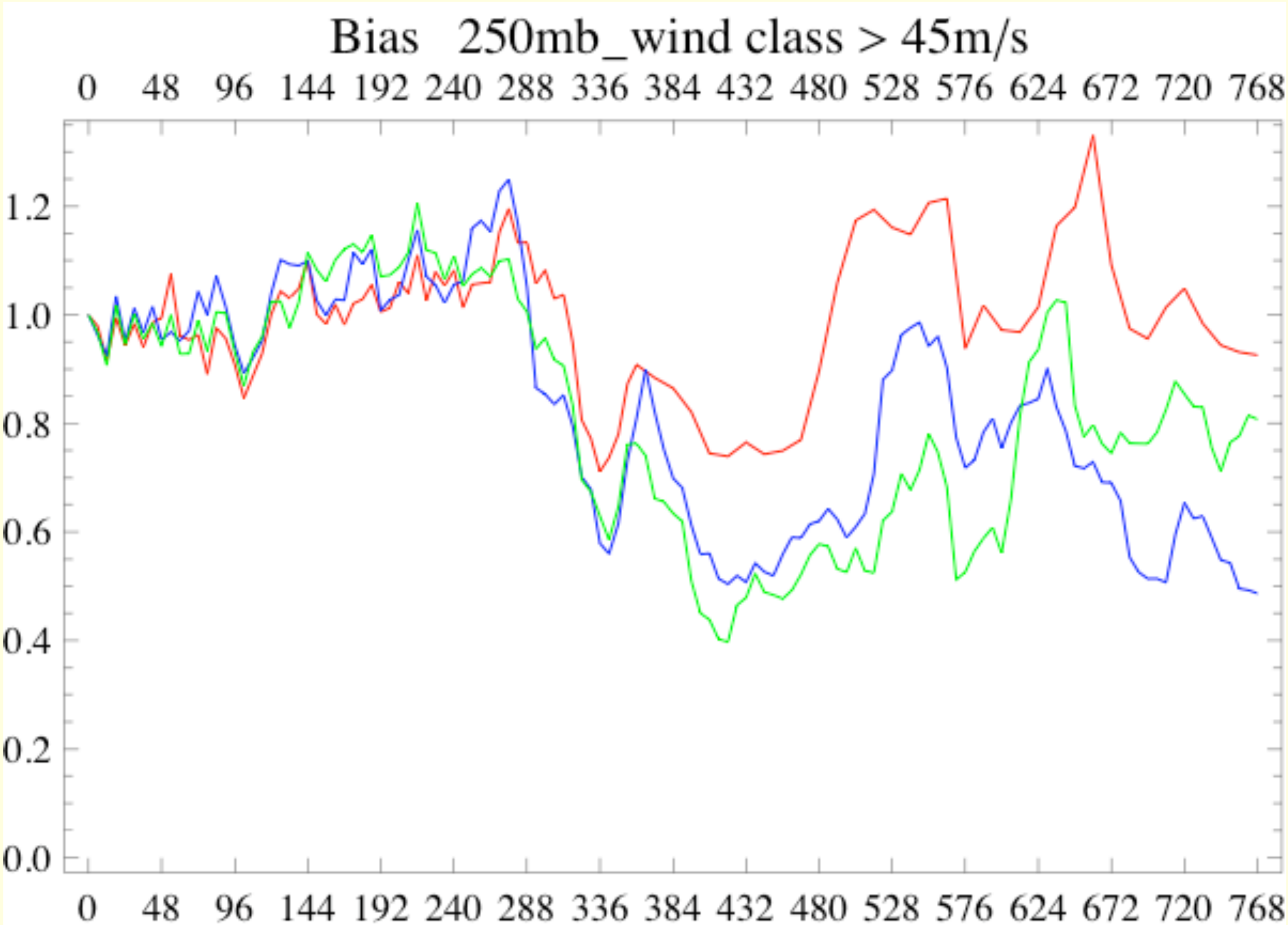
No benefit from relaxation







Red: ECMWF 32-day ensemble control and members E1, E2
Green: Eta using the Davies relaxation LBCs
Blue: Eta using the Eta LBCs (requiring driver model info at the outside bndry only



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Domain size ?

Many people:

things get worse as the domain size gets bigger

Reason: reanalysis used to prescribe the LBCs, and reanalysis used as truth ! (Internal variability !)

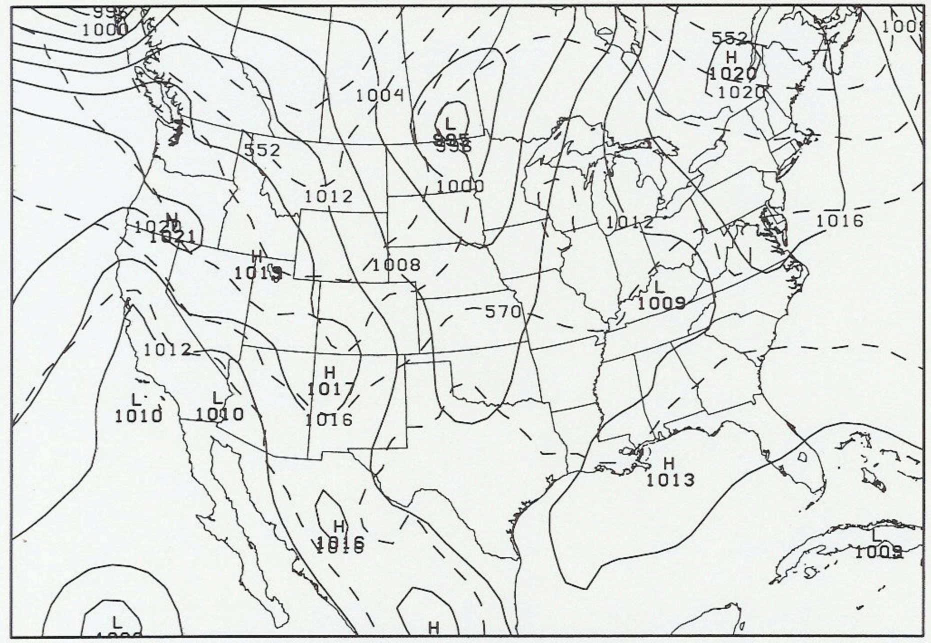
Suggestion: Improving on large scales is possible. However: One cannot improve on large scales if the domain size is small !

Why is this important?

A small gain in large scales is likely to result in large gains in small scales !! :-)

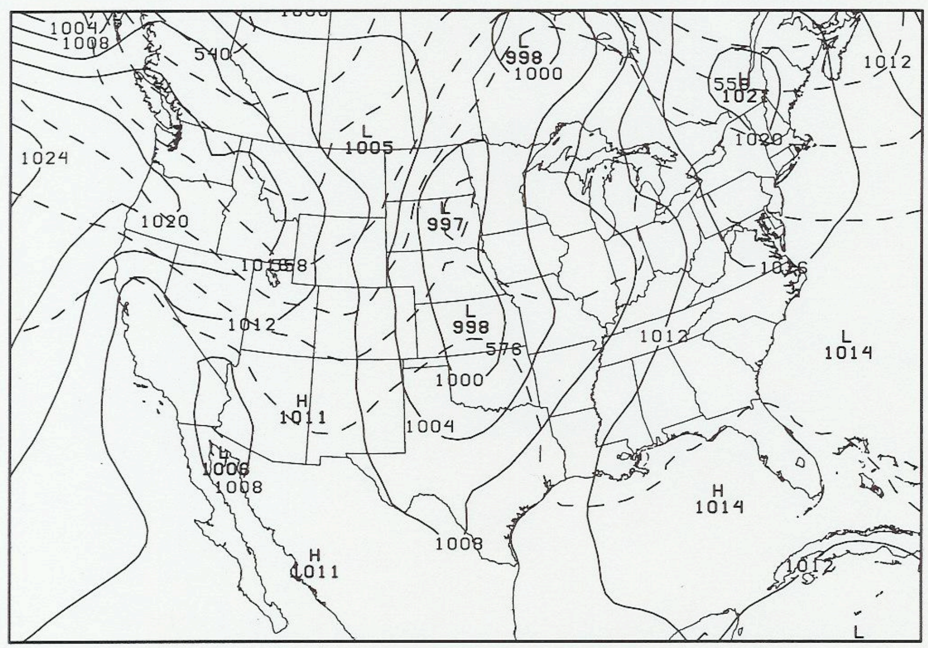
Can we learn from NWP? The three low centers case

Avn



020918/1200V060 SFC MSLP & THCK -- AVN

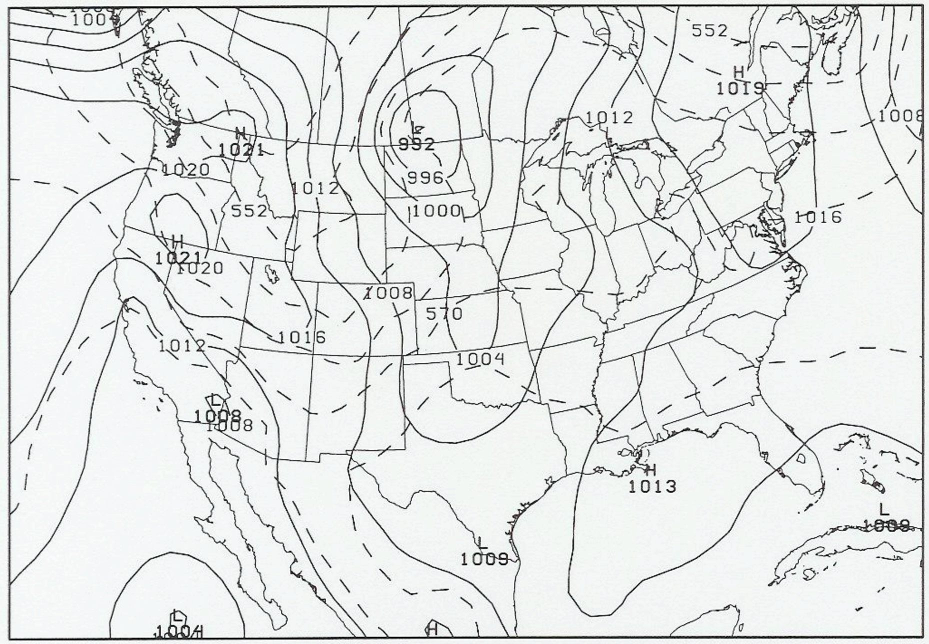
Eta



020918/1200V060 SFC MSLP & THCK -- ETA

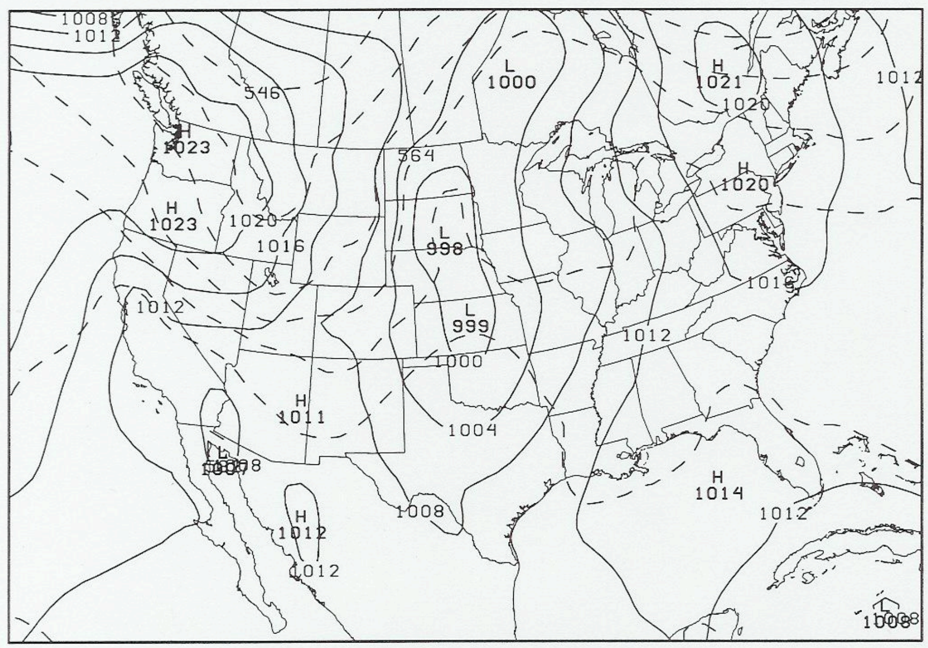
60 h fcsts

Avn



020918/1200V048 SFC MSLP & THCK -- AVN

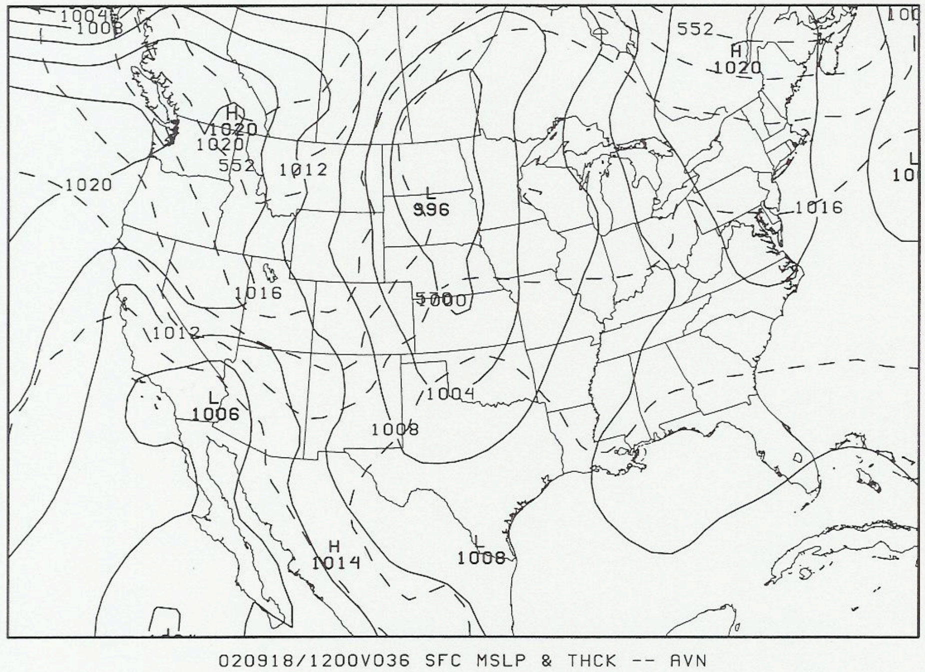
Eta



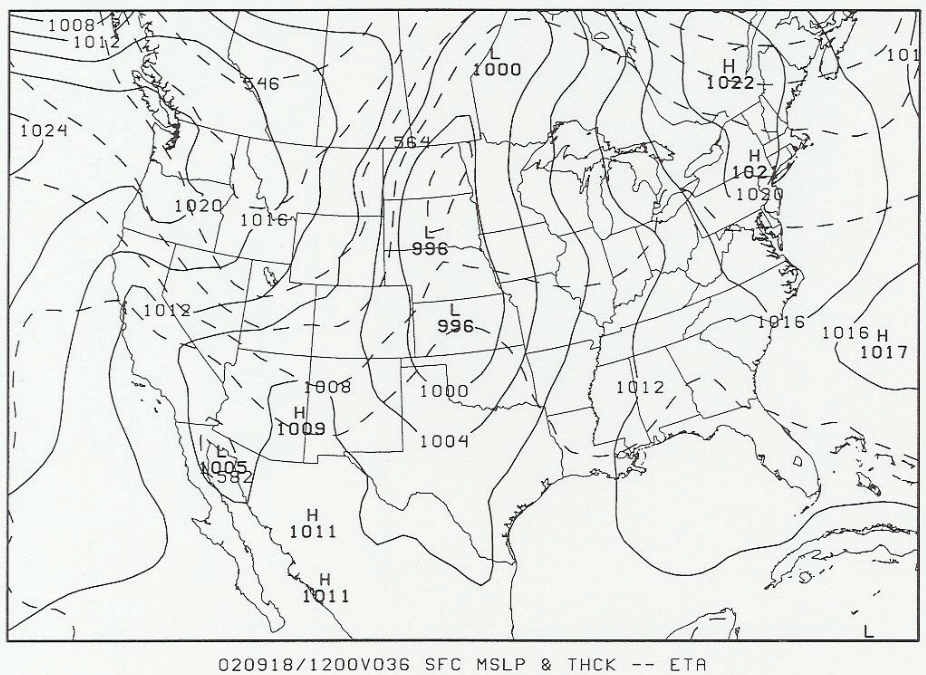
020918/1200V048 SFC MSLP & THCK -- ETA

48 h fcsts

Avn

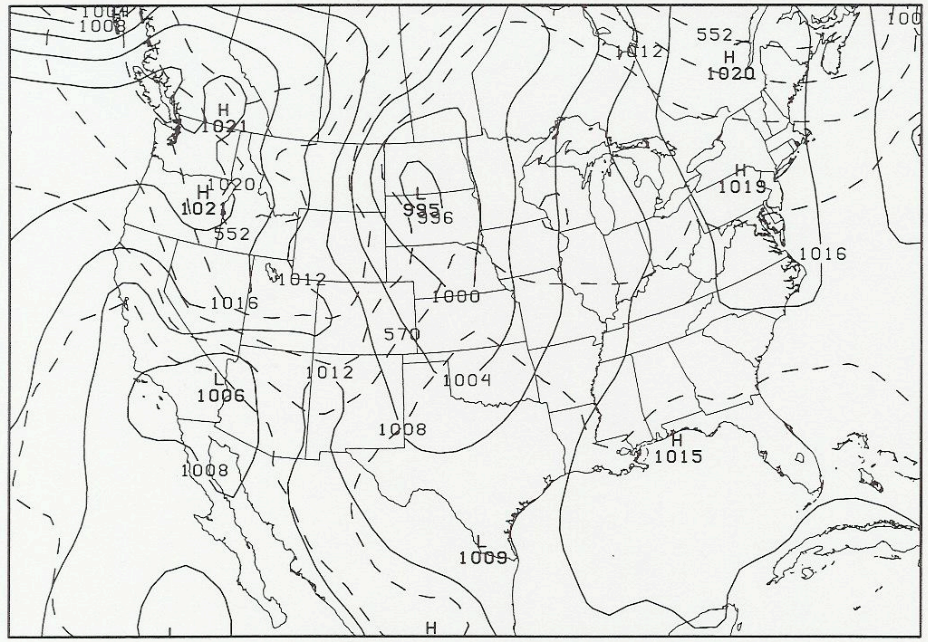


Eta



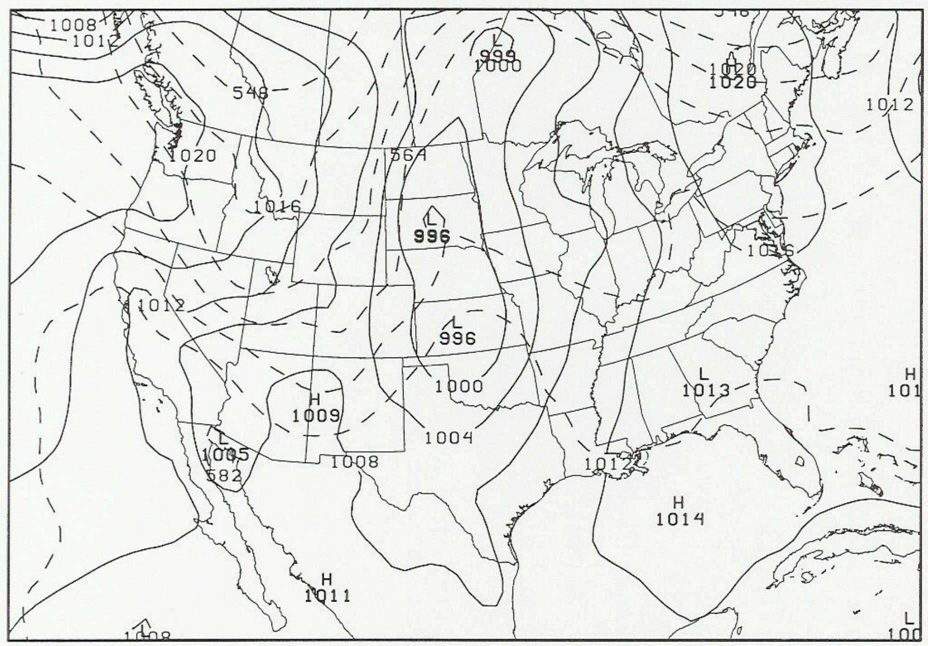
36 h fcsts

Avn



020918/1200V024 SFC MSLP & THCK -- AVN

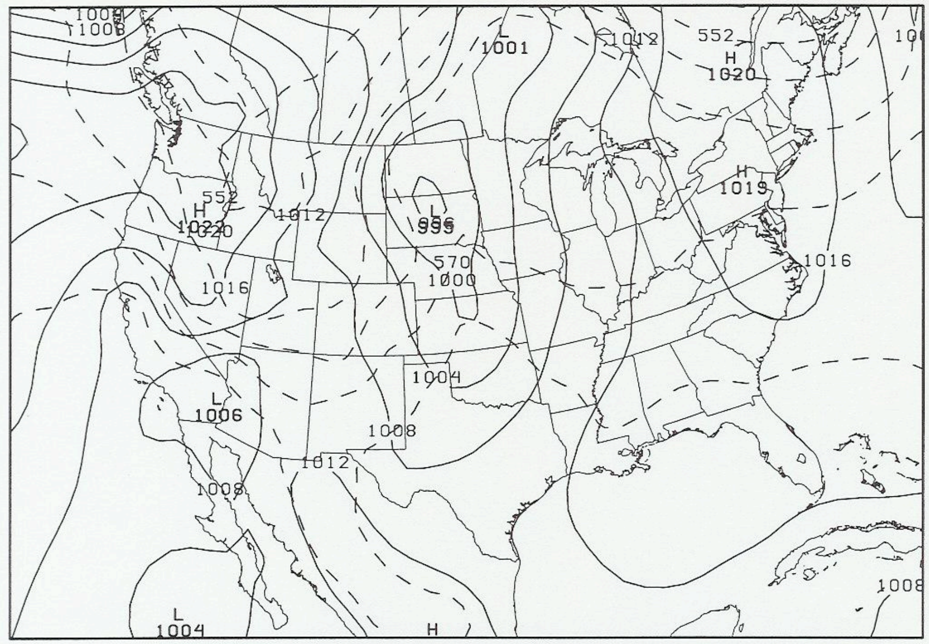
Eta



020918/1200V024 SFC MSLP & THCK -- ETA

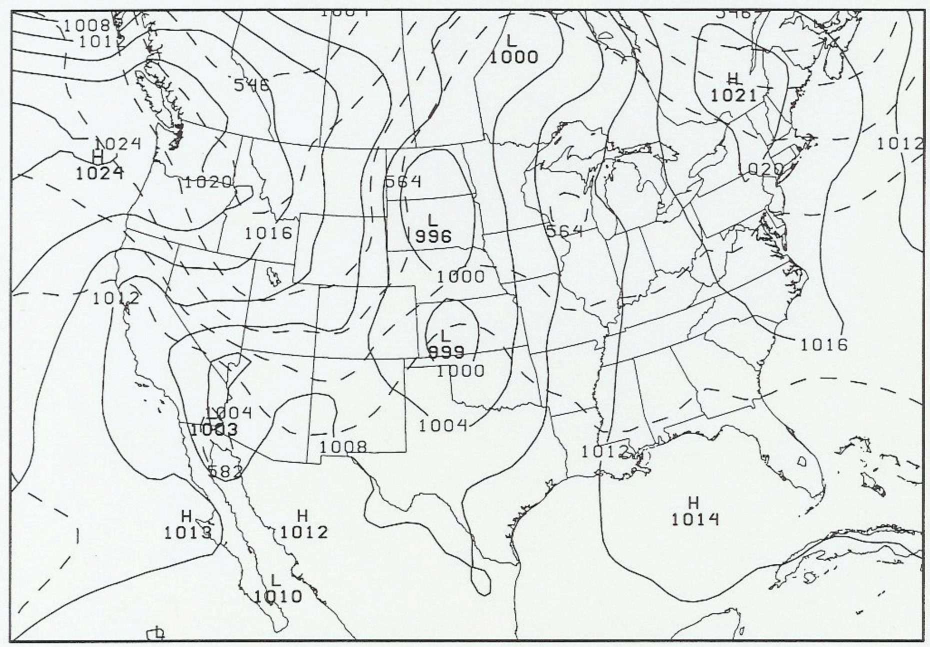
24 h fcsts

Avn



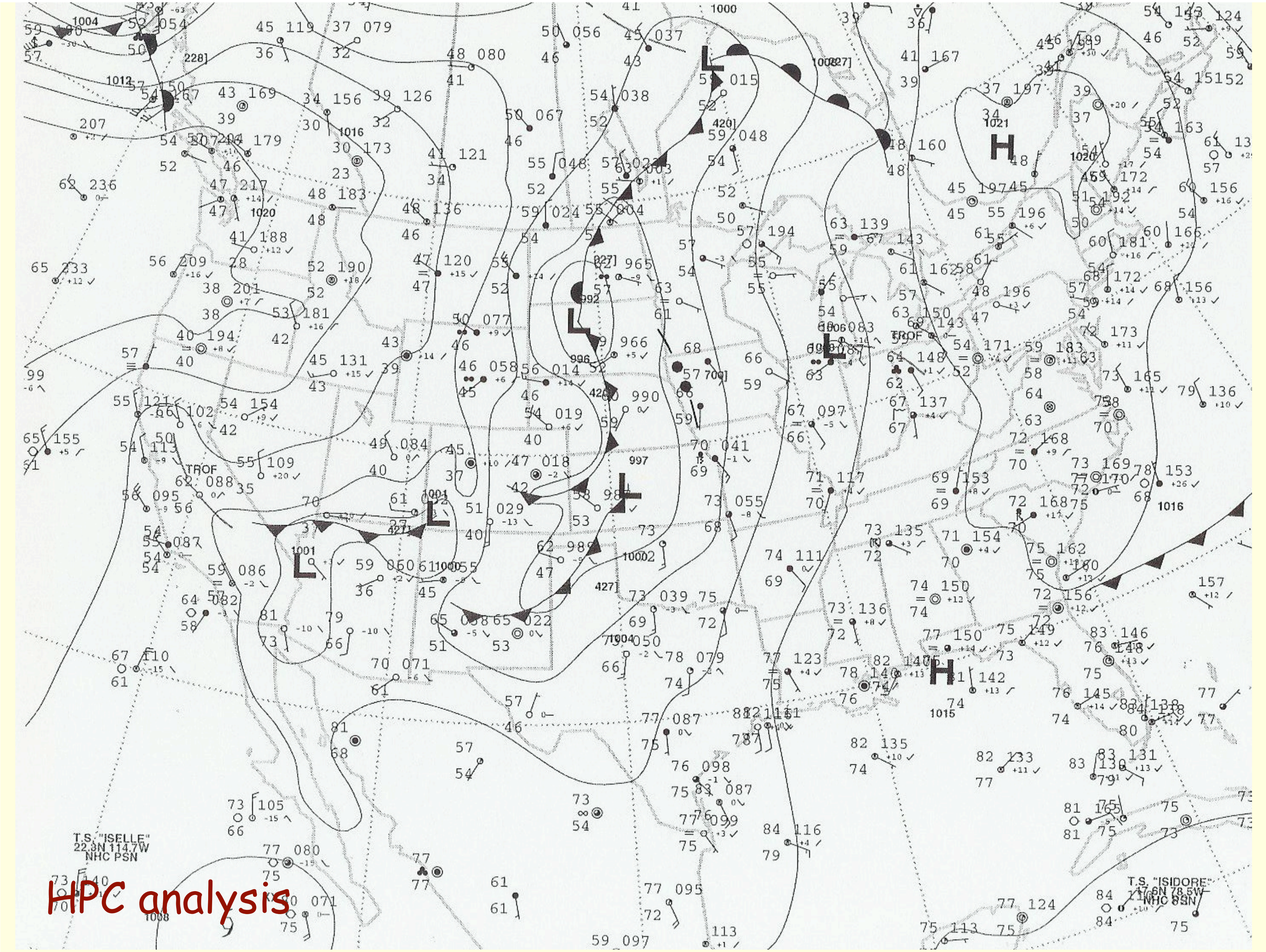
020918/1200V012 SFC MSLP & THCK -- AVN

Eta



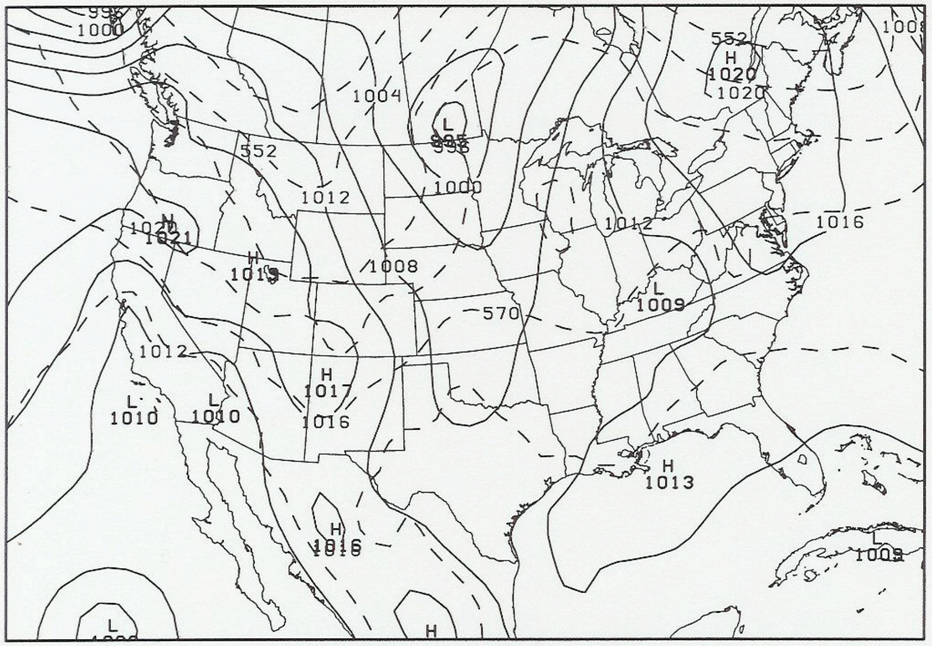
020918/1200V012 SFC MSLP & THCK -- ETA

12 h fcsts

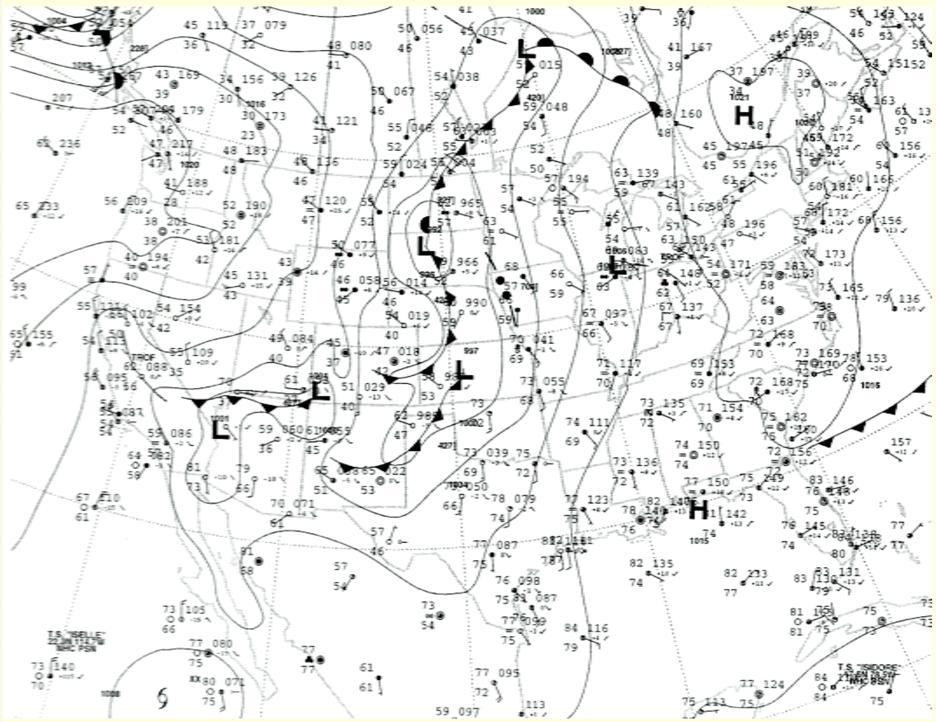


HPC analysis

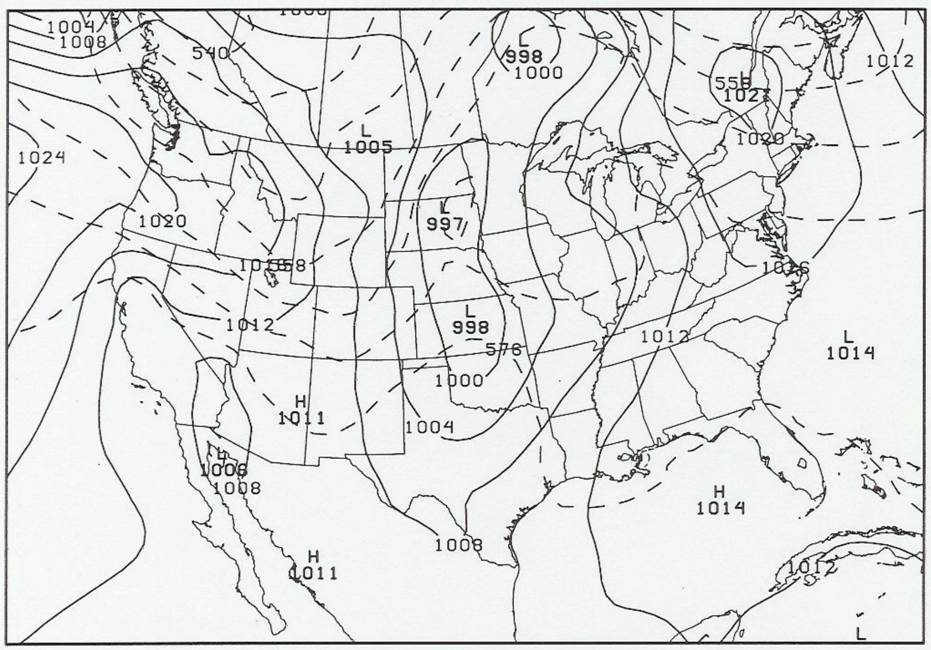
Avn, 60 h fcst



020918/1200V060 SFC MSLP & THCK -- AVN



HPC analysis



020918/1200V060 SFC MSLP & THCK -- ETA

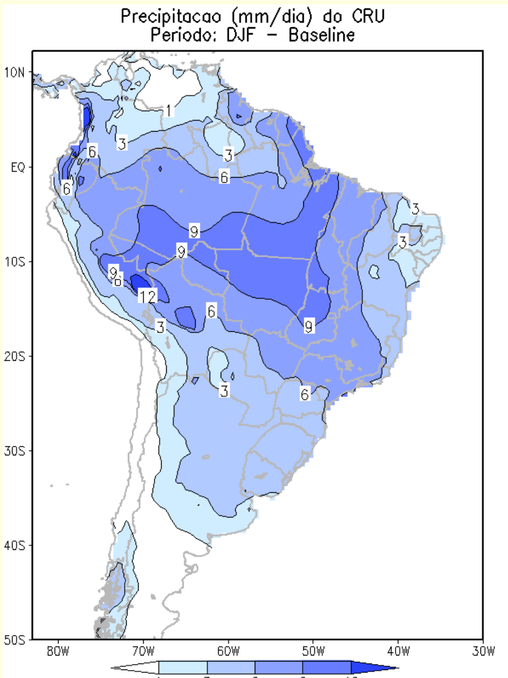
Eta, 60 h fcst

Several Sample Results

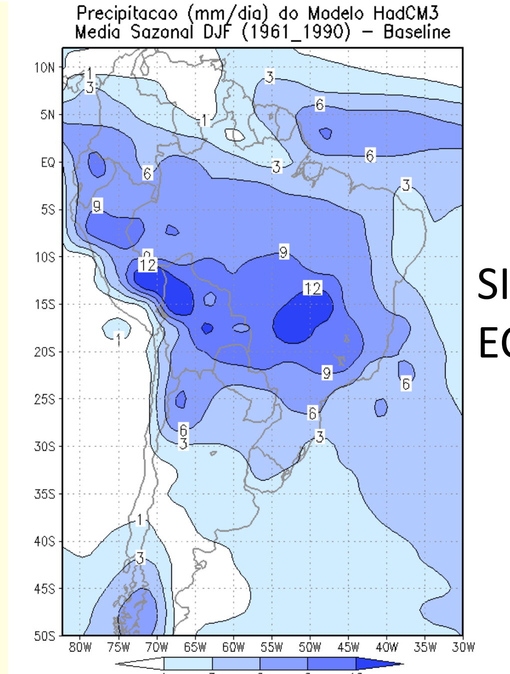
CPTEC, present climate

PRECIPITATION
DJF

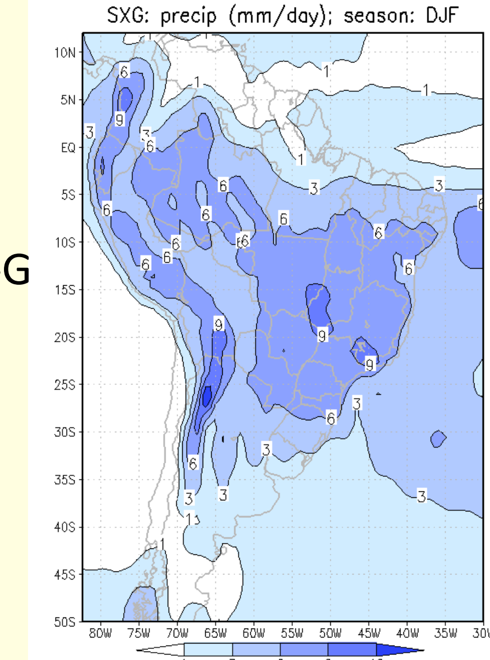
CRU



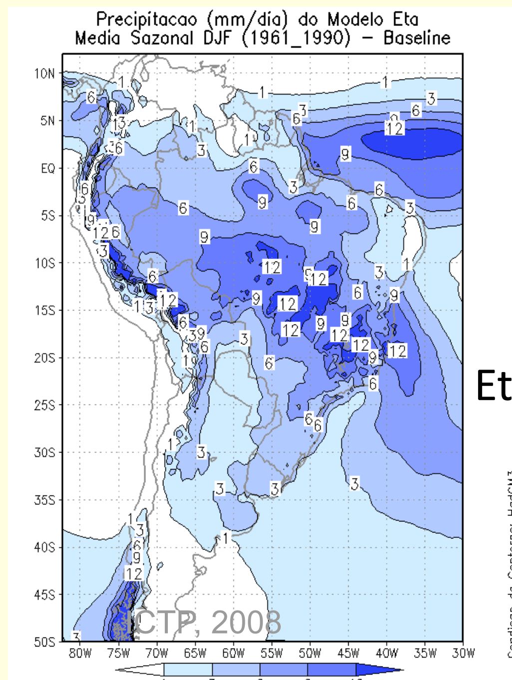
HADCM



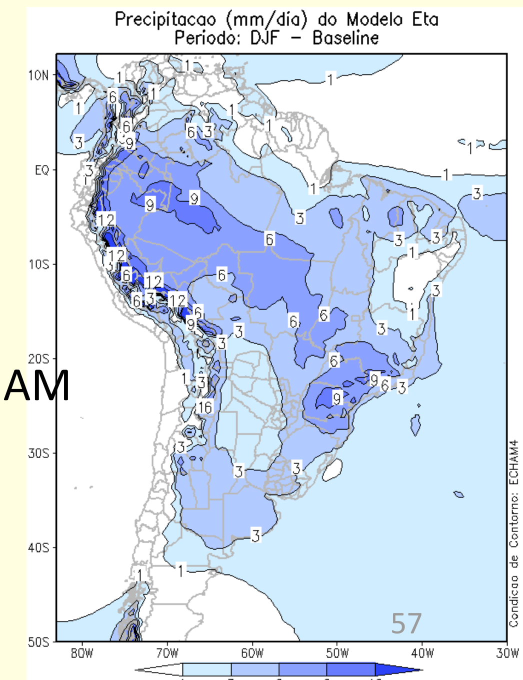
SINTEX-G
ECHAM



Eta-HADCM

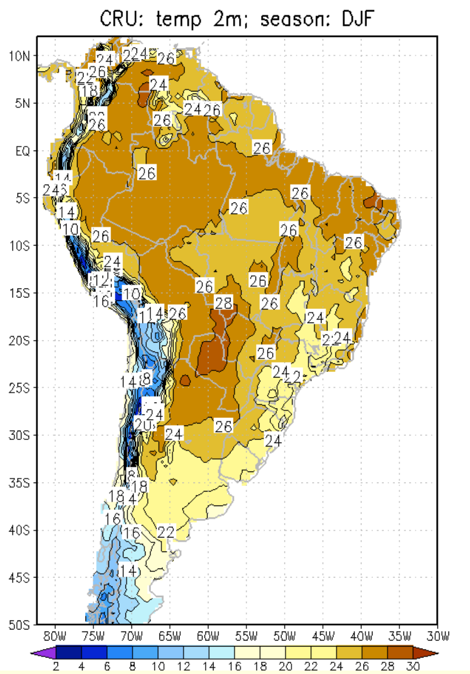


Eta-ECHAM

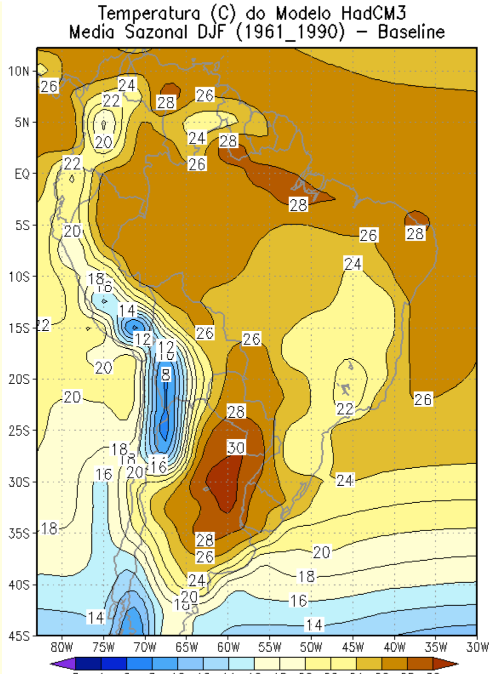


TEMPERATURE
DJF

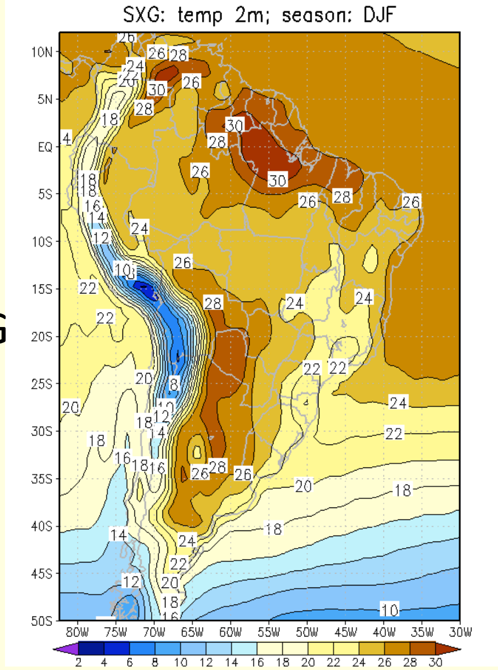
CRU



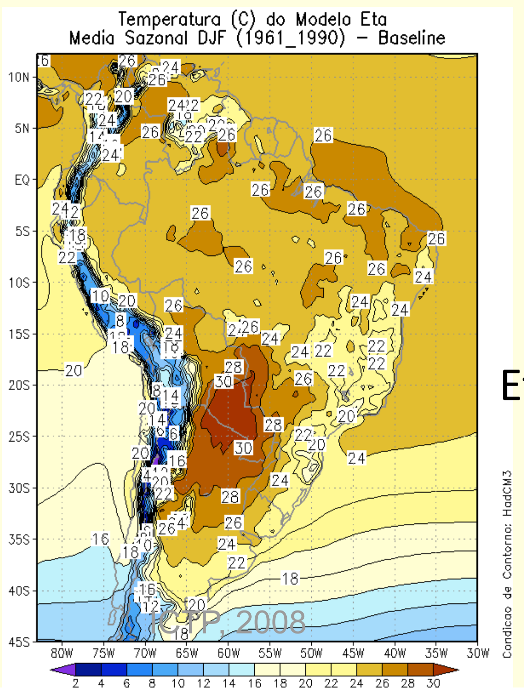
HADCM



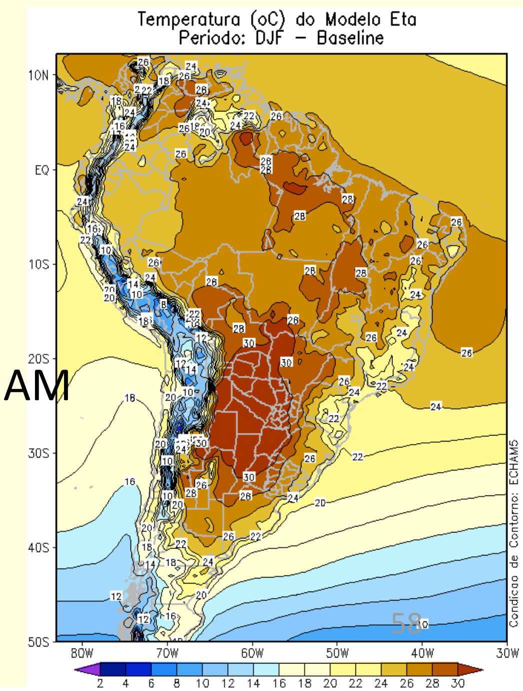
SINTEX-G
ECHAM

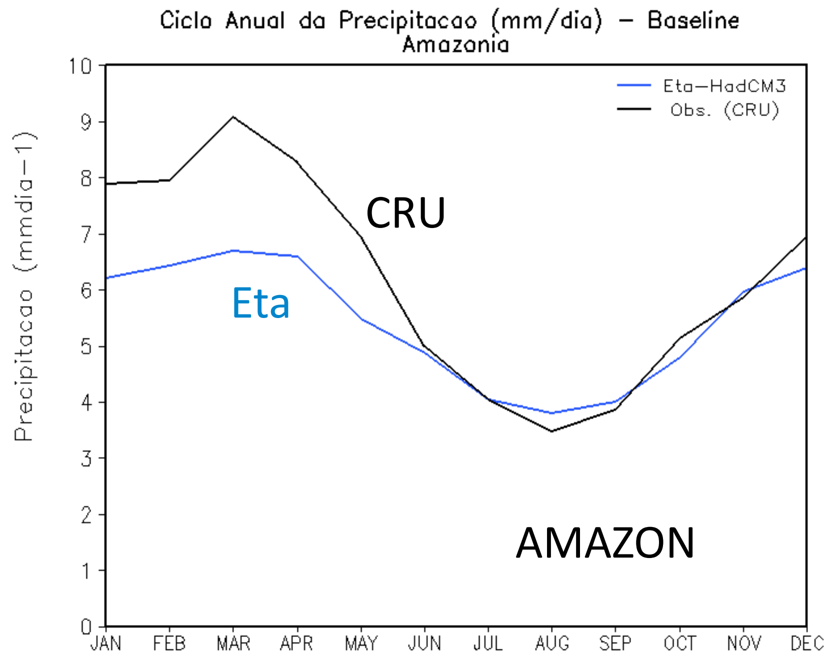


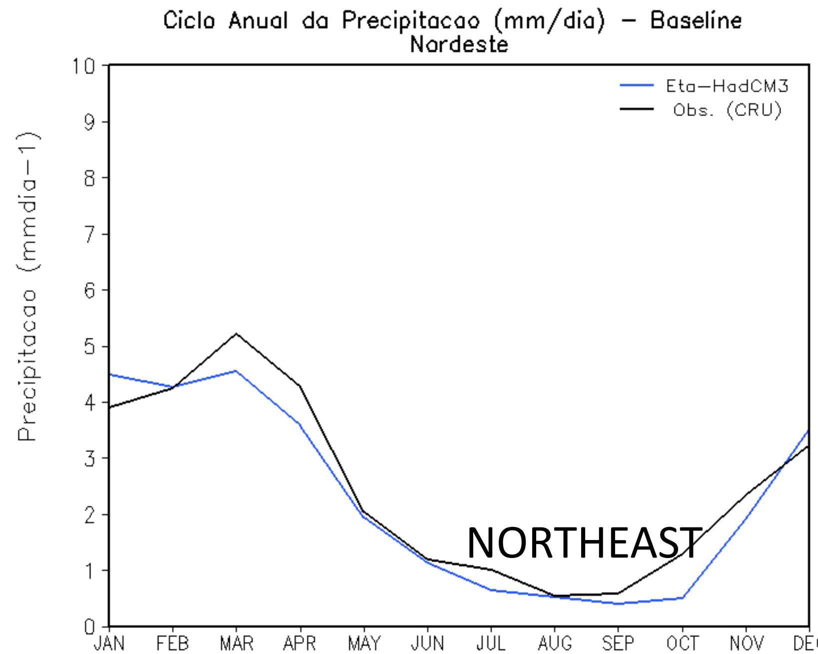
Eta-HADCM



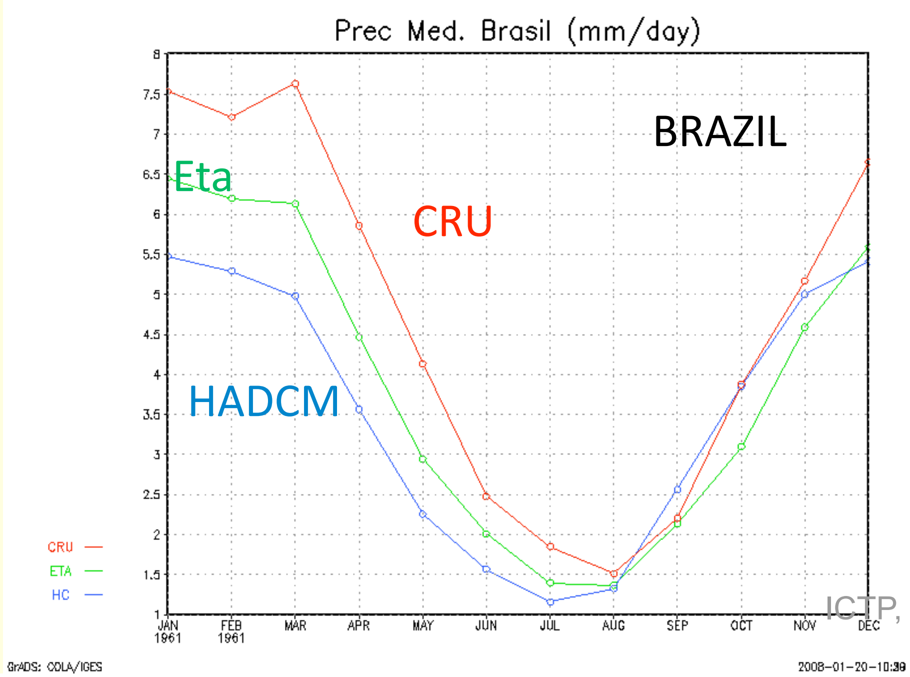
Eta-ECHAM

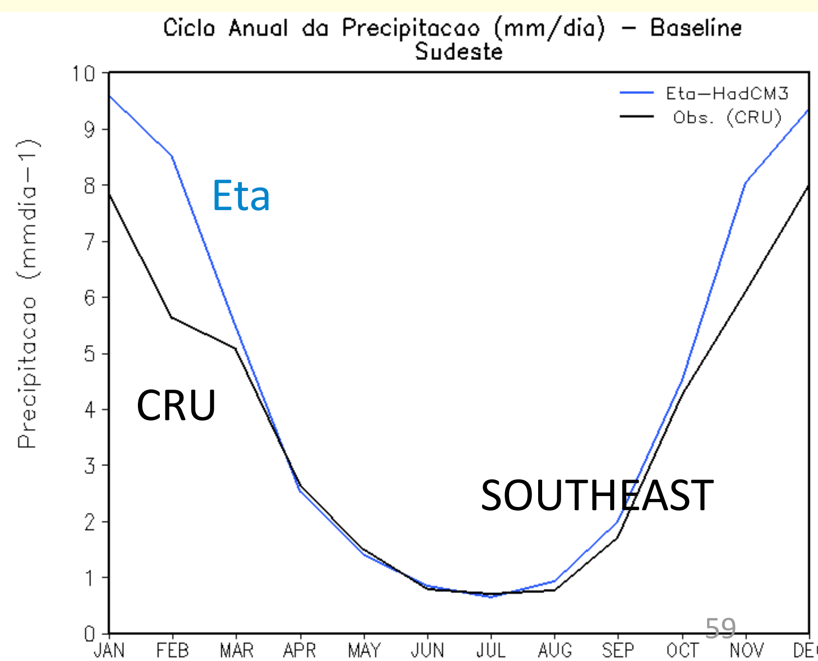






PRECIPITATION



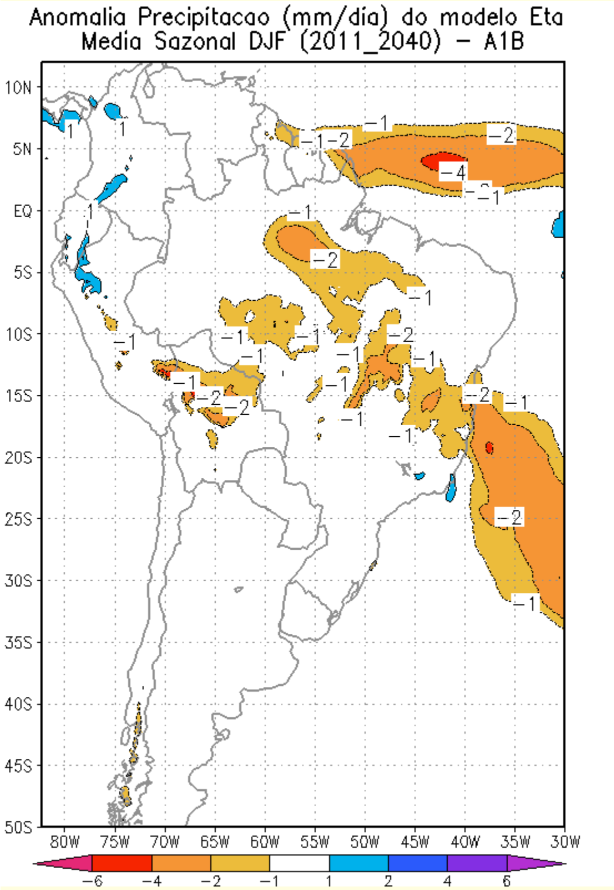


Rodada: Eta – HadCM3

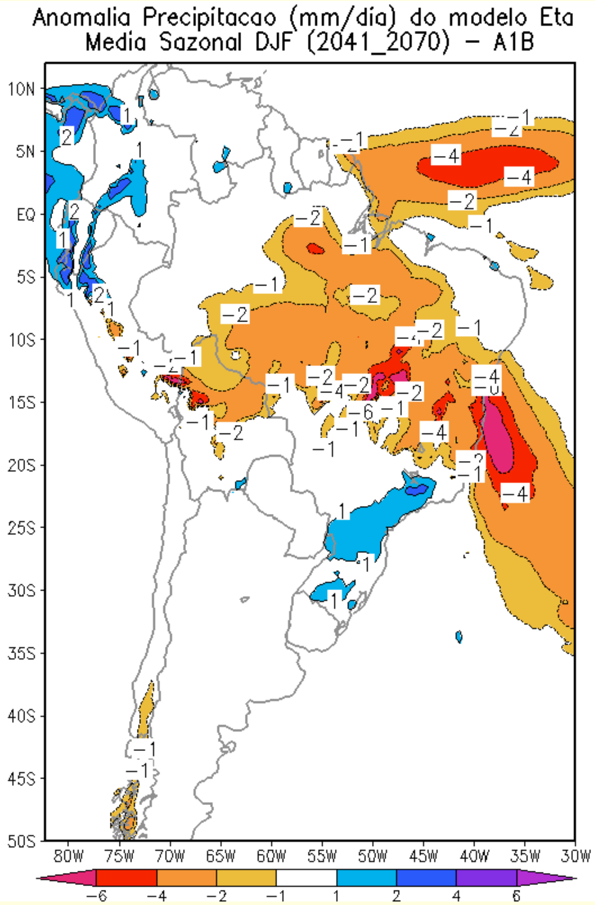
Temperatura e Precipitação: 11-40;41-70;70-99

José Fernando Pesquero – Pesquisador
CPTEC / INPE

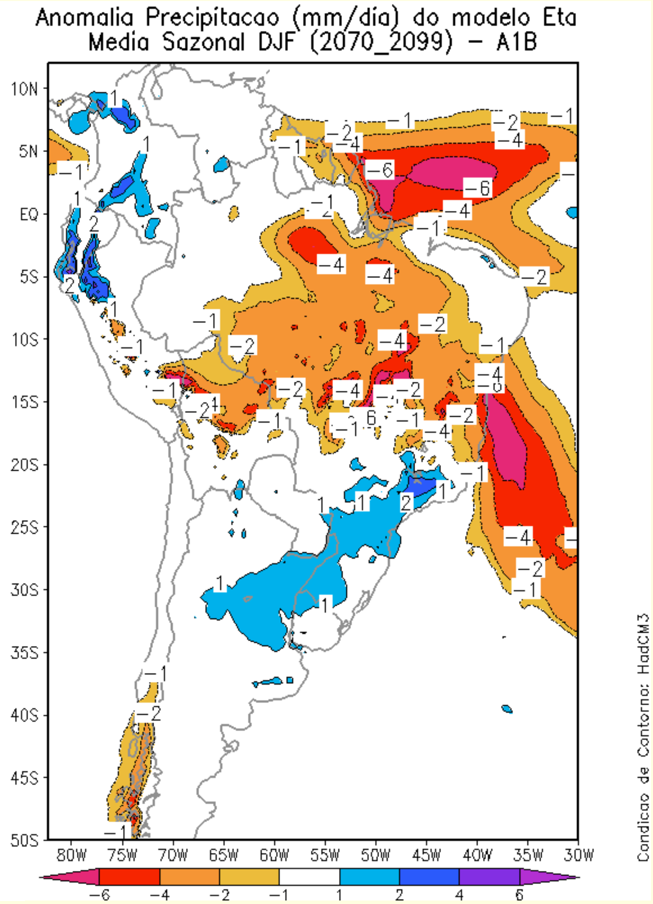
Eta Precipitação Média Sazonal 30 anos (DJF)



11-40

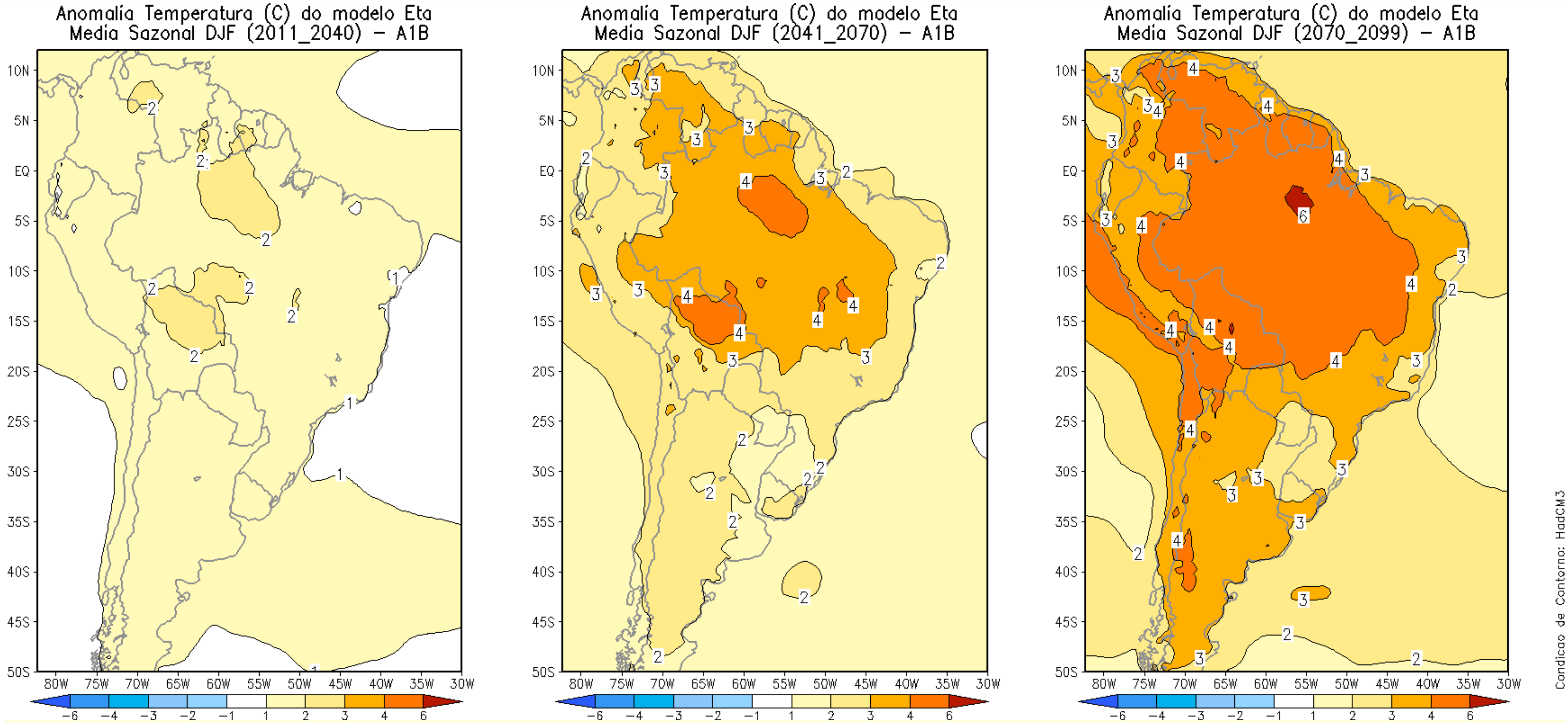


41-70



70-99

Eta Temperatura Média Sazonal 30 anos (DJF) (prox. superf.)



11-40

41-70

70-99

Example of a coupled atmosphere/ocean RCM:

MEĐUNARODNI SIMPOZIJUM

STVARALAŠTVO MILUTINA MILANKOVIĆA

EXAMPLE FROM THE "SINTA" PROJECT: IPCC A1B CHANGE SCENARIO DYNAMICAL DOWNSCALING FOR THE MEDITERRANEAN REGION

Borivoj Rajković

Vladimir Đurđević

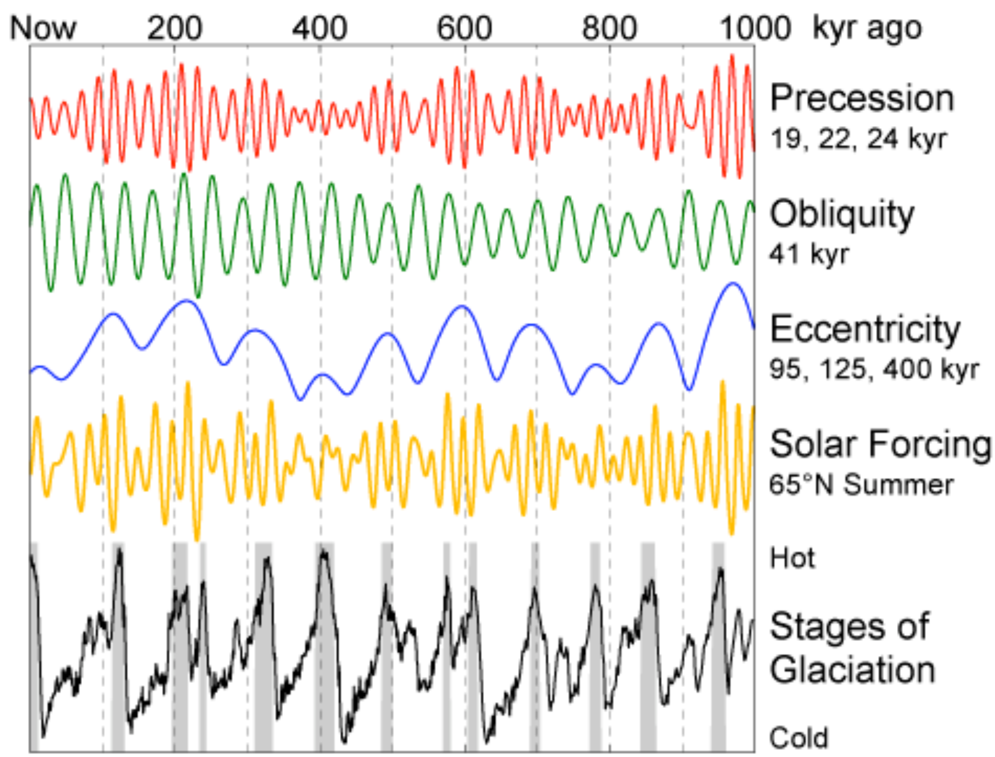
Minor changes: fm

Institute of Meteorology, Faculty of Physics, Belgrade University

Dalj, maj 2008.

•The first complete mathematical theory of ice ages

* Climate variability as consequence of astronomical parameters



* T1 19, 22, 24 kyr
* T2 41 kyr
* T3 95,125,400 kyr

+ Results from SINTA project (SImulations of climate chaNge in the mediTerranean Area)

Project partners:

+National Institute of Geophysics and Volcanology (INGV), Bologna, Italy.

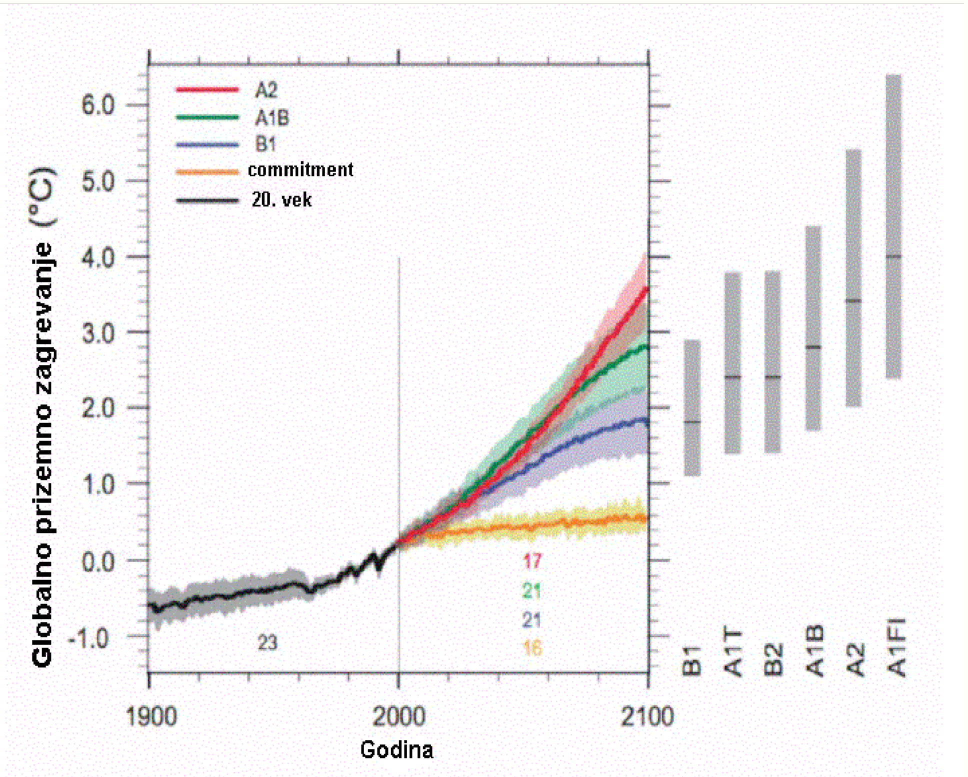
provide global climate change experiments integrations.

+Institute of Meteorology, Belgrade University, Belgrade, Serbia.

+Republic Hidrometeorological Service of Serbia, Belgrade, Serbia.

dynamical downscaling with a regional model, using initial and boundary condition from a global model.

The most probable estimates and their ranges of global surface worming for the period 2080-2099 relative to 1980-1999



SCENARIO	*MOST PROB.*	*RANGE*
B1	*1.8*	*1.1 - 2.9*
A1T	*2.4*	*1.4 - 3.8*
B2	*2.4*	*1.4 - 3.8*
A1B	*2.8*	*1.7 - 4.4*
A2	*3.4*	*2.0 - 5.4*
A1FI	*4.0*	*2.4 - 6.4*
#	*0.6*	*0.3-0.9*

CRCM: ClimEta/EBU-POM

- Two-way regional coupled model, grid point, primitive equation, and hydrostatic.
- Atmospheric component is Eta model (**EBU**=**E**ta **B**elgrade **U**niversity)
- Ocean component is POM
- Models exchange atmospheric surface fluxes and SST every physical time step of the atmospheric model (~180 s)

- Climate change experiment **setup**
- Present climate integration: **1961-1990**,
- Future climate integration: **2071-2100** (A1B Scenario)

- **Atmospheric model:**
  - 0.25° horizontal resolution (25-30 km) / 32 layers;
  - 6 h lateral boundary condition from SINTEX integrations;
  - Annual cycle of vegetation fraction;
  - Upgraded radiation (variable GHGs)
  - SST bottom boundary condition from SINTEX over uncoupled seas.
- **Ocean model:**
  - 0.2° horizontal resolution / 21 vertical levels (Mediterranean Sea),
  - Initial condition: MODB for 1961 / SINTEX for 2071.

Acronyms:

POM:

Princeton Ocean Model

SINTEX:

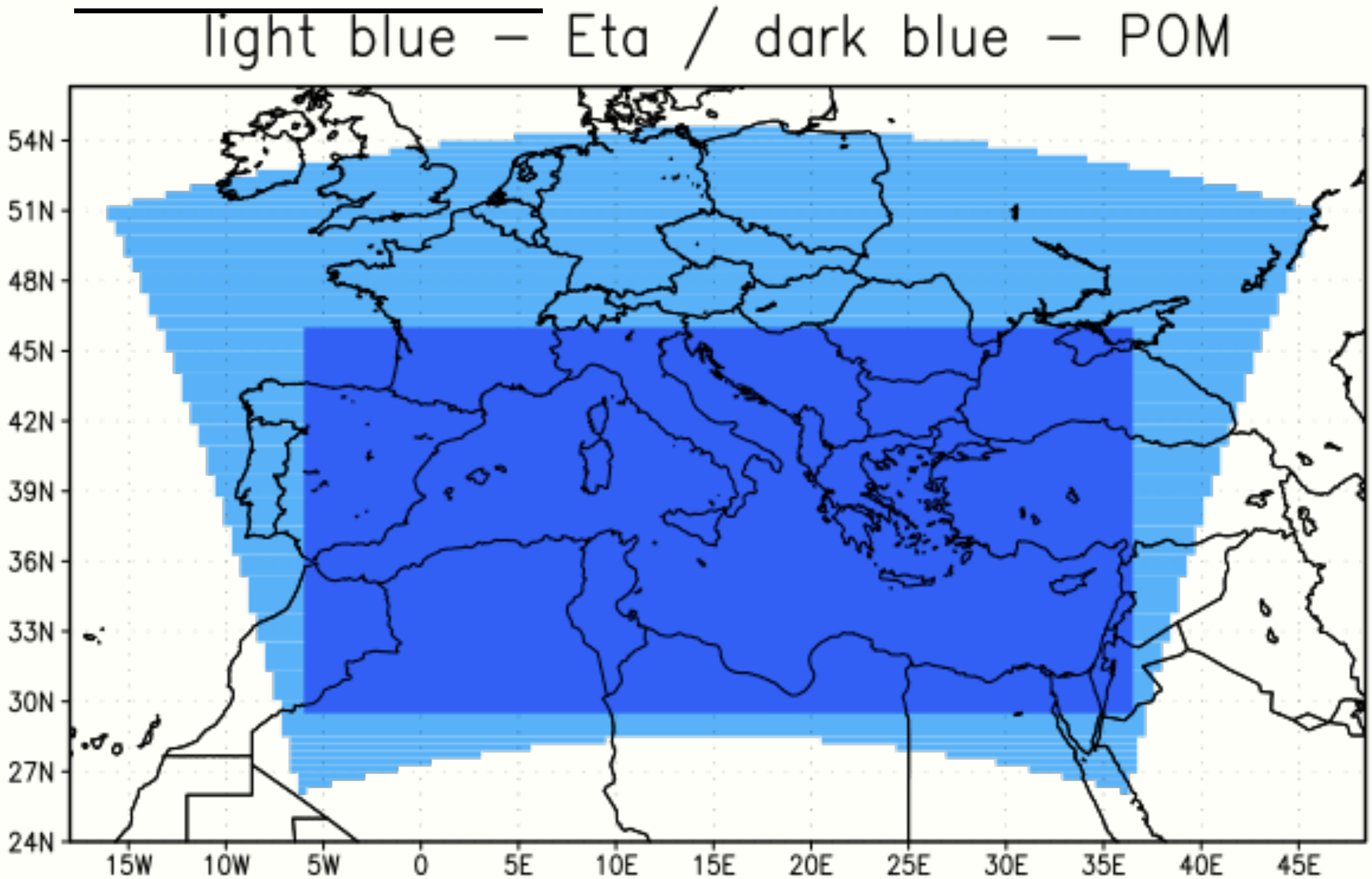
Istituto Nazionale di Geofisica e Vulcanologia (INGV, Bologna) Global GCM:

http://www.cmcc.it/web/public/ANS/models/ingv-sxg

MODB:

Mediterranean Oceanic Data Base

- Model domains

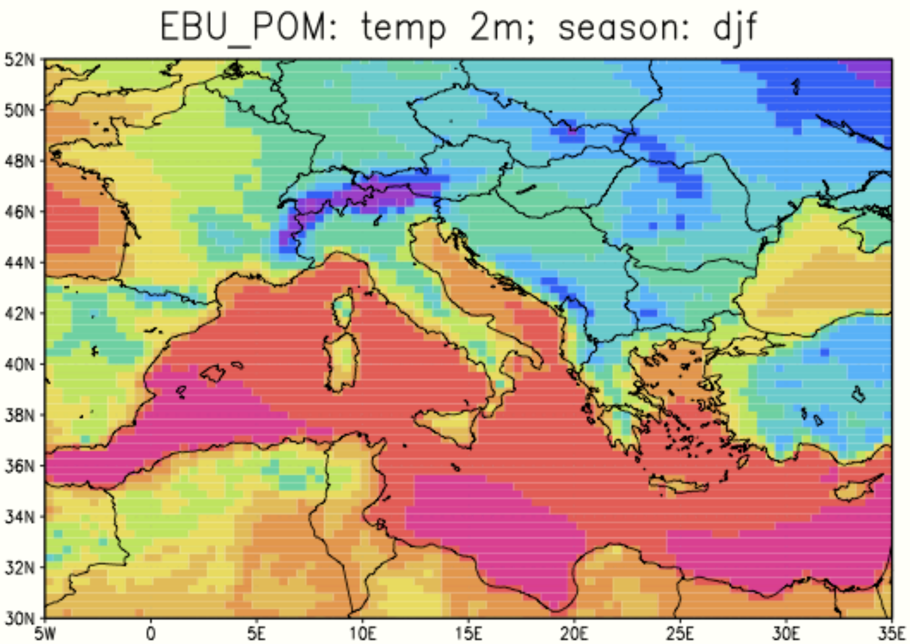


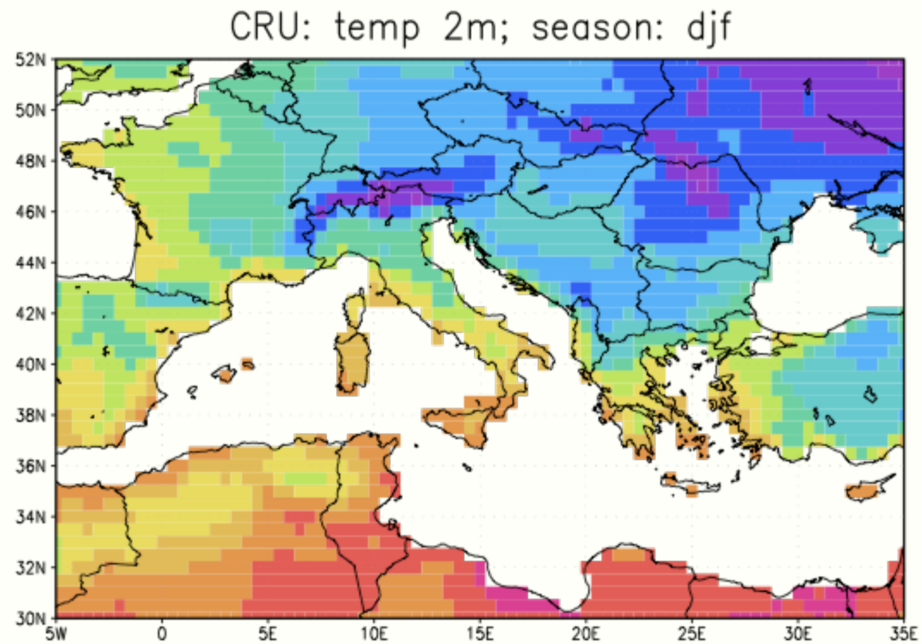
- **Verification of present climate (1961-1990) integration**

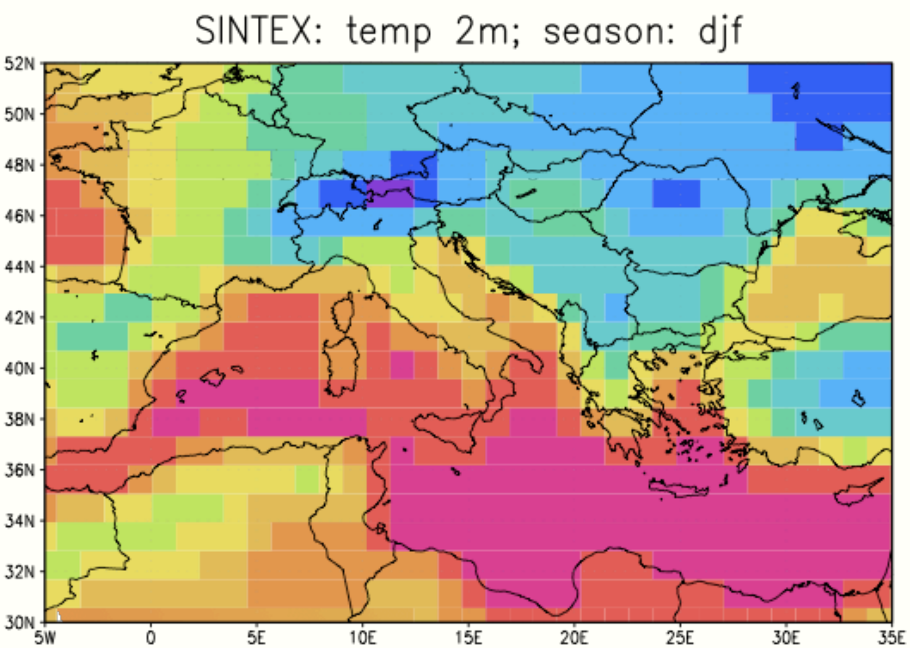
- This verification shows capability of model to reproduce present climate
  (*Annales Geophysicae*, 2008, **26**, 1935-1954)

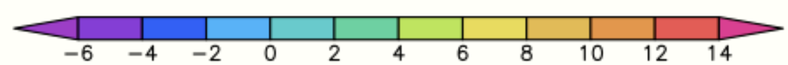
  - Seasonal means of 2 m temperature
    - Winter season: **D**ec/**J**an/**F**eb
    - Summer season: **J**un/**J**ul/**A**ug

DJF, 2 m temp 1961-1990





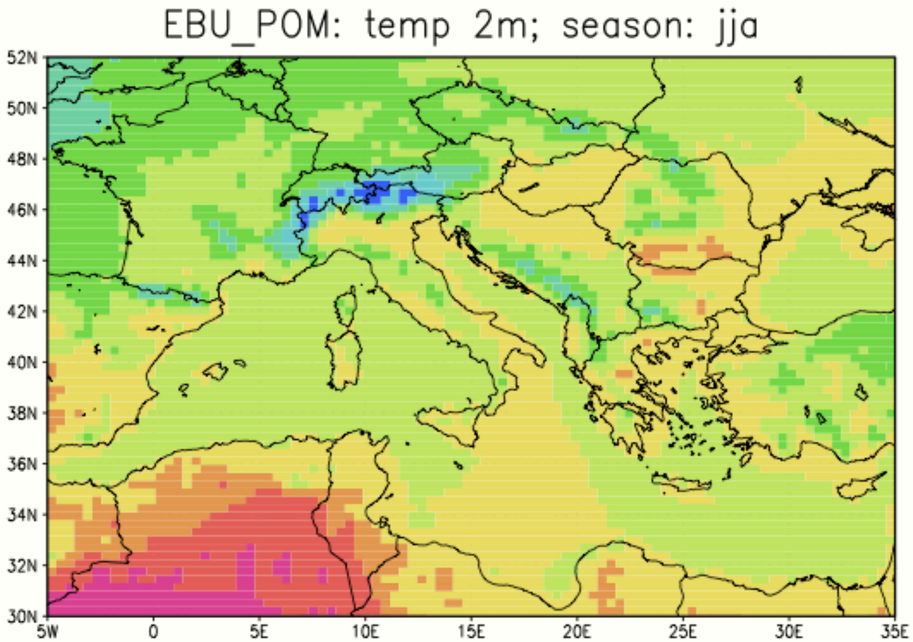


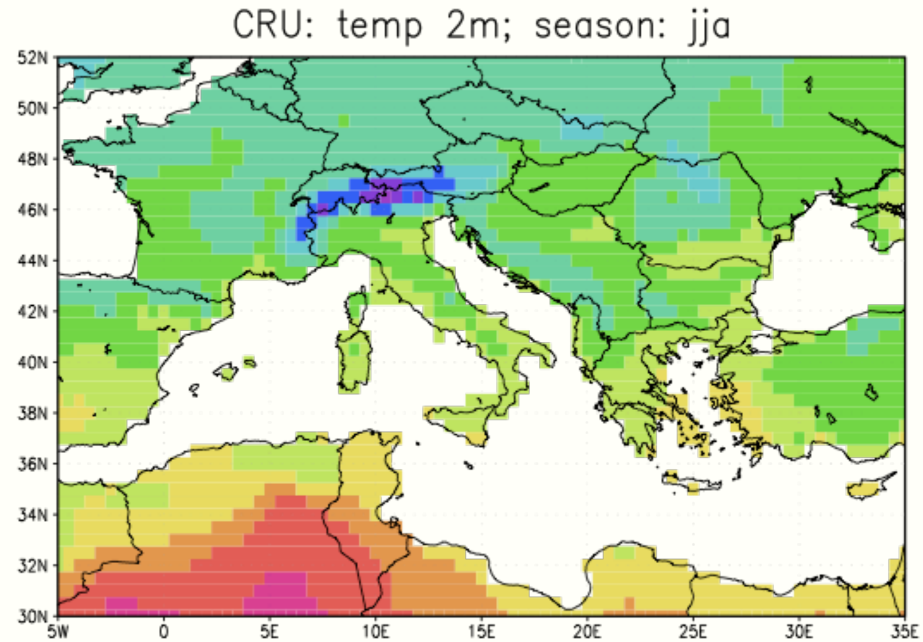


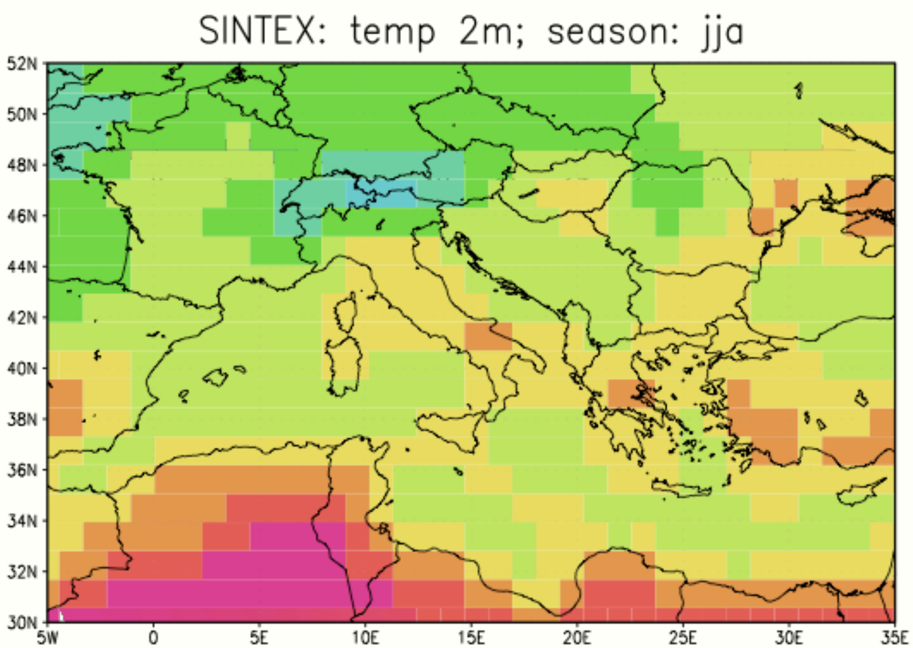
	bias	mae	rmse
EP/CRU	-0.21	1.88	2.15

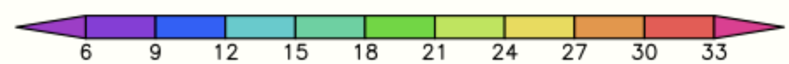
CRU: Climate Research Unit, Un. East Anglia

JJA, 2 m temp 1961-1990









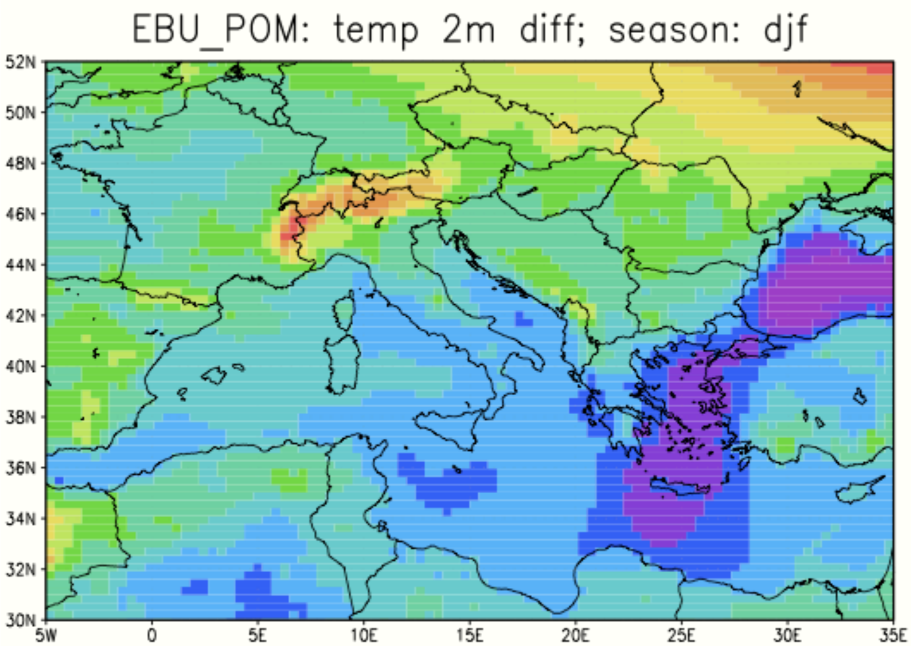
	bias	mae	rmse
EP/CRU	2.63	2.96	3.42

Differences between **2071-2100** and **1961-1990**:

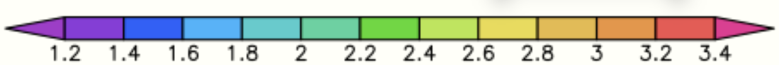
- Seasonal mean temperature, precipitation and 10 m wind speed differences.

2 m temp

December January February



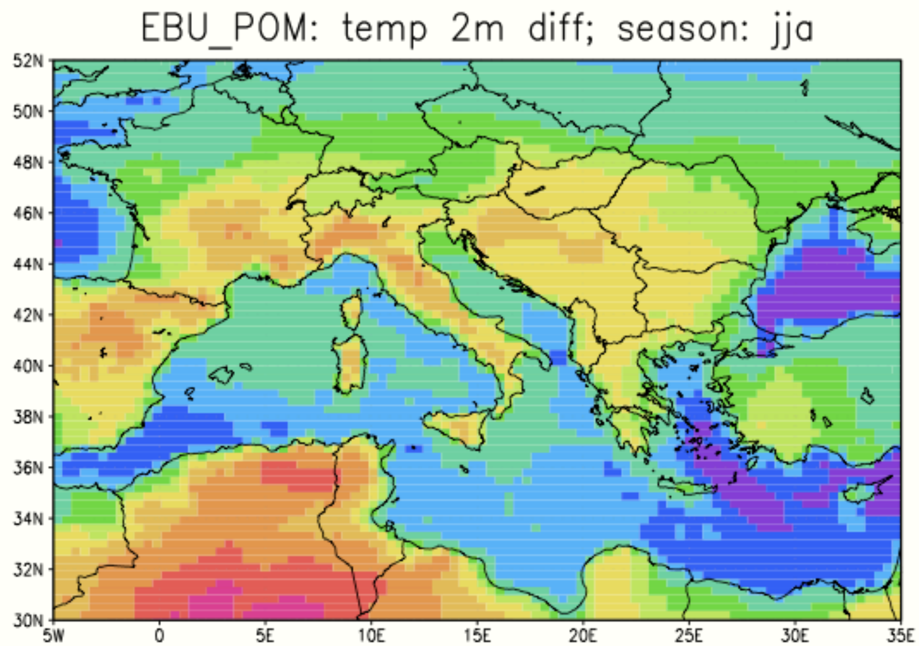
Alps: 2.6-3.2 deg.

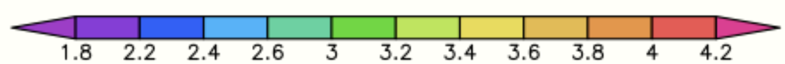


Serbia: temp. increase 2.0-2.4 deg

Italy: temp. increase 1.8-2.4 deg

Jun July August



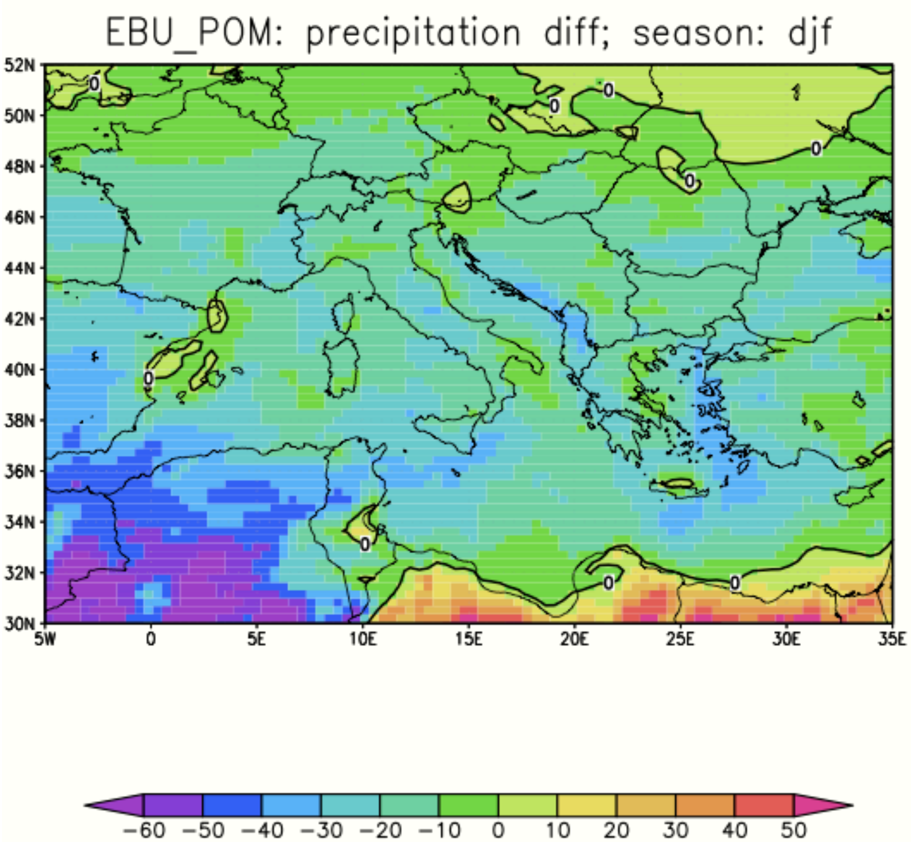


Serbia: temp. increase 3.4-3.8 deg

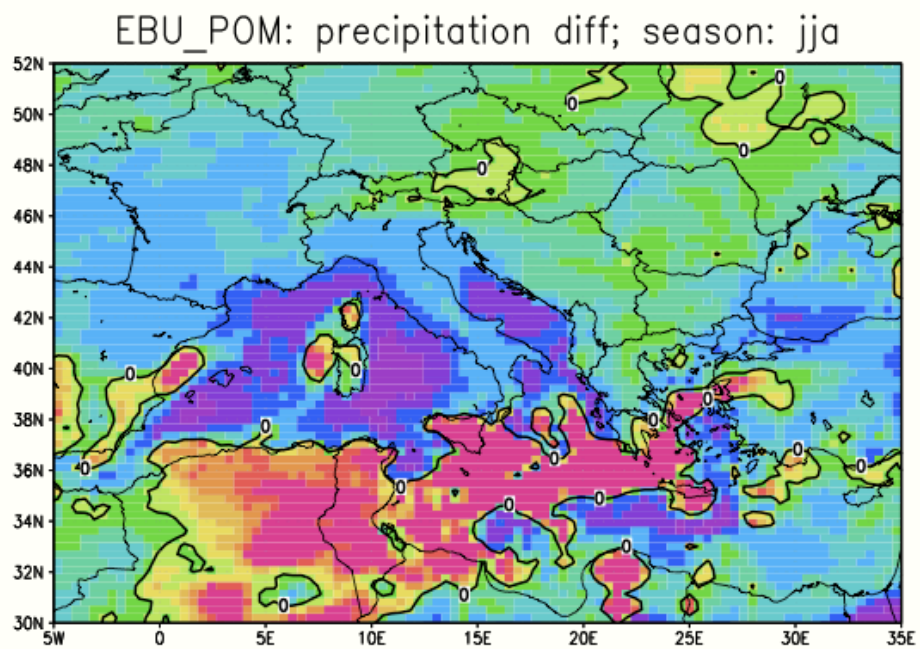
Italy: temp. increase 3.2-4.0 deg

Precipitation

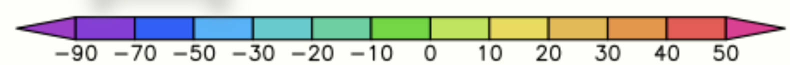
December January February



Jun July August



Italy costal area: over 70% less

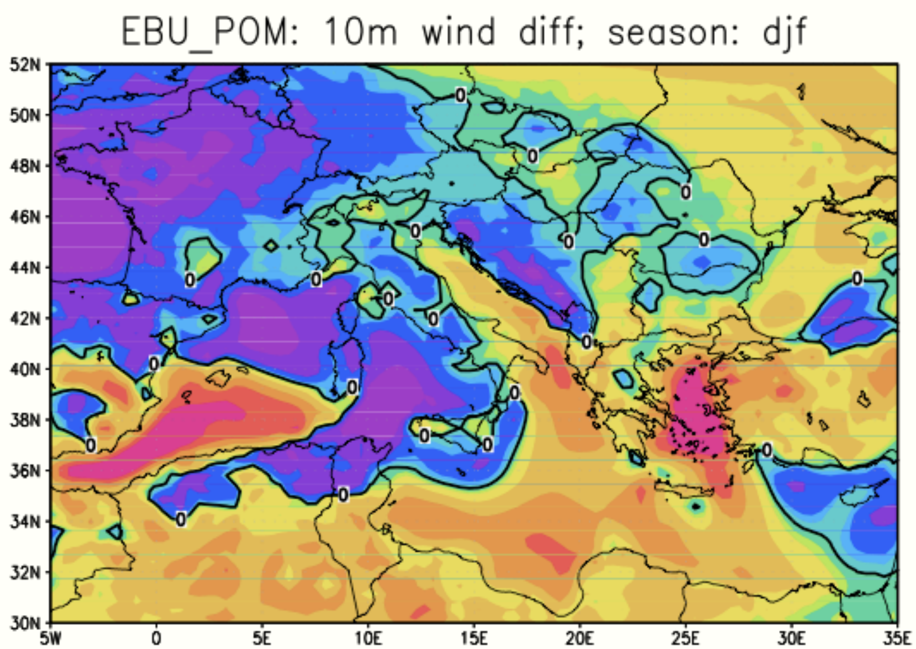


Serbia: prec. decrease 10-30%
Italy: prec. decrease 10-40%

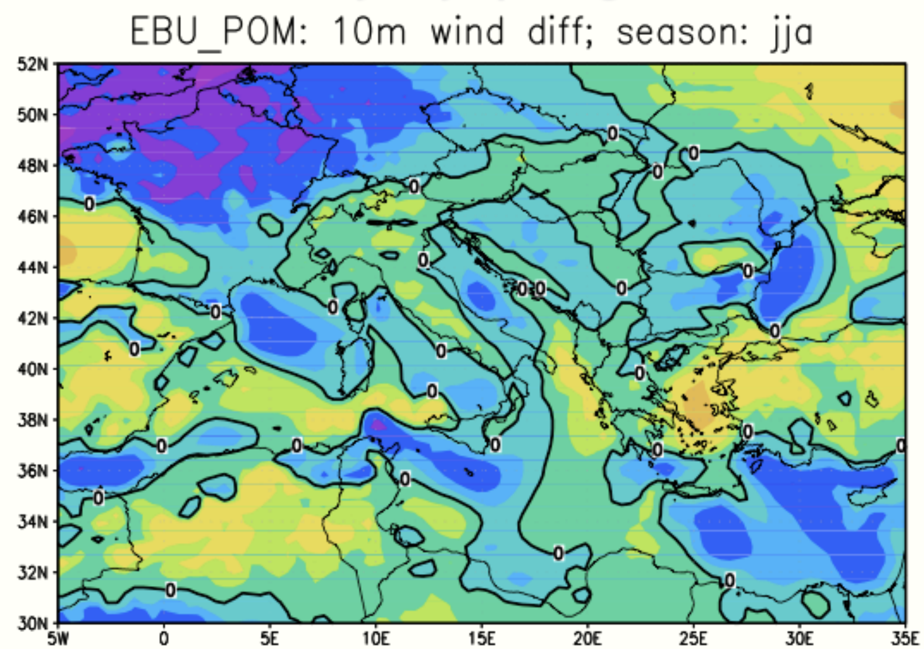
Serbia: prec. decrease 10-30%
Italy: prec. decrease 10-50%

10 m wind

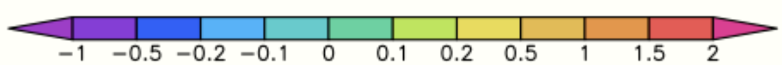
December January February

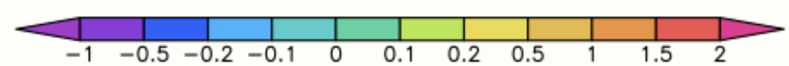


Jun July August



Bipolar changes





Serbia:

-North-west part decrease

+South-east part increase

Italy:

Max increase over Adriatic

Serbia:

-South-west part decrease

+North-east part increase

Italy:

Over land increase

This was done using:

PC processor : Intel Dual-Core Xeon 5160 @ 3.00GHz

4 GB ram

Intel Fortran Compiler Version 9.1

Model, atmosphere: 79 x 105 points, 32 layers

dlmd = dphd = 0.25, dt_b= 90 s

Model, Mediterranean: 193 x 153 points, 21 levels

dx = dy = ~20 km

exchange of fluxes and SST every 180 s

(every atmospheric physics time step)

The future of RCMs ?

To maintain their edge over global climate AOGCMs, RCMs of the future have to be/ continue to be

Dynamics

- Nonhydrostatic;
- Conservations (Example, Eta: mass, energy in advection, and in transformations potential to kinetic in space differencing, more …)
- "Not all models are created the same" (Bennert Machenhauer) that is, all roads (resolution !) do not lead to Rome. Specifically (fm):
  - Quasi-horizontal (eta, or eta-like coordinate) :)
  - Finite-volume
- LBCs (Savings are possible relative to what most groups are doing today !)
- Efficiency ! (To enable high resolution over a large domain !)

Physics

All standard NWP comprehensive physics, but in particular strong

- Boundary layer;
- Cloud physics (eventually, no convection parameterization);
- Land surface, ice if needed (region ?)

Coupled regional ocean / lakes model (if needed/ region ?)

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(Although a commendable effort, this should not be done to the detriment of basic research. It is true that basic research has less appeal for public funding than projects with applications of timely societal relevance. But at the same time, ...

Laprise et al. 2008)

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(Although a commendable effort, this should not be done to the detriment of basic research. It is true that basic research has less appeal for public funding than projects with applications of timely societal relevance. But at the same time, ...

Laprise et al. 2008)

How can RCMs achieve all this and yet maintain significantly higher resolution than the global climate models?

- Savings due to the smaller domain: factor of ~10 ? (In case of the NCEP Eta-like domain, only ~5) Not enough! However:
- RCMs have a parasitic relationship to global climate models, thus they can afford
  - not to have to undergo long simulations required to reach equilibrium between the components of the Earth climate system !
  - most likely to have the dynamics of quite a few components safely absorbed via lateral boundaries: note the extremely comprehensive shopping list of species of the "centennial" Met Office model of the G. Pankiewicz Workshop I talk (carbon, methane, nitrogen cycles, very long list of a variety of atmosphere, land, ocean, aerosols, trop. chemistry species);

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Critical RCM research issues !

How can RCMs … cont'd

- Simple geometry (no poles, no vertices);
- In some cases, they can save by being region specific (e.g., sea ice not needed in Mediterranean!)

However, no savings, just the opposite, on basic model dynamics and physics !

Some references (most other available in Giorgi 2006, and/or Laprise et al. 2008)

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