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Spring Colloquium on
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REGIONAL WEATHER PREDICTION
MODELLING AND PREDICTABILITY
(8 – 19 April 2002)

"The Eta Model and a decade + of its use at NCEP: Challenges overcome and lessons learned"

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The Eta Model and a decade + of its use at NCEP: Challenges overcome and lessons learned

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The Eta: a "limited area model"
(LAM)
= a regional model

In NWP: forecast boundary conditions

The first operational implementation of a limited area model (LAM) run using forecast boundary conditions seems to be the one at the Swedish Meteorological and Hydrological Institute (SMHI) by BENGTSSON and MOEN. The system was tested in experimental predictions apparently starting in 1967. After some efforts in looking at available records, BENGTSSON and MOEN have become "convinced that [the system] actually was put into operation in 1969" (BENGTSSON, personal communication). The same model, a 3-level quasi-geostrophic model, was used at two resolutions, 300 and 150 km, with the higher resolution run using forecast boundary conditions from the lower resolution one (BENGTSSON and MOEN, 1971).

Forecast boundary conditions for the "rectangle" version of the U.K. Meteorological Office, or, as referred then, "BUSHBY-TIMPSON 10 level primitive equation model", were implemented in 1972, apparently in August (BURRIDGE and GADD, 1977). A 64×48 rectangular grid was used for the rectangle, with a 100 km grid spacing at 60°N; an extremely impressive resolution at the time. The introduction of boundary changes is reported by BURRIDGE and GADD (1972) to have "resulted in a marked improvement of the fine mesh forecasts near the British Isles, which are situated near the centre of the fine mesh area."

At the U.S. National Meteorological Center (NMC), even though the venerable "LFM" (Limited-area Fine-mesh Model) traces its beginnings to as early as 1966 (HOWCROFT, 1966) and had been operational since 1971 – so that it had its "coming of age" birthday party in 1992 (ANONYMOUS, 1993) – forecast boundary conditions were incorporated somewhat later, on 7 February 1973 (NWS, 1973). LFM's horizontal resolution at the time was half a "Bedient", which means 190.5 km, using the then ubiquitous NWP resolution unit, alive even today, stemming from Art BEDIENT's role in the 381 km resolution of the so-called SHUMAN-HOVERMALE model (SHUMAN and HOVERMALE, 1968), again at the customary 60°N.

The very same year, and just a few months later, in October, a 6-level, 152-km nested primitive equation model was implemented at the Japan Meteorological Agency. It used boundary conditions supplied by a Northern Hemisphere, 6-level 304-km quasi-geostrophic model (OKAMURA, 1975; KITADE, 1990). This seems to

The first operational use of forecast BCs ?

50th Anniversary of Num. Wea. Pred. Comm. Symp., 2001

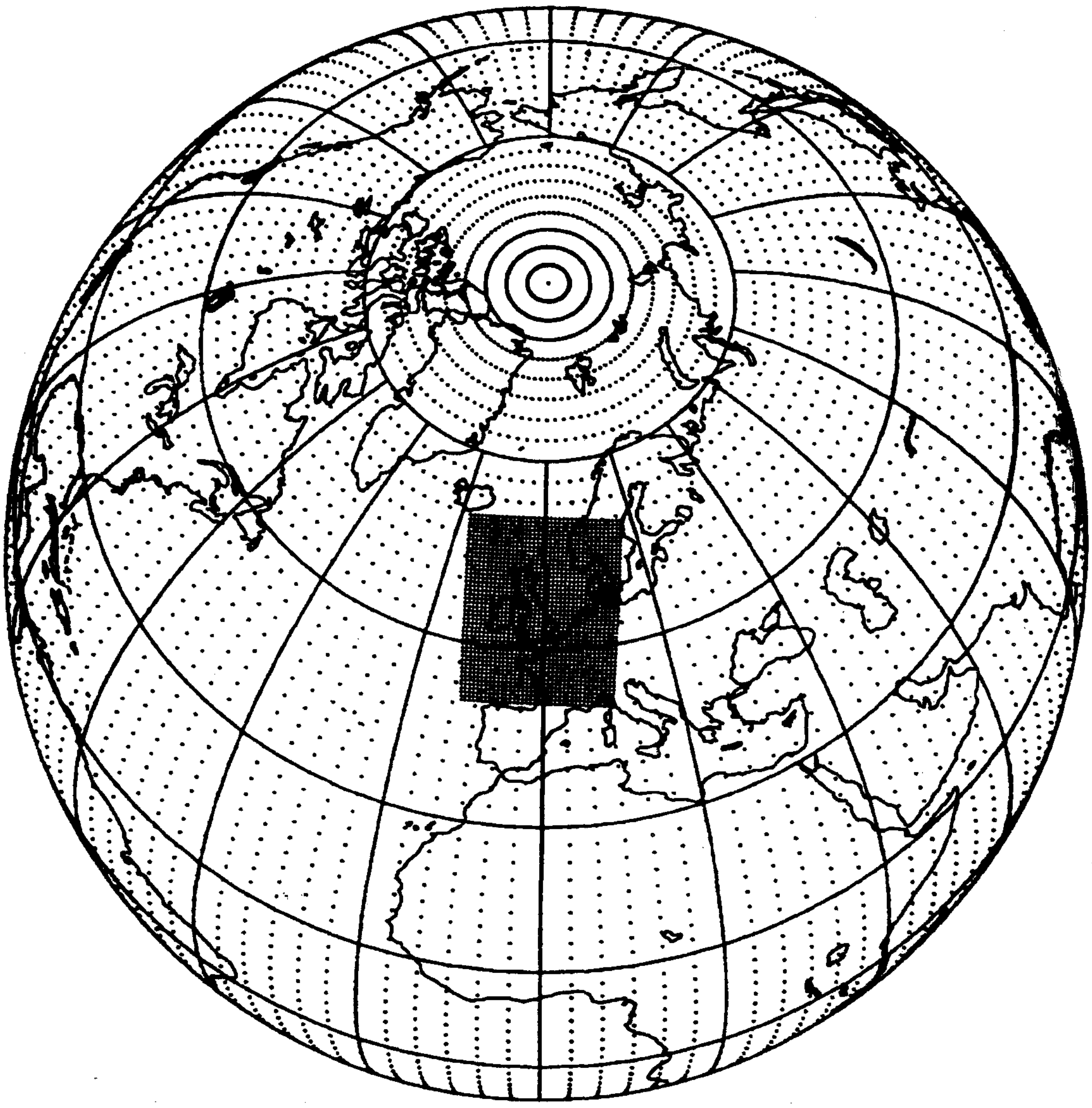


Figure 1: The current operational global (432 × 325) and mesoscale (146 × 182) horizontal **meshes for the** UK Met Office's Unified Model, with approximate respective mesh spacings of 60 km (at **mid-latitudes) and** 12 km (over the U.K. mesoscale window): for pictorial clarity, only every 4^{th} meshpoint in each **direction** is plotted.

Staniforth, 50th Anniv. of NWP, 2001

small region of the globe, and to do so within the severe computational constraints imposed by forecast timeliness.

If the global and regional cycles are centred around two distinct models, the strategy requires the maintenance, improvement and optimisation of two complex sets of computer programme libraries and procedures. This is very labour intensive. First, numerical-weather-prediction models and data-assimilation systems need signif-

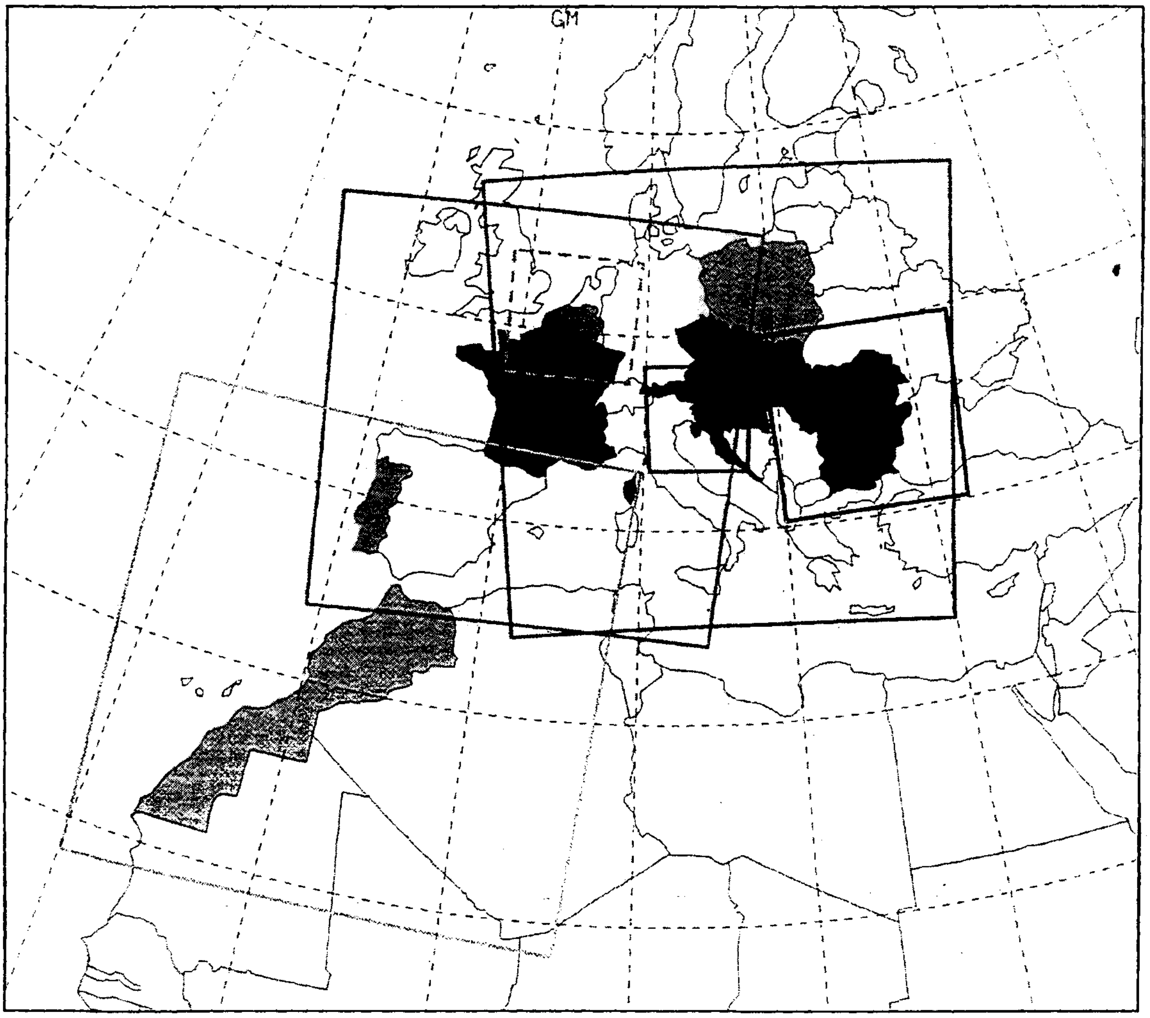
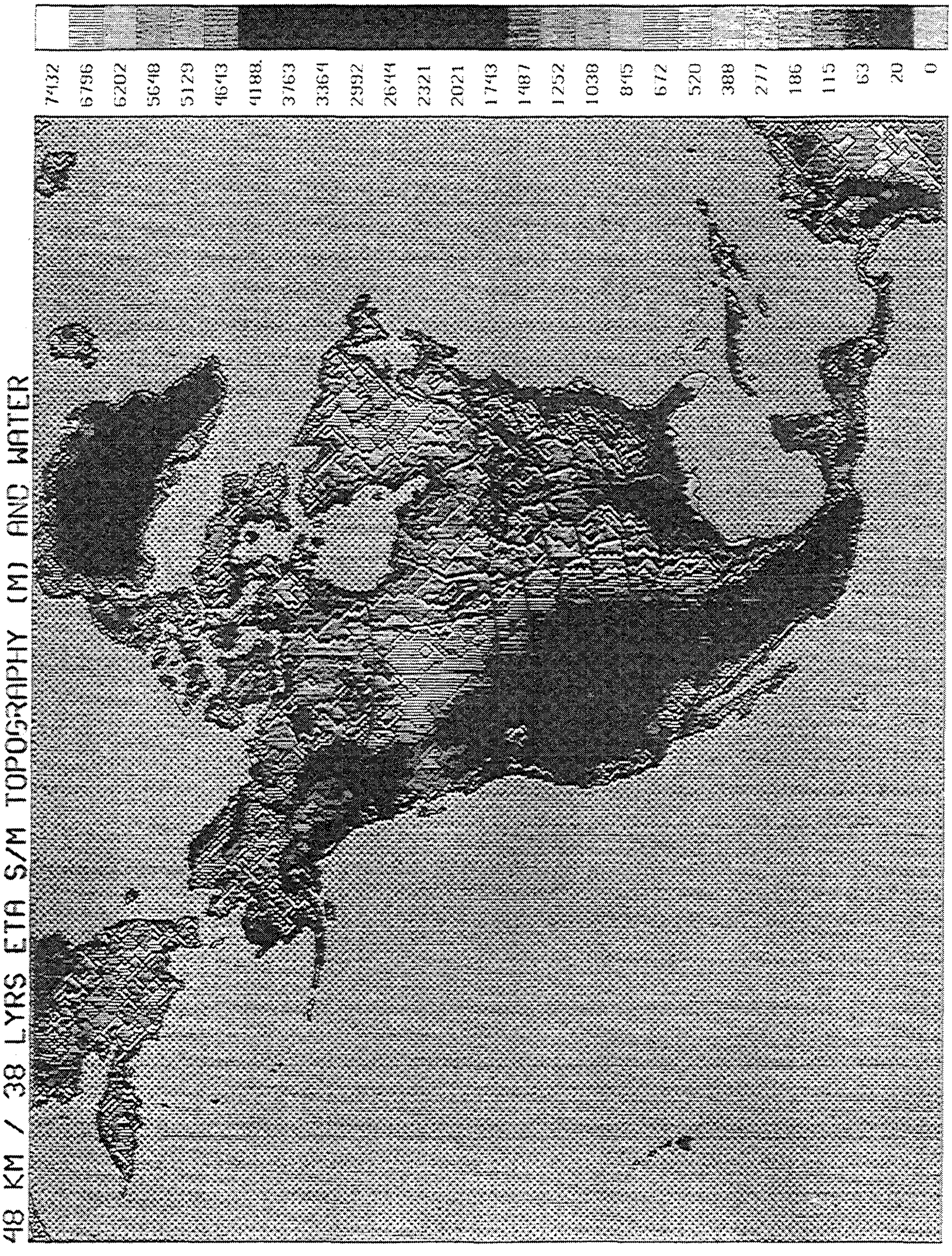


Figure 1 — Map of the ALADIN partners (with RC-LACE and SELAM grouped under one shade of grey each) and the operational pre-operational (broken lines) domains

WMO Bull., 1997

12 October 95 - 9 February 98:



.189 of the Earth's surface

Domain of the operational Eta at NCEP:

Lateral BCs of the previous global model run! (Initial, 12h, now 6h ago)

Chapter 13

Numerical Methods: The Arakawa Approach, Horizontal Grid, Global, and Limited-Area Modeling

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I. INTRODUCTION: THE ARAKAWA APPROACH IN NUMERICAL METHODS

It is perhaps a remarkable characteristic of atmospheric numerical modeling that in spite of the steady progress during the past more than four decades the diversity of points of view on what are the most promising

General Circulation Model Development

principles to follow shows little sign of diminishing. Within these points of view, I find it fitting to refer to the Arakawa approach in numerical modeling as the one in which attention is focused on the realism of the physical properties of the discrete system within given computational resources. In other words, with the Arakawa approach one is not relying on these properties to automatically become satisfactory as the resolution is increasing, merely as a result of the observation of basic requirements of computational mathematics. Instead, one is striving to achieve properties deemed desirable with the resolution at hand. This is achieved by consideration of the physical properties of the finite difference analog of the continuous equations.

With this formulation, there is clearly some room left for searching as to what exactly are the physical properties to which attention is best paid, and to what should be the priorities among various possibilities. Historically, the incentive for the approach came from Norman Phillips's (1959) discovery of the mechanism of nonlinear instability as consisting of a systematic distortion of the energy spectrum of two-dimensional nondivergent flow. A straightforward remedy used by Phillips was one of Fourier filtering aimed at preventing the fatal accumulation of energy in shortest scales. Akio Arakawa, however, realized that the maintenance of the difference analogs of domain-averaged kinetic energy and enstrophy guarantees no change in the average wave number, thus preventing nonlinear instability with no damping in the terms addressed; and demonstrated a way to achieve this with his famous (Arakawa, 1966) horizontal advection scheme. (For additional historic comments see, e.g., Lilly, 1997.) The Arakawa advection scheme and subsequent numerous conservation considerations as discussed in Arakawa and Lamb (1977, hereafter AL), for example, have established the maintenance of the difference analogs of chosen integral constraints of the continuous atmosphere as the hallmark of the approach. Yet, more generally, emphasis was placed by Arakawa, and by others, on reproducing numerous other properties of physical importance of the fluid dynamical system addressed. Dispersion and phase speed properties, avoidance of computational modes, and avoidance of false instabilities are the typical examples, as succinctly summarized in Section 7 of a recent review paper by Arakawa (1997) or, more extensively, in Arakawa (1988).

In striving to achieve goals of this type, no advantage tends to be obtained from increasing the order of the accuracy of the scheme. For example, as gently stated by Arakawa (1997) in summarizing the problem of the computational mode, "The concept of the order of accuracy . . . based on the Taylor expansion . . . is not relevant for the existence or non-existence of a computational mode." Similarly, Mesinger (1982; see also Mesinger and Janjić, 1985) demonstrated that an increase in resolution that entails an increase in the formal Taylor series accuracy does not necessarily help in achieving a physically desirable result and can even result in an increase of the actual error.

Underlying the Arakawa approach is the determination to understand the reason of a numerical problem—including those at the shortest represented scales—and try to address its cause as opposed to using artificial diffusion or filtering to alleviate its consequences and presumably lose some of the real information in the process. Yet, a different emphasis, or different views on what may be the best road to follow, are not hard to find among leading atmospheric modelers. For example, in a recent paper by Pielke *et al.* (1997) citing also supporting sources, one reads that "such short waves [wavelengths less than $4\Delta x$] are inadequately resolved on a computation grid and even in the linearized equations are poorly represented in terms of amplitude and/or phase. For these reasons, and because they are expected to cascade to even smaller scales anyway, it is desirable to remove these waves." In yet another recent paper (Gustafsson and McDonald, 1996), one reads that "Unwanted noise is generated in numerical weather prediction models, by the orography, by the boundaries, by the 'physics,' or even sometimes by the dynamics. The spectral approach provides two useful filters for attacking this problem *at no computational cost*. . . . It was now necessary to write and test new filters for the gridpoint model if it was to continue to compete with the spectral model."

I will return to some of these issues in more detail later. For examples of physical properties that have been and can be considered in the Arakawa style I will start with a retrospective of the horizontal grid topic. This will permit me to review and also present some recent developments in this area. I then proceed with an exposition on the experience from the operational running of the Eta model at the U.S. National Centers for Environmental Prediction (NCEP), to the extent that it can be viewed as a contribution to the issues raised. A number of other global and limited-area modeling topics, having to do with the pole problem, the viability of the limited-area modeling approach, and the resolution versus domain size trade-off, are also discussed. Use will again be made of the Eta model results where appropriate. I conclude by illustrating the remarkable progress that has been accomplished in the atmospheric numerical modeling field during the past decade or so and by commenting on thrusts taking place or expected.

PGF with sloping coord. surfaces:

$$-\nabla\Phi - RT\nabla \ln p_s \qquad (1)$$

or any of many other equiv. forms:

Using any consistent discretization of (1)

T in a sloping coordinate surface, does not necessarily contain the information that went into the calculation of Φ (T of the vertical column from the ground up)

Increasing resolution and/or increasing formal accuracy does not necessarily help, in fact may (is likely?) to increse the error

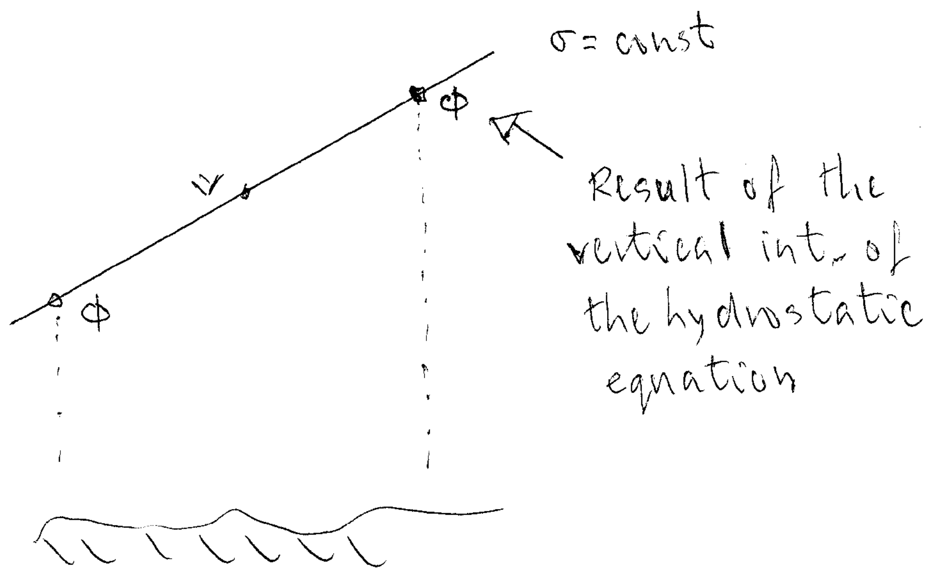

TABLE 1.

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

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

The error increases with increasing resolution!

Vertical resolution does not affect the error!

Pielke, Mesosc. Meteor. Modeling, 2nd Ed., Acad. Press, 2002

Examples of other studies using this model include Zängl (1999), Bao *et al.* (2000), Colle and Mass (2000), Mass and Steenburgh (2000), Ritchie and Elsberry (2000), Stensrud *et al.* (2000), Wang *et al.* (2000), and Xiao *et al.* (2000). Derivatives of earlier versions of this model are reported in Giorgi *et al.* (1993a, b) and Liu *et al.* (1996) for RegCM2, and Lynch *et al.* (1999a, b), and Lynch and Wu (2000) for ARCSyM.

Model: Eta Model

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A. Group: NOAA/NCEP Environmental Modeling Center; numerous other weather services and/or centers. The current NCEP operational version is described in the sequel, unless specifically mentioned otherwise.

B. Equations: Primitive hydrostatic equations. Nonhydrostatic version available (Janjić *et al.* 2001).

C. Dimensionality: 3-D.

D. Grid: Arakawa E-grid in horizontal, Lorenz grid in vertical.

E. Minimum horizontal resolution: Minimum resolution extensively used 10 km (e.g., Black *et al.* 1998). The lowest resolution on which the model was run was 4 km.

F. Vertical resolution: 50 layers, more for horizontal resolutions higher than the operational 22 km.

G. Model domain: 106 × 80 degrees of rotated longitude × latitude.

H. Initialization: 3-D fully cycled variational data assimilation (EDAS) (e.g., http://www.nws.noaa.gov/om/tpeta.htm). Digital filtering for 10-km runs with no EDAS.

I. Solution technique: Time; split-explicit time differencing; forward-backward adjustment terms, with trapezoidal-implicit Coriolis terms, and adjustment time step of 60 s; forward-then-off-centered horizontal advection of momentum and temperature; "forward-in-time" horizontal advection of moisture variables; Matsuno vertical advection of momentum and temperature. Space: Arakawa-type, Janjić (1984) horizontal advection of momentum and temperature; conserving, among other quantities, energy and C-grid defined enstrophy; conserving momentum apart from the effect of mountains; Smolarkiewicz-type, Janjić (1997) horizontal moisture advection; Arakawa vertical advection of momentum and temperature, conserving momentum and energy; piecewise-linear (Mesinger and Jovic 2001) vertical moisture advection; energy conservation in transformations between the kinetic and potential energy in space differencing (Mesinger 1984, Mesinger *et al.* 1988); gravity-wave coupling scheme (Mesinger 1973, 1974; Janjić 1979) preventing separation of gravity waves on two C-subgrids of the E-grid.

J. Coordinate system: Rotated spherical coordinates in horizontal; eta (step-mountain) coordinate in vertical.

K. Lateral boundary condition: Prescribed/extrapolated along a single outer boundary line, followed by a buffer line of four-point averaging of the boundary and the third line variables (Mesinger 1977). Integration starting in the third line, with no relaxation or enhanced diffusion.

L. Top boundary condition: Eta vertical velocity set to 0 at the model top at 25 mb.

M. Surface boundary: Topography. Silhouette-mean step topography (Mesinger 1996). Mason–type parameterization of orographic roughness; surface fluxes over land. Monin–Obukhov, Paulson similarity functions. Zilitinkevich parameterization of viscous sublayer; land surface schemes. Multilayer (currently four layers) soil/vegetation/snowpack land surface model ("NOAH" LSM) (Chen *et al.* 1996, 1997; Chen and Mitchell 1999; Mitchell *et al.* 1999, 2000). Provides, or provides input to, soil moisture/temperature, skin temperature, and surface fluxes of heat, moisture, and upward radiation (longwave, shortwave). Uses as input spatial databases of 12 vegetation types, 9 soil types, seasonal albedo, and a NESDIS satellite-based NDVI-derived seasonal cycle of vegetation greenness, as well as a daily updated, 23-km, Northern Hemisphere, operational snow cover analysis produced by NESDIS. The LSM land state variables cycle continuously in the Eta EDAS and are driven by EDAS precipitation, surface radiation, etc. Surface fluxes over water. Monin-Obukhov, Lobocki (1993) Mellor-Yamada level-2 derived similarity functions. Viscous sublayer (Janjić 1994), linear approximation of Liu *et al.* (1979), with parameters according to Mangarella *et al.* (1973) and Brutsaert (1982b).

N. Parameterization of subgrid mixing: Vertical: Mellor-Yamada level-2.5 turbulence closure (Mellor and Yamada 1982), with improved treatment of the master length scale/realizability problems (Mesinger 1993a, b; Janjić 1996); Horizontal: Second-order, Smagorinsky-like, aimed to parameterize the impact of advection by subgrid-scale motions.

O. Cumulus parameterization: Betts–Miller–Janjić scheme for deep and shallow convection (Betts 1986; Betts and Miller 1986; Janjić 1994).

P. Radiation parameterization: GFDL radiation scheme (Lacis and Hansen 1974; Fels and Schwarzkopf 1975).

Q. Stable precipitation parameterization: Explicit prediction of grid-scale cloud water/ice mixing ratio (Zhao and Carr 1997; Zhao *et al.* 1997), with predicted clouds used by the radiation scheme.

R. Other: Divergence damping (optional/not required for stability).

S. Phenomena studied: QPF performance, depending on systems, regions, and/or model features; moisture transport impacts and basin/subbasin budgets, return flow; land surface phenomena, in particular vegetation and soil moisture/water transport impacts; effects of topography, depending on the choice of the vertical coordinate; tropical cyclones; slantwise instability; other.

T. Computer used; example of time of integration for a specific problem: On an Origin 2000, the Eta 32-km (about 2.2×10^7 atmospheric prognostic variables) in a dedicated run (32 processors) takes about 30 minutes for a 48-hour forecast; in a nondedicated run (25 processors), it takes about 43 minutes. On the IBM SP, in a dedicated run (160 nodes and threading) 48-hour forecast takes about 11 minutes (times as of October 1999, from T. Black and E. Rogers). The code is regularly run on numerous other computers workstations and on upper-end PCs.

The three challenges of the Eta during the past ~ a decade/ computational design relevant:

- Comparison against the Nested Grid Model (NGM), the "official regional model " of the U.S. Nat'l Meteor. Center (NMC). (NGMs fourth-order accuracy implemented in Dec. 1990)

- Comparison against the Regional Spectral Model (RSM) in mid-nineties;

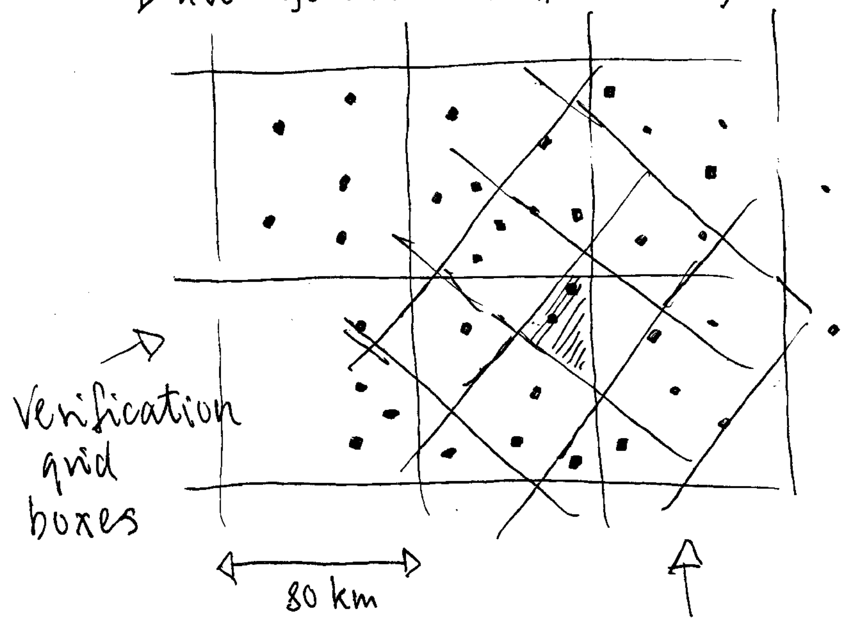
- Comparison against the Avn, in particular at later forecast times, when to stay competitive the Eta needs to compensate for the inflow of the less accurate, previous Avn run produced, lateral boundary information

An unintended resolution/domain size exp., ~1996-1997;

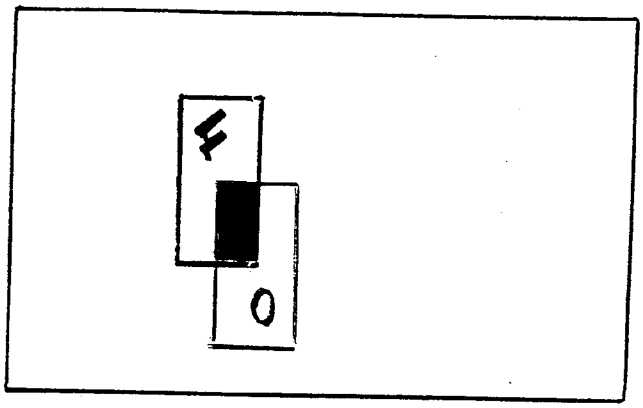
Verification?

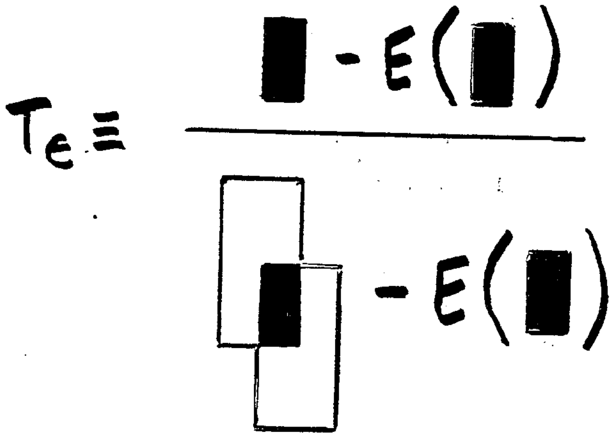
- Analyses;
- rms fits to obs;
- fits (?) to analyzed obs

At NCEP, most emphasis:
Precipitation: ~ 8,000 rain gauge obs over CONUS:
→ averaged over verification grid boxes



The Equitable Threat Score:





= 0 for a random forecast ;
= 1 for a perfect forecast

$$E = F \cdot O / N$$

First 24 months of 3-model scores:

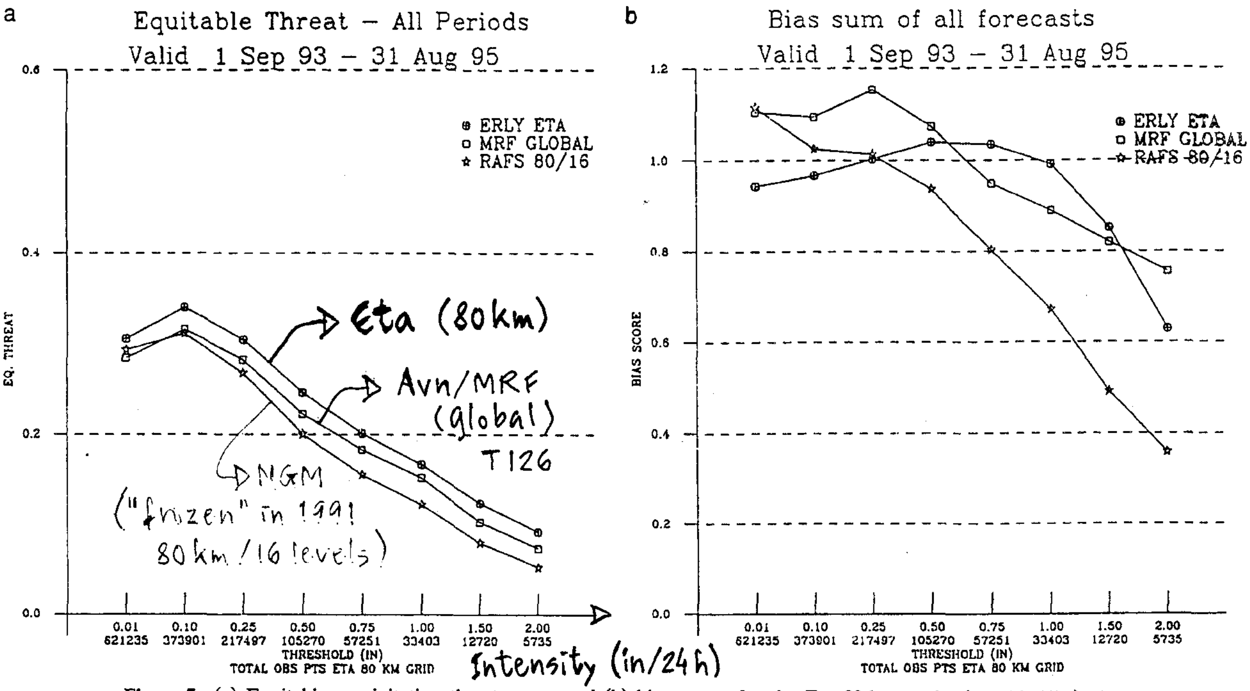


Figure 7 (a) Equitable precipitation threat scores and (b) bias scores for the Eta .80-km model (ERLY ETA), the Aviation/MRF model (MRF GLOBAL), and NGM (RAFS), for the 24-month period September 1993–August 1995. The upper row of numbers along the two abscissas shows the precipitation thresholds, in inches/24 hr and greater, which are verified. Scores are shown for a sample containing three verification periods, 0–24, 12–36, and 24– 48 hr. The sample contains 1779 verifications by each of the three models.

NGM: "fourth order" accuracy;
Eta: formally, never more than second

Bias ≡ F/O

Next 24 months:

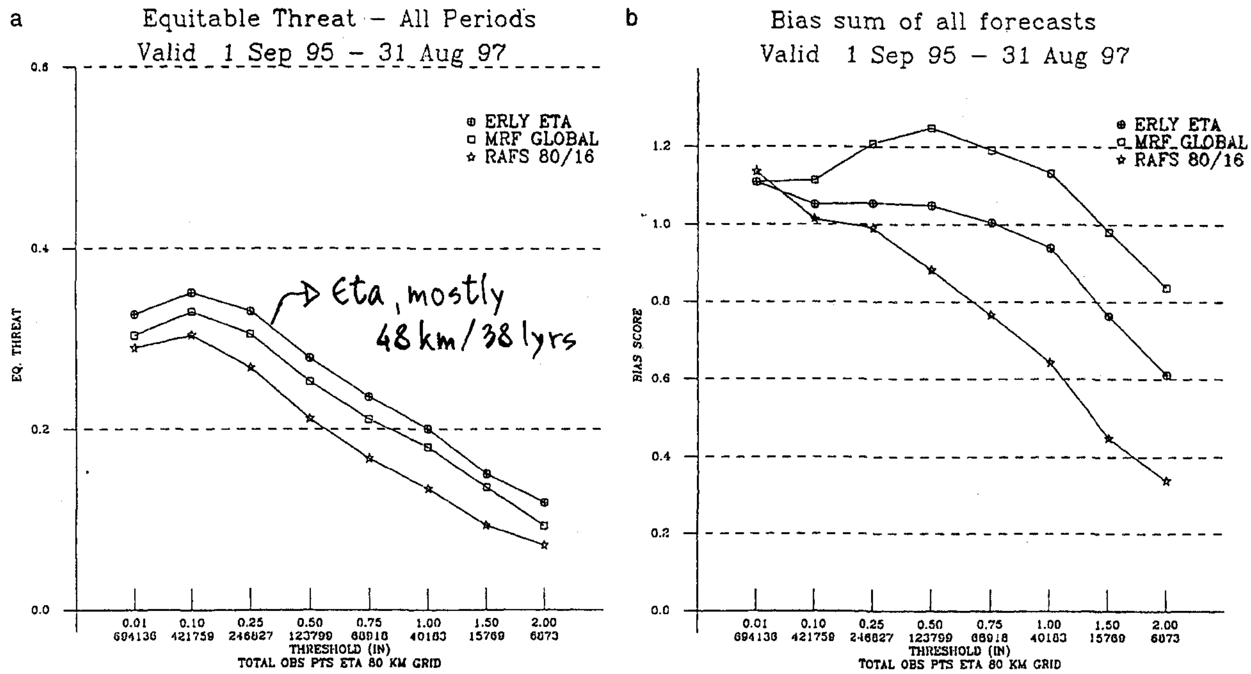


Figure 8 Same as Fig. 7, except for the 24-month period September 1995–August 1997. The sample contains 1970 verifications by each of the three models.

Eta overcoming handicaps of:

- Avn lat. bnd. conditions 12h "old"
- Less data (shorter cutoff time)

WAF Conf., 1993: 340-343

Modeling Plans at NMC for 1993-1997

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1. Introduction.

In this paper we briefly present the current modeling plans and expected operational model suites for the next five years. They are based on modeling and data assimilation research currently ongoing at NMC, in collaboration with other research centers and universities. Since there are a number of models that NMC runs or expects to run operationally, the plans are organized by model, including some experimental systems. For the sake of clarity, they are presented for two specific times (Fig.1):

a) March 1994 (assumed to be 3 months after the arrival of a Class 7 computer which is about 5 times as fast as the present Cray Y-MP8), and for

b) October 1996 (assumed to be 6 months

March 1994: Run only for Alaska's MOS

System: Frozen

Computer time per day: 1 min

October 1996: Not used

2.2 Nested Grid Model (NGM)

March 1994:

System: Frozen (since 1990) at its present 80 km/16 levels. 48 hour forecasts twice a day. Used only for MOS.

Computer time per day: 20 min

October 1996: Not used

Computer time per day: 90 min.

2.4 Early ETA Forecast model (ETA)

March 1994:

System: 80 km/38 levels. 48 hour forecasts twice a day. First guess from the EDAS, followed by an ETA OI.

Computer time per day: 6 min

October 1996:

Phased out assuming AVN precipitation guidance 24-48 hour is comparable or better.

2.5 Mesoscale ETA Forecast model:

March 1994:

System: 30 km/38-50 levels. Initial conditions from the EDAS. 36 hour forecasts twice a day, offset 3 hours (03,15Z), to get updated boundary conditions from the AVN model. Will explore running it 4 times a day. Alaska ETA forecasts twice a day to 33 hours.

Computer time per day: 50 min

October 1996:

System: 15-30 km/50 levels. Four times a day, offset 3 hours to get updated boundary conditions from the AVN (03, 09, 15Z, 21Z). Alaska forecasts TBD. A comparison with Regional Spectral Model (RSM) will determine possible replacement by RSM.

Computer time per day: 50 min

2.6 Regional Spectral Model (RSM)

Currently under development and testing

March 1994:

System: 40 km/28 levels run experimentally over C-grid domain. One experimental forecast (48 hours) per day. Routine comparisons with the ETA forecasts.

Computer time per day: 30-40 min

October 1996:

System: RSM is a possible replacement of Mesoscale ETA (TBD, depending on the previous comparisons). Non-hydrostatic version of RSM (10 km) under experimentation.

Computer time per day: 30-40 min

2.7 Hurricane model

March 1994:

System: Quasi-Lagrangian Model (QLM) operational at 40 km/18 levels. 3-day forecasts when needed. GFDL's Multiple-nested Movable Mesh (GMMM) model, inner grid 20 km/18 levels, run experimentally. The AVN model, at about T180/28 levels, and with the Synthetic Data System, should also provide very good guidance.

Computer time per day: About 3-5 min per run for each QLM 3-day forecast, about 30 min for the GMMM forecast. Sometimes needed for several storms, twice a day.

October 1996:

System: GMMM system at 10-20 km for both hurricane track and intensity forecasts. The T200+/50 levels AVN forecasts should also be very useful for these purposes.

Computer time per day: 15 min/forecast (GMMM)

2.8 Rapid Update Cycle (RUC, aka MAPS, developed by NOAA/FSL)

March 1994:

System: 3 hour RUC cycle with 6 hour forecasts 8 times a day. Resolution: 60 km/25 levels. Also, a lower resolution RUC over Alaska.

Computer time per day: 40 min

1996–1997: RSM: 1,023 verifications "current" bnd. conditions

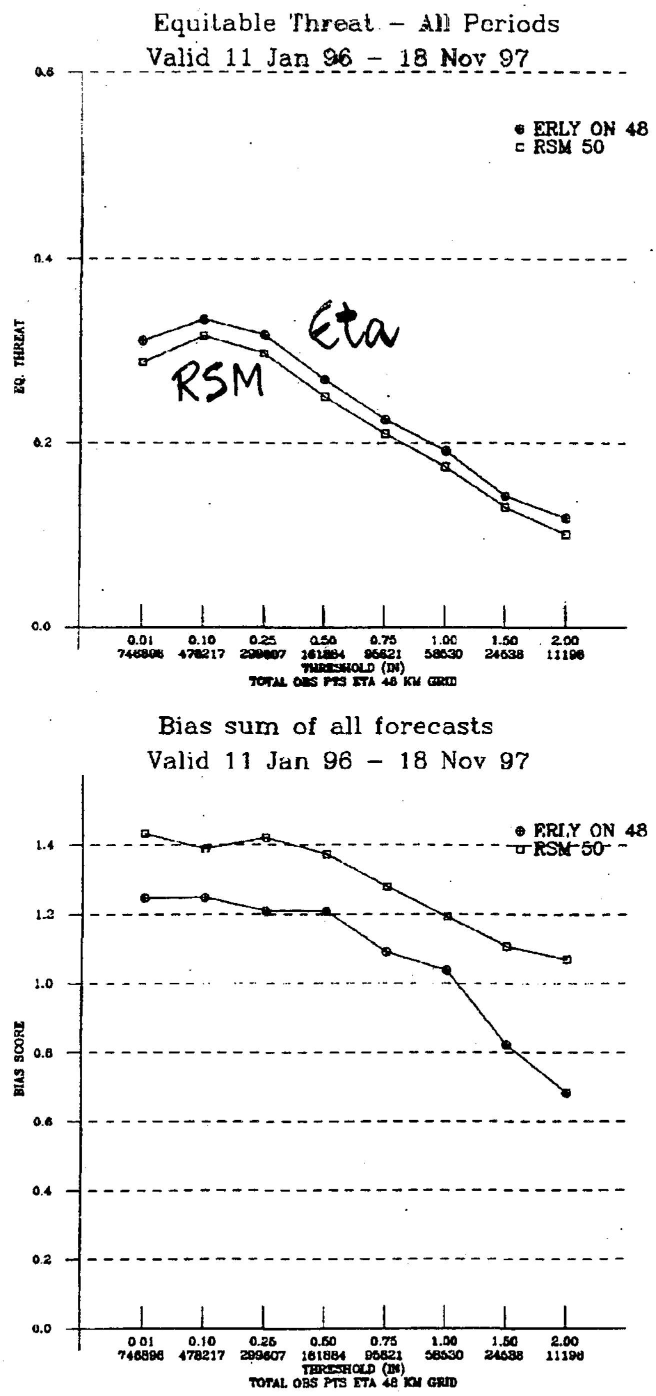

Figure 2: The Eta ("ERLY") vs RSM precipitation threat (top panel) and bias scores (bottom panel), for 1996–1997. The upper row of numbers along the two abscissas shows the precipitation thresholds, in inches/24 h and greater, which are verified. Scores are shown for a sample containing three verification periods, 0–24, 12–36, and 24–48 h, and are verified on model grid boxes, 48 and 50 km, respectively.

were compared at 80-km resolution, December 1994-September 1995, in twice a day 10-month parallel, their precipitation scores looked very much a tie. But at 50 km, in a two-year parallel 1996–1997, including 1,023 24-h verifications, the Eta was significantly better, winning all eight precipitation categories (Fig. 2), and has not any more been considered a contender to replace the Eta.

Why the comparison at 50 km has turned out so much less favorable for the RSM than that at 80 km I am not aware has even a tentative explanation. A higher bias, relative to the Eta, could be considered to have hurt the RSM scores at lower categories, but should have only helped them at the two highest categories. Certainly the proponents of the RSM have not lost their belief in the approach used, and if anything subsequently have only multiplied in numbers.

The diversity of the modeling approaches pursued clearly reflects the fact of the world of model development being one in which mathematics goes only so far. Experiments, with simple problems and with real data, and perhaps not too scientific components such as insight, intuition, common sense, add just as much if not more. And on an institutional level, power of persuasion, and management clout, in many cases may play not a

from: 50th Anniv. of NWP Comm. Symp., 2001

An unintended experiment of a few years ago, in which two different resolution versions of the Eta were run for more than two years:

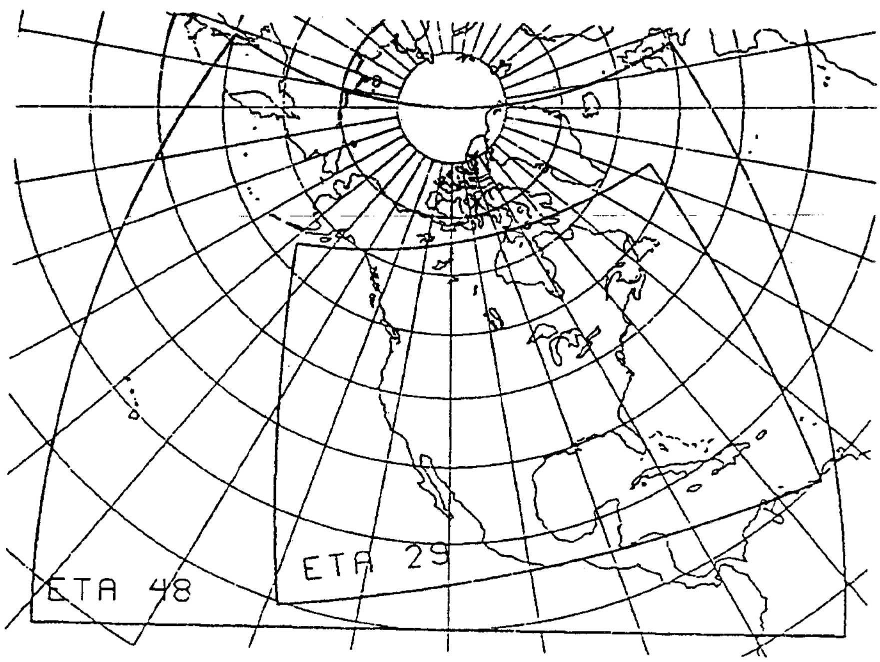

Figure 10 The domains of the Eta 48-km and of the Eta 29-km model.

2

48 km: 12 h "old" Avn bnd. cnd.;

29 km: Current Avn bnd. cnd., more data (run later)

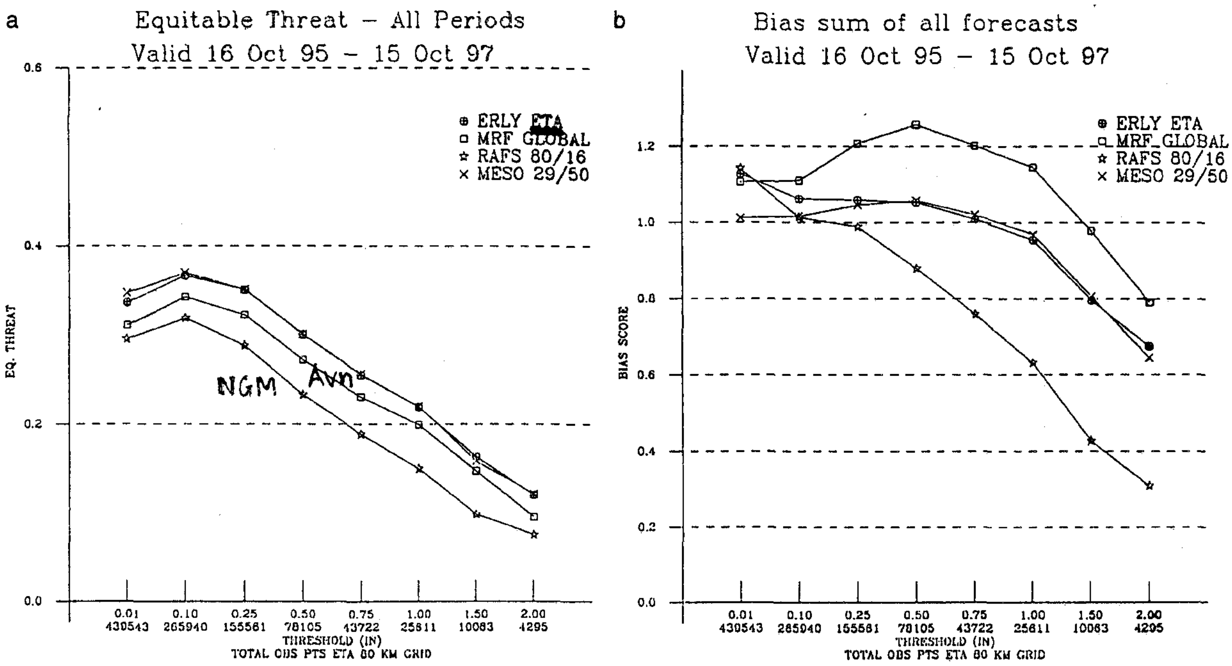

Figure 11 (a) Equitable precipitation threat scores for four of NCEP's operational models, those of preceding figures and for the 29-km Eta (MESO), for various precipitation thresholds, and for the period 16 October 1995–15 October 1997. (b) Bias scores for the same models and period. "All Periods" refers to two verification periods, 00–24 hr and 12–36 hr; note that the 29-km model was run only 33 hr ahead. It was initialized 3 hr later than the remaining models. The sample contains 1245 forecasts by each of the four models; 618 of them verifying at 24 hr and 627 verifying at 36 hr.

2 years / 1245 forecasts

What is going on ?

The Eta is able to improve, considerably (12 h !) on Avn bnd. condition,

but to do that it needs <u>space</u>

(and not so much higher resolution / higher than the 48 km / 38 lyr !)

Of the Eta advantages over the Avn, resolution (> 48km !) not the most significant one !

Several recent efforts, of the time when the Eta forecast period was increased to 60 and then to 84 h:

- Inspection of the precipitation skill at later compared to that at earlier forecast times;
- RMS fits to raobs as a function of time;
- Accuracy in forecasting the position of the centers of major storms at 60 h:

Aimed at identifying a possible loss in accuracy of the Eta compared to the Avn of the same initial time due to the inflow into the Eta of the less accurate boundary information.

J1.14

LIMITED AREA PREDICTABILITY: WHAT SKILL ADDITIONAL TO THAT OF THE GLOBAL MODEL CAN BE ACHIEVED, AND FOR HOW LONG?

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1. INTRODUCTION

Extensions of the Eta Model forecasts at NCEP to 60 and then 84 h have much increased possibilities for a new look at the limited area predictability: ***What skill additional to that of the "driver" global model can be achieved by a limited-area model* (LAM), *and for how long*?** The traditional view is that "the contamination at the lateral boundaries ... limits the operational usefulness of the LAM *beyond some forecast time range*" (Laprise et al. 2000). If so, what is that time range? Note that this would also represent the limit of the usefulness of the LAM ensemble approach, given that usefulness of the control is a prerequisite for the usefulness of the ensemble as a whole.

This statement of the problem differs from that of the initial stages of the LAM predictability research (e.g., Anthes et al. 1985, 1989, Errico and Baumhefner 1987). Following in the footsteps of global predictability studies, attention was then focused on the growth of mean square error, in a LAM, nested, almost always, with *analyses* at the controversial regional climate simulation area; thus, following for 2) and 3) below again Laprise et al. (2000), we list

1) High-resolution information in the initial condition; and the ability to maintain smaller scales, as a result of higher resolution, irrespective of any forcing;

2) LAM forecast will develop small-scale feature: that are dynamically consistent with the large scales provided at its lateral boundaries;

3) LAM forecast will develop small-scale feature: consistent with the small-scale forcings at its lower boundary.

Recall that 2) and 3) in the regional climate context are referred to as "downscaling". To above, we add

4) LAM could, in some aspects and independent of resolution, be more successfully designed than it: driver global model. One intrinsic advantage of LAM is that they have no pole problem. Thus, optimal aeometrv can be used. In addition and related to th

What kinds of errors are we talking about/
The "contamination" at the LB:

- Lower resolution of the "driver" global model ;
- The mathematical problem (e.g. "well-posedness", ...)
- In the setup as that of the Eta and the Avn: LBCs are of the previous Avn run (At "on" times, 00 and 12z, ~8h loss in accuracy)

Eta 24-48 h;
NGM 00-24 h:

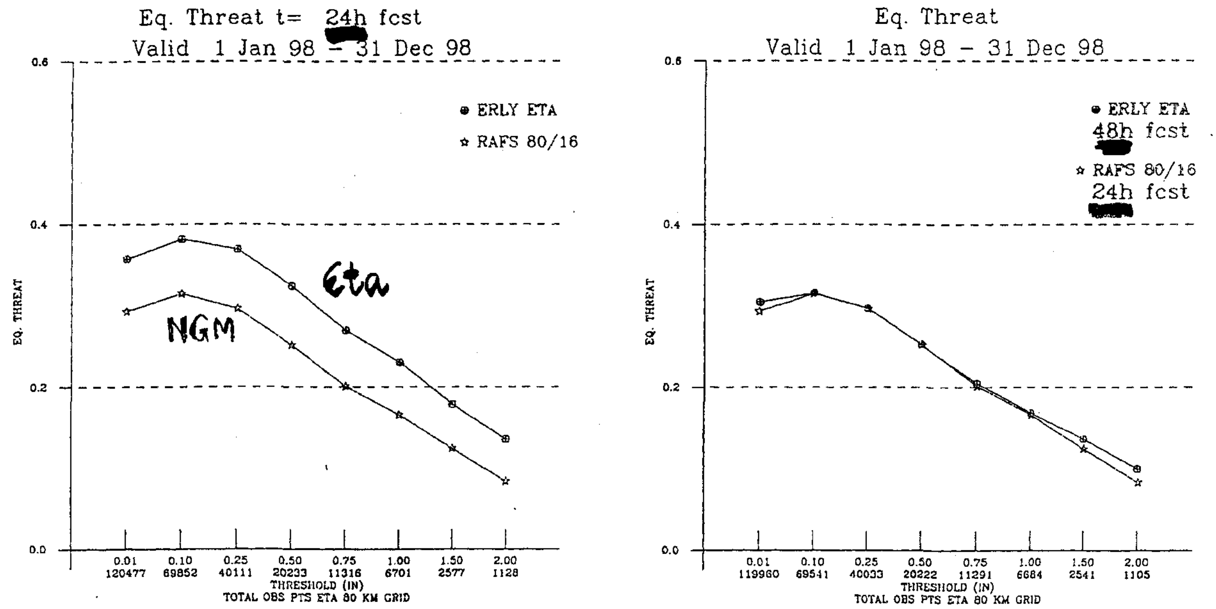

Fig. yy, Equitable precipitation threat scores of the Eta and of the NGM/RAFS for 00-24 h forecasts, left panel; and of the 24-48 h Eta shown against the 00-24 h NGM/RAFS scores, right panel. See the caption of Fig. xx for the definition of the equitable threat score.

8 h loss in accuracy: ~1/3 of the Eta advantage in the left panel

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Limited Area Predictability: Can "Upscaling" also Take Place?

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Introduction. A standard situation in all major forecasting centers is the existence of a global and of at least one regional, or "limited-area" forecasting system, with the latter using the lateral boundary data forecast by the former. Yet, the strategies as to what is apparently expected of the limited-area models (LAMs) can be radically different. For example, at the U.K. Met Office (Fig. 1, Staniforth 2001) and at various ALADIN partners (Fig. 1, Members of the ALADIN international team 1997) LAM domains of the order of 2000 x 2000 km and even smaller are used. In contrast, the operational Eta at NCEP is run on a domain greater than 11500 x 8500 km. Is this done to have "the contamination at the lateral boundaries" (Laprise et al. 2000) as far away from the region of interest as possible, or does the Eta strategy imply an attempt to achieve not only downscaling, but an improvement in the large scales as well?

An additional factor in the Eta operational setup is that its lateral boundary condition is obtained from the previous run of the global (Avn) model, which is at the "on" times (00 and 12z) estimated to represent about an 8 h loss in accuracy. It takes a day or two at the most for some of the forecast jet-stream entering the western Eta boundary to reach the region of most interest, the contiguous United States. Shouldn't then at later forecast times the skill of the Eta fall behind that of the Avn of the same initial time? Recent extensions of the Eta forecasts at NCEP to 60 h and then, in April 2001, to 84 h, have much improved the possibilities for looking into these issues. We here present and summarize the results of three efforts in that direction: examination of precipitation threat scores, of the rms fits to raobs, and of the accuracy in placing the centers of major storms at later forecast times.

Precipitation scores. It was pointed out earlier that out to 48 h, and then out to 60 h (Fig. 5, Mesinger 2001) no signs of the deterioration of the Eta precipitation threat scores compared to those of the Avn were evident. At the time of this writing nine full months are available of the Eta scores out to 84 h. In Fig. 1 these nine months, May 2001-January 2002, of the Eta and the Avn threat scores are shown, for the sample of 00-24, 12-36, and 24-48 h, left panel, and that of the 36-60, 48-72, and 60-84 h forecasts, all verifying at 12z, right panel. There are more than 700 verifications in each of the panels. The advantage of the Eta over the Avn in the forecast periods going beyond the two days is seen to have remained overall just about the same as it was in the up to two day periods.

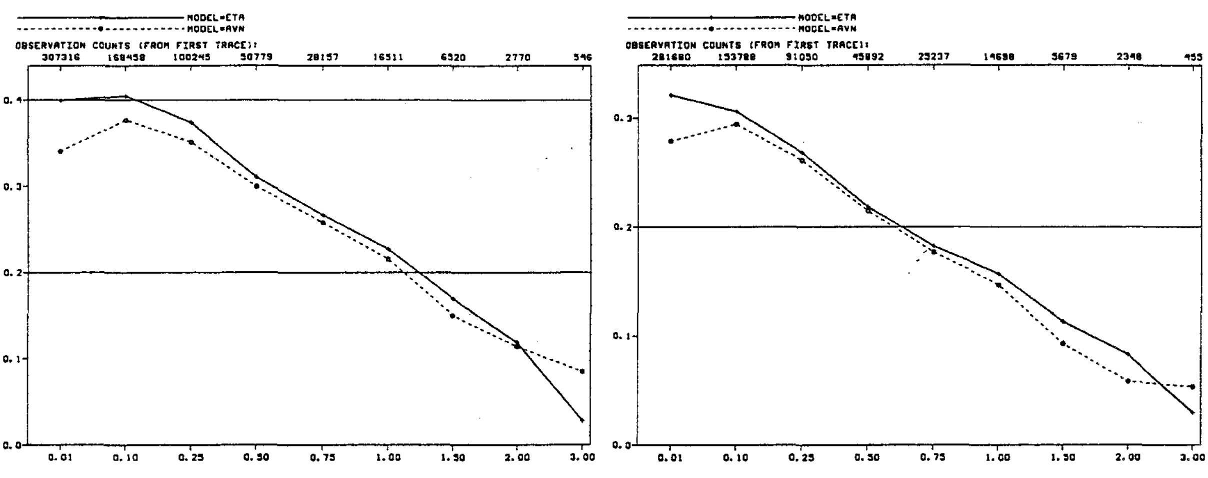

Fig. 1. Equitable precipitation threat scores of the Eta (solid) and the Avn (dashed lines), 00-24, 12-36, and 24-48 h forecasts, left panel, and 36-60, 48-72, and 60-84 h forecasts, right panel, May 2001-January 2002.

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RMS fits to raobs. EMC Forecast Verification System offers numerous possibilities for compilation of various statistics of NCEP model forecasts' fits to data. RMS fits to raobs for the last 30 days for four forecast variables, including 250 mb winds, 500 mb heights, and 850 mb temperatures, are posted at http://sgi62.wwb.noaa.gov:8080/VSDB/. In compiling those, each model results are interpolated to an output grid; the Avn is interpolated to an 80-km grid ("211") while the Eta is interpolated to a 40-km grid ("212"). This presumably favors the Avn, but should not affect much the "error growth" rate.

Plots of the rms fits to raobs of the three variables mentioned, for spring 2001 out to 60 h, and for the summer 2001 out to 84 h, have been shown in Mesinger et al. (2002). No general tendency of the Eta "errors" to increase at later forecast times faster than those of the Avn was seen. In Fig. 2 we show rms plots for 250 mb winds, left panel, and 500 mb heights, right panel, for 00 and 12z verifications during December 2001-January 2002, the two full months of winter 2001-2002 available at the time of this writing. Even though in winter the inflow of the lateral boundary information is the fastest, the Eta "error growth" after 60 h happens to be in fact on both plots somewhat slower than that of the Avn's.

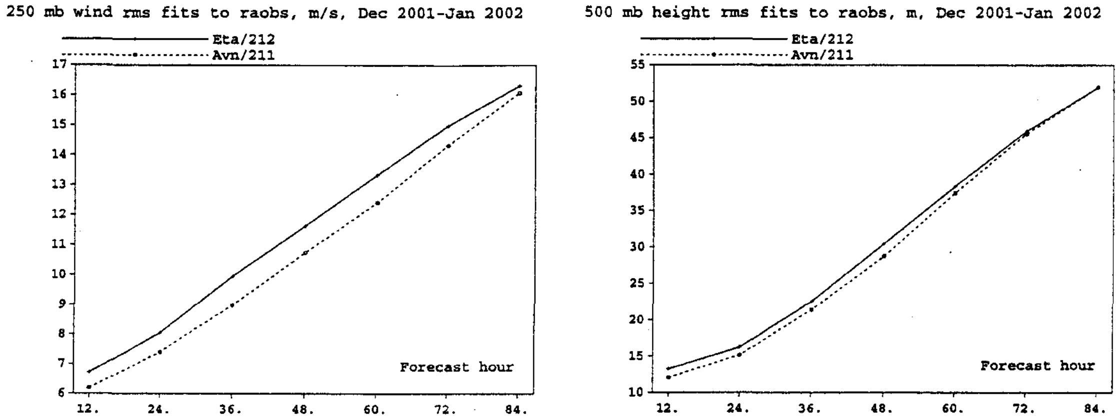

Fig 2. RMS fits to raobs, 250 mb winds (m/s, left) and 500 mb heights (m, right panel), for the Eta (solid) and the Avn (dashed lines) models, as a function of forecast hour, December 2001-January 2002.

Placing the centers of major storms. In (Mesinger et al. 2002) rules were set up for identification of major surface lows, and the accuracy of the Eta and the Avn in forecasting the positions of these centers at 60 h forecast time during December 2000-February 2001 was inspected. It was found that the Eta was considerably more accurate, winning about 2/3 of the 31 cases identified, and having a 100 km smaller median error. But when one case was rerun by the Eta switched to use the sigma coordinate (Fig. 2, Mesinger et al. 2002) the position error, at 48 h, increased from 215 to 315 km.

Concluding comments. Results shown and summarized indicate that the Eta is able to compensate for the inflow of the less accurate "old" Avn boundary condition, so that out to 3.5 day forecast time it remains competitive with the Avn of the same initial time. One experiment referred to suggests that the eta coordinate is a significant contributor to this ability.

The large-scale character of the various statistics presented and cited indicates that the Eta is indeed generally improving on the largest scales it can accommodate in its relatively large domain, of about 1/5 of the globe, over the Avn information it is receiving at its lateral boundaries.

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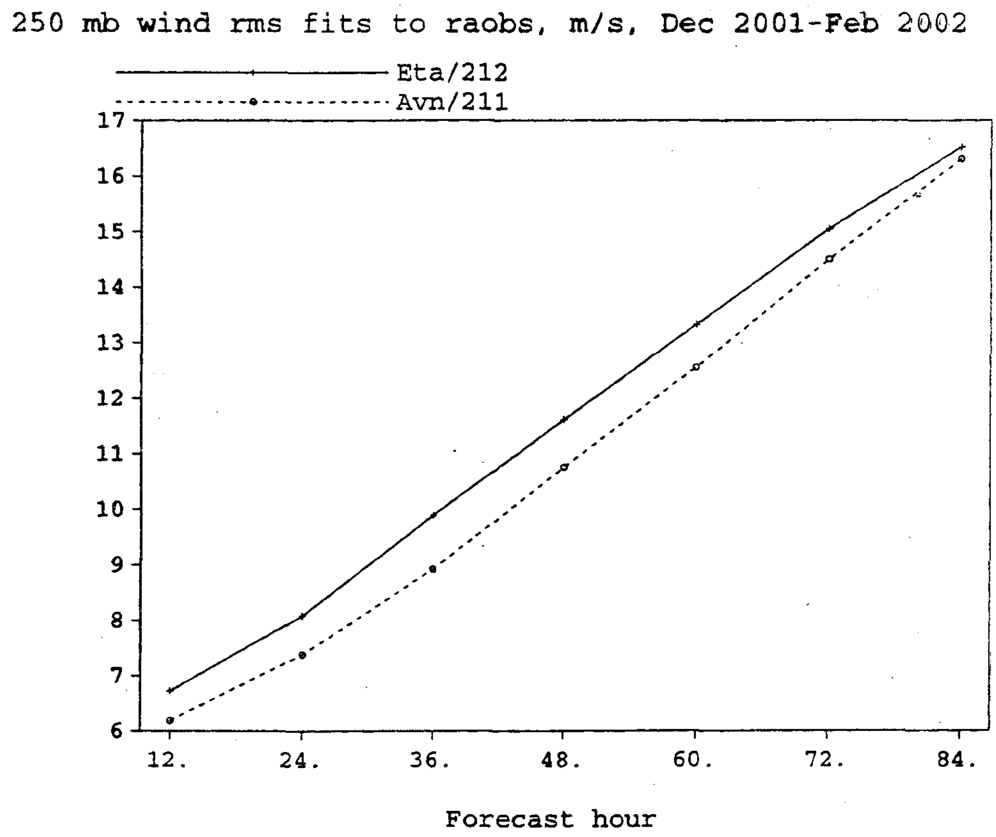
RMS fits issues:

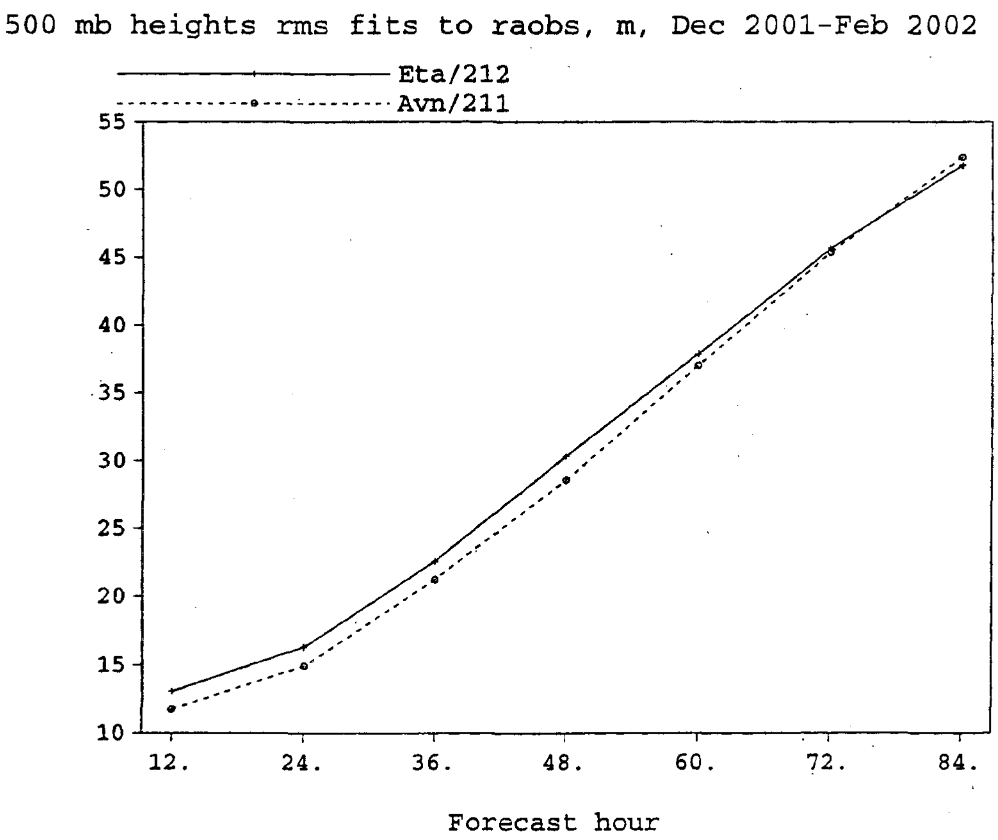
- In NCEP's FVS each model results interpolated to an output grid, the Avn being to an 80-km grid (#211) and the Eta to a 40-km grid (#212). Should favor the Avn because of a greater smoothing of sharp features, since most times and in particular later in the forecast they are not likely to be predicted at precisely the right locations;

- Even if the two models were to be output to the same grid the Eta as the higher resolution model probably at a disadvantage - its features should be expected to be sharper than those of the Avn;

Hopefully: the impact of these differences should not change, or at least not change significantly, with time;

-> Look at growth rates


250 mb wind rms fits to raobs, m/s, Dec 2001-Feb 2002
Eta/212
Avn/211
17
16
15
14
13
12
11
10
9
8
7
6
12.
24.
36.
48.
60.
72.
84.
Forecast hour


500 mb heights rms fits to raobs, m, Dec 2001-Feb 2002
Eta/212
Avn/211
55
50
45
40
35
30
25
20
15
10
12.
24.
36.
48.
60.
72.
84.
Forecast hour

Synoptic features. Intention:

Identify low centers which one would expect to be clearly forecast at 60 h, that is, unambiguously identifiable on the EMC's so-called "four-pane" forecast plots; and would be associated with major systems crossing or interacting with the Rockies over the contiguous United States and nearby Canada. Do not include centers over the "intermountain West", to minimize the impact of the differences in the pressure reduction to sea level; and centers over or formed over the ocean, to minimize the impact of different SSTs used by the Eta and the Avn.

Find out if at this extended forecast time, when one would expect the lateral boundary condition to have the most impact, the Eta's skill in forecasting major synoptic features is competetive with the Avn's.

Rules

Rules

Inspecting the series of consecutive 00 and 12z HPC surface analyses for December 2000 - February 2001, identify cases containing low centers that satisfy the following requirements:

In the first verification, the center

(1) has to be the deepest inside at least two closed isobars (analyzed at 4 mb intervals);

(2) must have its central sea level pressure analyzed at < 1000 mb;

(3) has to be located east of the Continental Divide, over land or Great Lakes, and between 30° and 55°N;

(4) must not have entered this verification area from the Atlantic; and

(5) must be stamped on four-pane 60-h forecast plots of both the Eta and the Avn model.

At subsequent analyses, the requirement (2) is relaxed to < 1010 mb, but only if the center is the only center analyzed inside the two closed isobars.

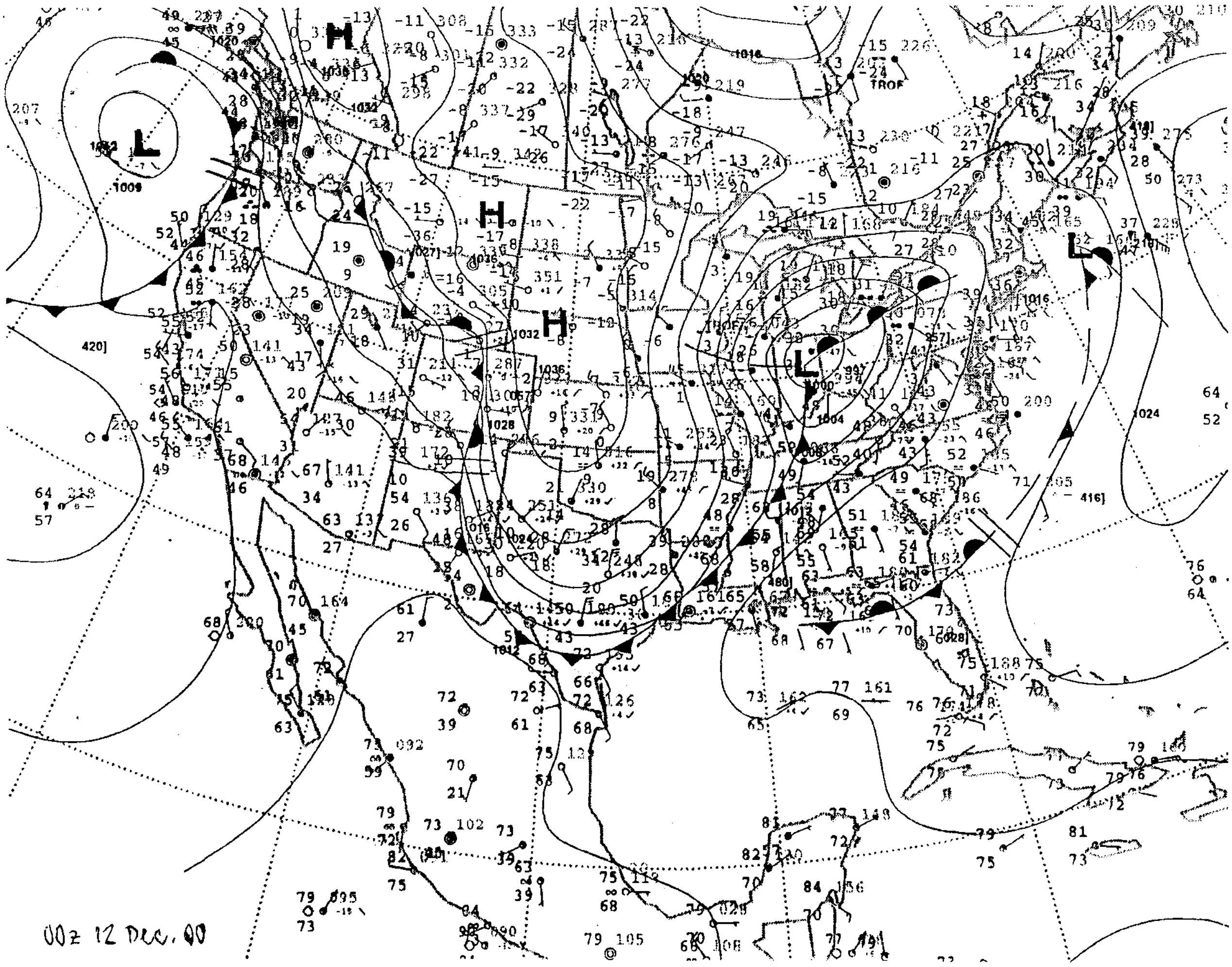
Rule (5), by the way, did not result in elimination of any cases. If a double center were to be stamped, the average position of the two "L"s was defined to represent the forecast position. This occurred in one Eta forecast.

There were twelve events that satisfied these rules, with a total of 31 verifications.

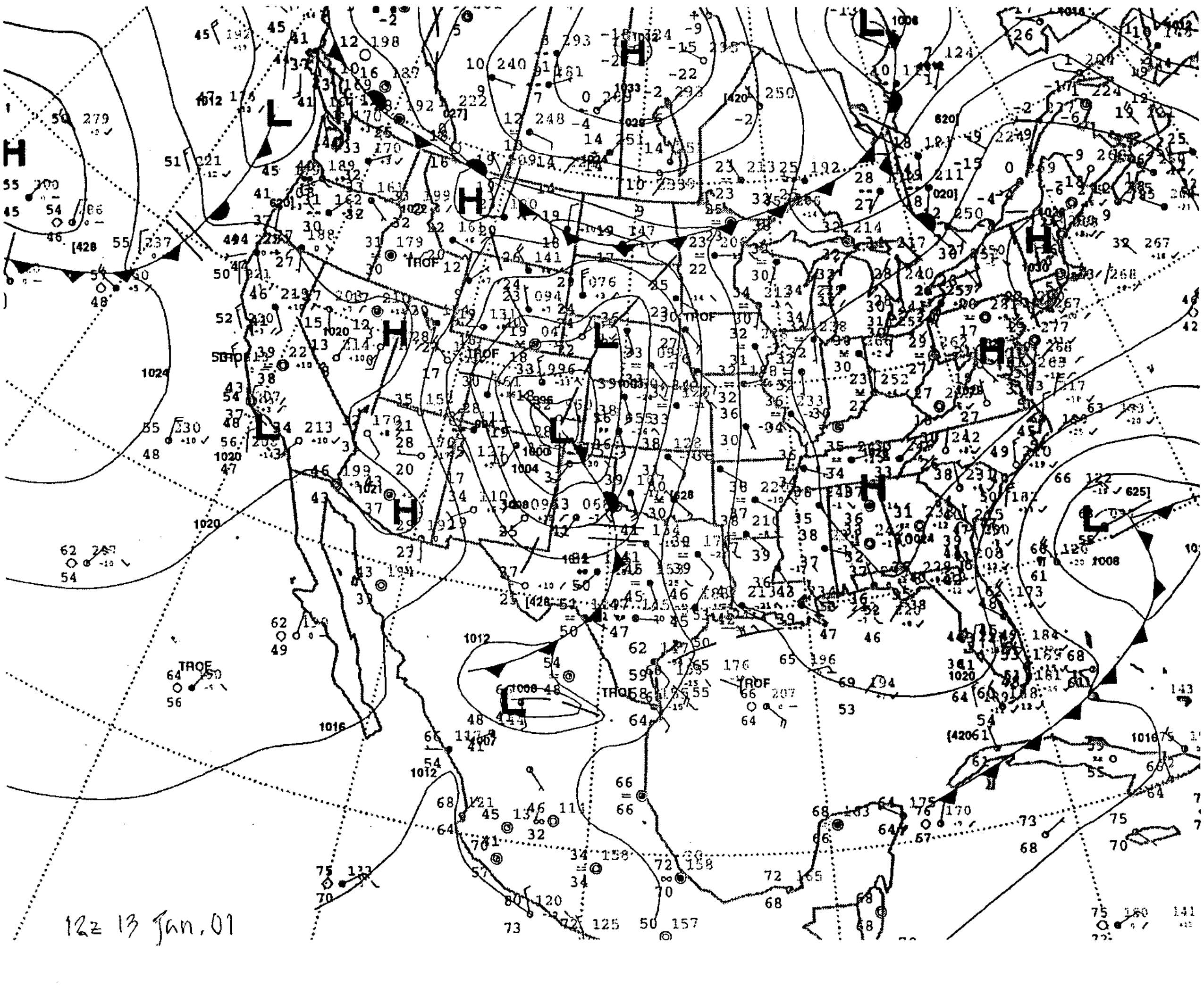
In several events the lows formed or deepened to < 1000 mb only over the Mid-West or, in one case, over the Great Lakes area. A number of "Alberta Clippers"; they tended to be short-lived, not satisfying the intensity criteria for more than one or two verifications. In one Alberta Clipper case, intensity criteria were satisfied for three verifications, but the 3rd time the Eta forecast was missing.

In two events, the lows of < 1000 mb formed over the southeastern Colorado, and moved east and then northeast (six verifications each time). Rockies Lee cyclogeneses!

Examples of lows which qualified:



00z 12 Dec. 00



12z 13 Jan. 01

Forecast position errors, at 60 h, of "major lows" east of the Rockies and over land, December 2000-February 2001

Valid at	HPC analyzed depth	Avn error	Eta error
00z 12 Dec.	997 mb	125 km	275 km
12z 12 Dec.	988 mb	325 km	150 km
00z 17 Dec.	997 mb	475 km	125 km
12z 17 Dec.	990 mb	175 km	425 km
00z 18 Dec.	984 mb	450 km	575 km
12z 18 Dec.	963 mb	75 km	100 km
00z 20 Dec.	997 mb	250 km	350 km
12z 20 Dec.	1002 mb	175 km	175 km
00z 5 Jan.	988 mb	400 km	350 km
12z 5 Jan.	985 mb	125 km	350 km
12z 6 Jan.	993 mb	1,175 km	500 km
12z 10 Jan.	999 mb	325 km	150 km
00z 11 Jan.	1000 mb	425 km	75 km
12z 13 Jan.	994 mb	475 km	150 km
00z 14 Jan.	999 mb	50 km	350 km
12z 14 Jan.	1006 mb	175 km	150 km
00z 15 Jan.	1009 mb	350 km	300 km
12z 15 Jan.	1008 mb	225 km	175 km
00z 16 Jan.	1006 mb	225 km	275 km
00z 30 Jan.	989 mb	175 km	350 km
12z 30 Jan.	988 mb	300 km	275 km
00z 9 Feb.	996 mb	350 km	325 km
00z 10 Feb.	993 mb	150 km	175 km
12z 10 Feb.	972 mb	225 km	200 km
12z 21 Feb.	997 mb	575 km	325 km
00z 24 Feb.	992 mb	325 km	100 km
12z 24 Feb.	990 mb	300 km	100 km
00z 25 Feb.	991 mb	275 km	150 km
12z 25 Feb.	983 mb	325 km	300 km
00z 26 Feb.	985 mb	475 km	75 km
12z 26 Feb.	998 mb	575 km	175 km
Average error		324 km	244 km
Median error		300 km	200 km

Median error: Avn 300 eta 200 km

Average error: Avn 324 eta 244 km

More summary numbers:

The Eta more accurate 20 times, the Avn 10 times;

Suppose verifications when the error difference is small (25 km) were not counted. What is the result then?

The Eta more accurate 15 times, the Avn 8 times.

Number of "large" and "small" errors:

"Large errors" (400 km and more)

Avn: 9, Eta: 3

"Small errors" (100 km and less)

Avn: 2, Eta: 5

In most of these cases, the position of the surface low would seem to reflect differences in relatively large-scale mid- or upper-tropospheric jet-stream features.

Suggestion:

A LAM (Eta) is able to improve upon *large-scale* features at time ranges beyond those when it should have been "contaminated" by boundary errors of the global model.

Why? A good question.

ECMWF:

		Analysis			Forecast			
Time	Date	Depth(hPa)	Latitude	Longitude	Depth(hPa)	Latitude	Longitude	Position error (km)
00UTC	12-Dec	997	40.5	-85	1001	37.8	-90.6	568
12UTC	12-Dec	988	44.8	-74.8	991	44	-78	269
00UTC	17-Dec	998	38.3	-84.1	997	42.8	-82	531
12UTC	17-Dec	991	44.4	-80.2	988	45.8	-80.8	163
00UTC	18-Dec	984	47.6	-74.9	978	50.6	-74.6	334
12UTC	18-Dec	961	49.1	-70.4	970	51.1	-70.3	222
00UTC	20-Dec	997	50	-103.1	1000	50.4	-104.4	103
12UTC	20-Dec	1004	36.4	-102.2	1009	38.2	-104.3	273
00UTC	5-Jan	987	55	-92.3	988	54.2	-88.3	273
12UTC	5-Jan	986	47.9	-83.5	991	48.8	-83	107
12UTC	6-Jan	994	48.6	-94.5	994	54	-101.2	759
12UTC	10-Jan	998	54.4	-89	1009	52.7	-92	274
00UTC	11-Jan	999	52.1	-79.3	1009	49.8	-84.1	422
12UTC	13-Jan	1000	38.4	-103.7	1000	38.2	-102.9	73
00UTC	14-Jan	1000	37.8	-99	997	38.6	-99.2	91
12UTC	14-Jan	1008	40.3	-94.2	1006	39.5	-94.6	95
00UTC	15-Jan	1011	43.3	-90.8	1012	40.7	-91.7	298
12UTC	15-Jan	1009	45.3	-87.4	1012	42.7	-86.9	292
00UTC	16-Jan	1007	45.8	-82	1009	44.7	-82.4	126
00UTC	30-Jan	990	42.2	-94	992	41.2	-92.8	149
12UTC	30-Jan	990	41.9	-96.3	993	43.7	-91.3	454
00UTC	9-Feb	999	37.5	-106.2	996	38.8	-106.5	147
00UTC	10-Feb	991	47.3	-77	996	46.1	-81.6	375
12UTC	10-Feb	974	49.4	-71.1	983	48.9	-71.6	66
12UTC	21-Feb	998	49.5	-66.5	1002	50.1	-65.4	103
00UTC	24-Feb	992	39.8	-104.8	988	40.4	-104.5	71
12UTC	24-Feb	995	37.4	-103.4	994	39.8	-99.8	411
00UTC	25-Feb	992	40.4	-96.6	987	40.2	-100.1	298
12UTC	25-Feb	983	46	-87	985	45.8	-89.9	225
00UTC	26-Feb	985	49.4	-79.4	991	48.6	-79.4	89
12UTC	26-Feb	995	52.9	-74.1	997	50.7	-73	256
							Mean	255
							Median	256

ECMWF, same lows:

Ackn.: Adrian Simmons

Mean: 255, Med. 256 km

This in spite of ECMWF adv. over the Eta:

- No "lateral bnd. errors" (including no δh accuracy lost);
- Verification to its own analysis (including same slp reduction!)

Eta vs Avn at later forecast times, summary:

No loss in accuracy evident! Component(s) must exist in the Eta that are advantageous to those of the Avn, so as to compensate for this inflow of the less accurate boundary data.

Not likely that parameterizations of a medium-range global model of a major NWP center are inferior to those of its short range LAM. Along with, to some extent, resolution, the dynamical core of the Eta thus a better candidate.

Resolution ?

The Eta resolution changes:

80 km/38 lyr: Implemented 12z 8 June 1993

2 yr 4 months

48 km/38 lyr: 12z 12 October 1995

2 yr 4 months

32 km/45 lyr: 12z 9 February 1998

2 yr 7 months

22 km/50 lyr: 12z 26 September 2000

1 yr 2 months

12 km/60 lyr: 12z 27 November 2001

The 12 km/ 60 lyr Eta:

$\boxed{\Delta t = 30\ s}$ IM=606, JM=1067, LM=60

IMJM=646,602 IMJMLM=38,796,120

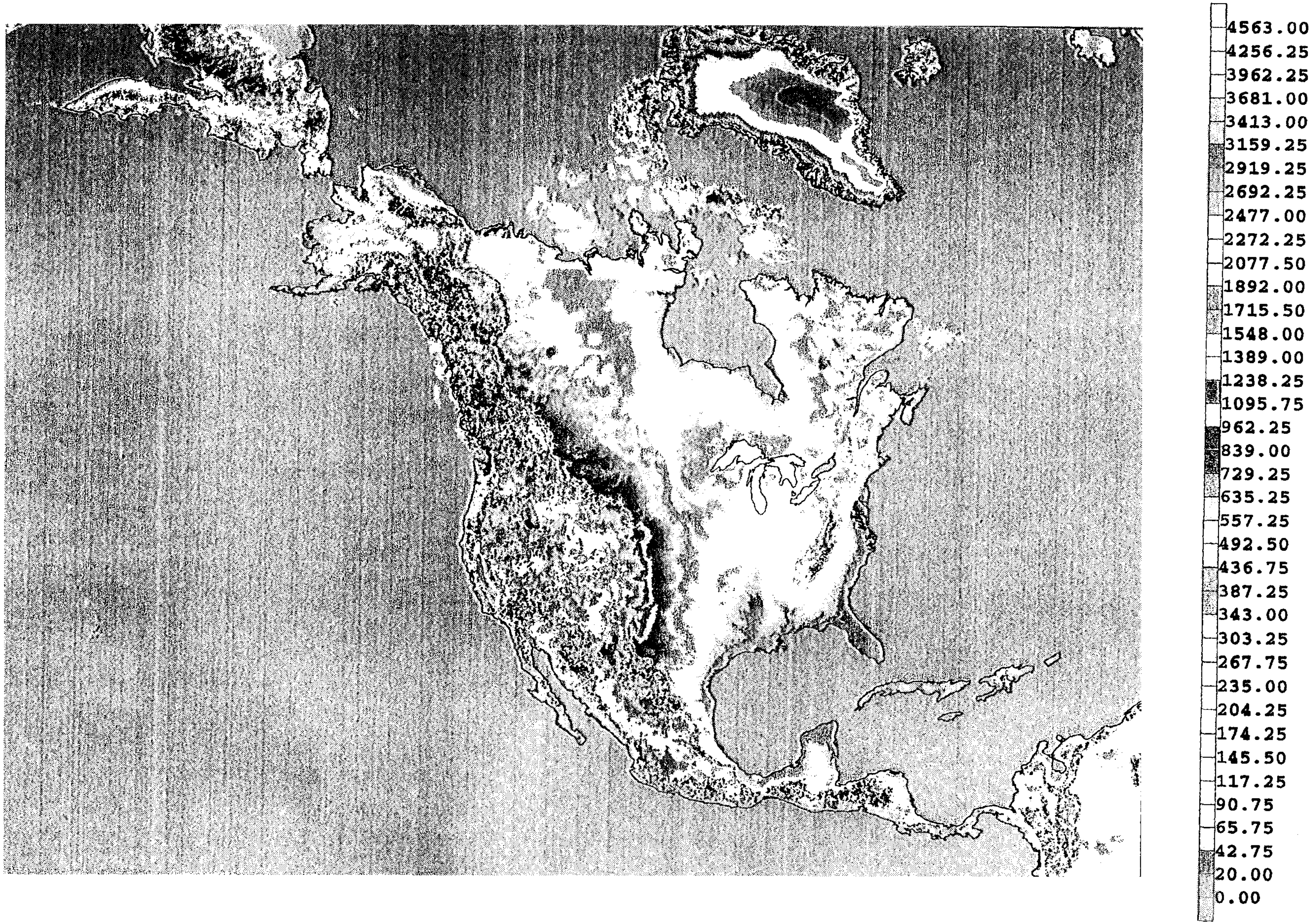
8 3D prognostic variables -> 310×10^6 3D time dep. variables

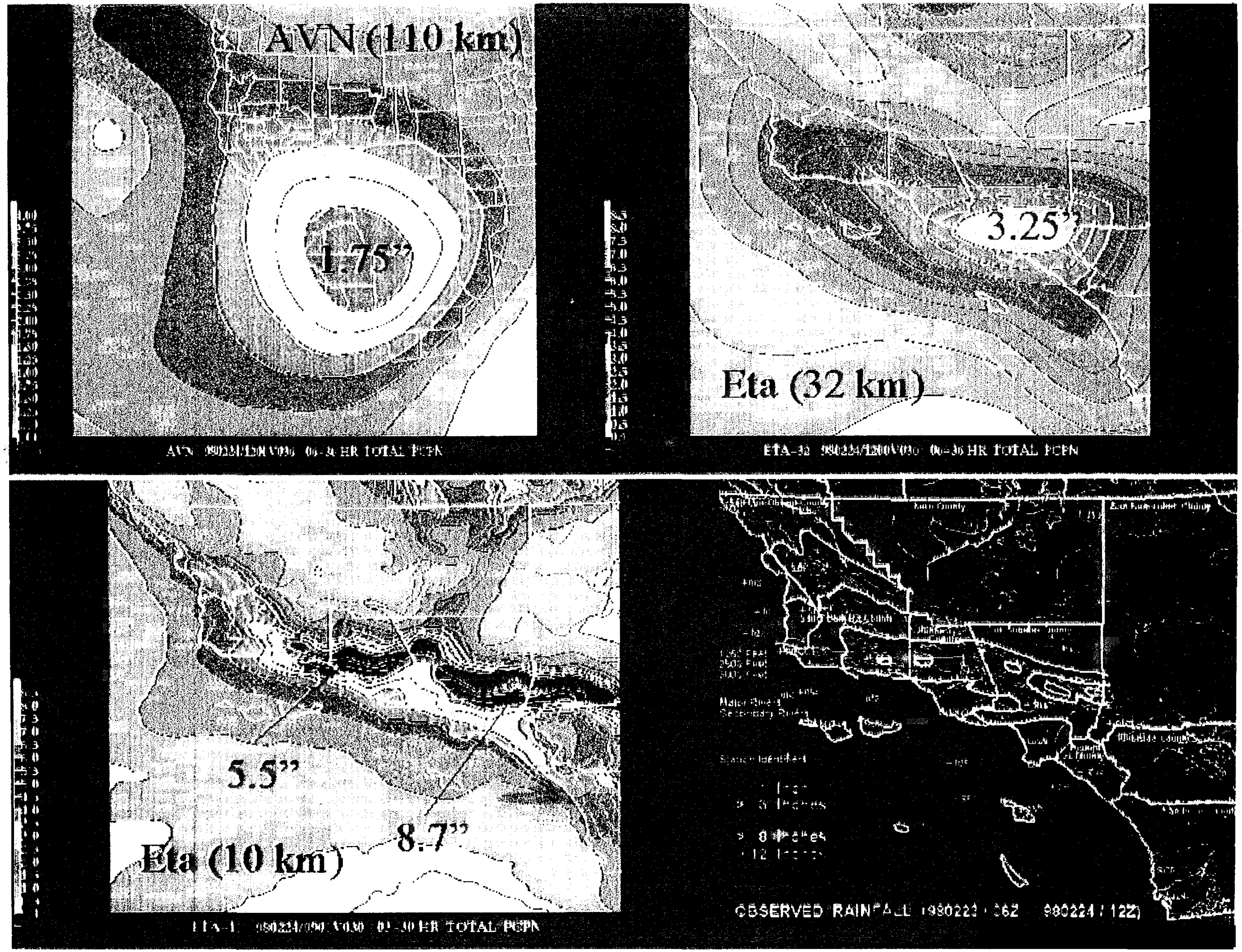
3.1×10^8

3.5 day forecast is done in ~ 60 minutes real time

(Tom Black, Jim Tuccillo)

Eta 12 km/60 layer topography




AVN (110 km)
1.75"
Eta (32 km)
3.25"
ETA-32 980224/1200V036 00-36 HR TOTAL PCPN
5.5"
8.7"
Eta (10 km)
OBSERVED RAINFALL (980223 / 06Z - 980224 / 12Z)

An Overview of Numerical Methods for the Next Generation U.K. NWP and Climate Model

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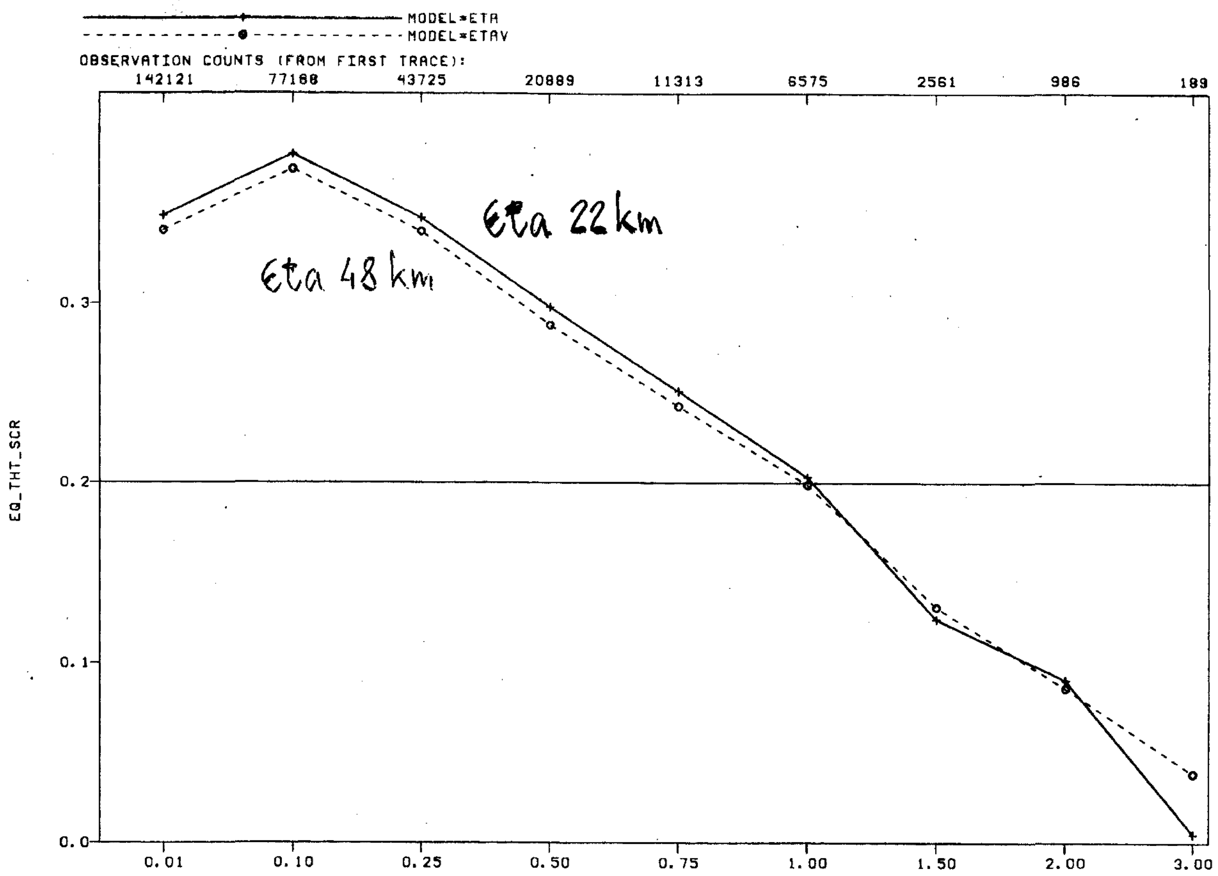
value needed for stability. The use of the fourth order Heun scheme is essential to obtain results of this quality in the test problem. However, the sensitivity of the complete model to the choice between second and fourth order schemes at forecast resolutions (grid lengths less than 100 km) has been slight.

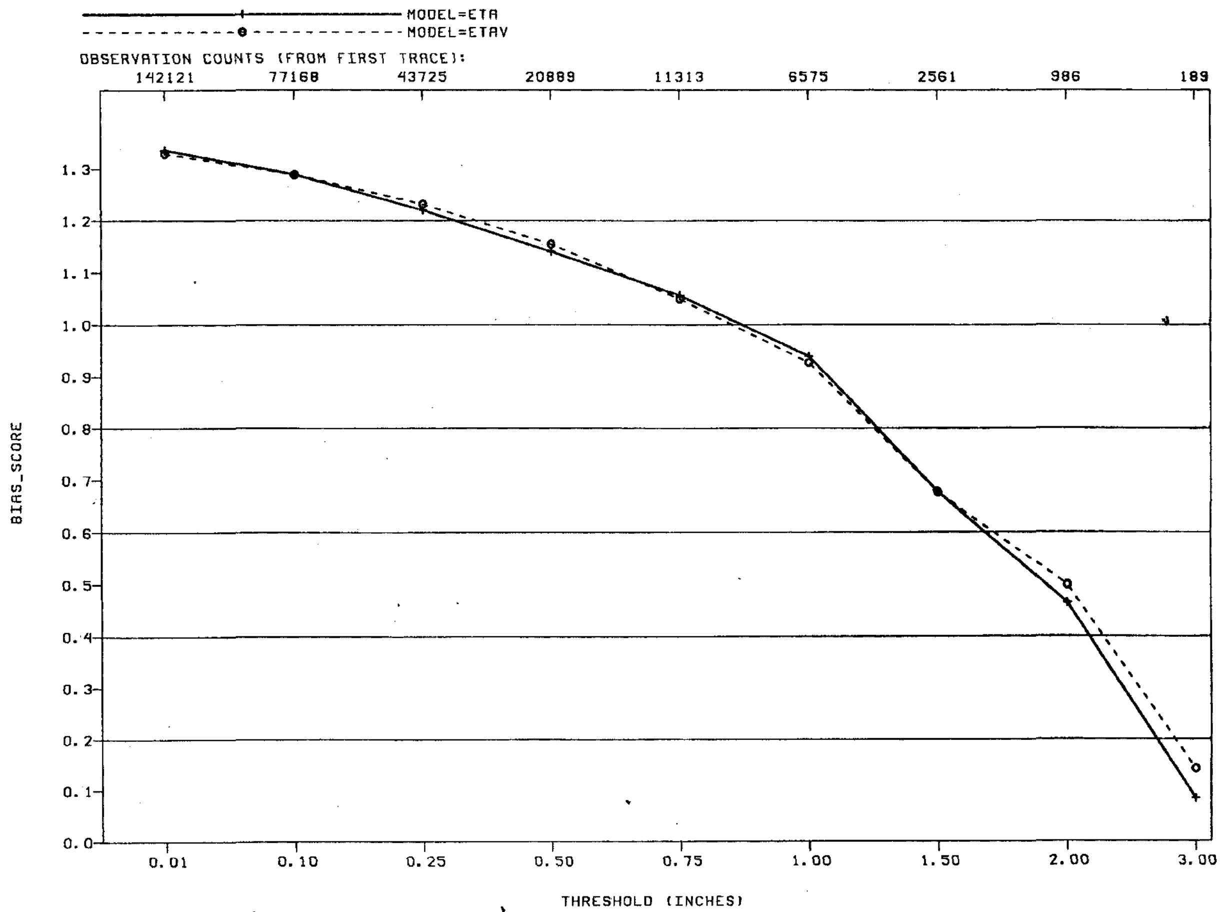
The performance of the unified model is found to be remarkably insensitive to horizontal resolution in many respects. Figure 3 illustrates the simulation of the southern hemisphere circumpolar jet from 10 year integrations using 96 × 73 and 288 × 217 grids as compared with a climatology derived from U.K. operational

STAT=FHO PARAM=APCP/24 FHOUR=24+36+48+60 V_ANL=MB_PCP V_RGN=G211/RFC LEVEL=SFC VYMDH=200102260000-200106132300



321 verifications

STAT=FHO PARAM=APCP/24 FHOUR=24+36+48+60 V_ANL=MB_PCP V_RGN=G211/RFC LEVEL=SFC VYMDH=200102260000-200106132300



Very little impact!

If this is the case, the outcome would be that, after several hours, forecasts of the details of small-scale structures would be no better than guesswork, and subsequent representations of their effects on the larger scales would be no better than parameterization. In other words, if we could use such a model with its unbelievably high resolution for perhaps the first half day, we might as well return to one of today's models for the remainder of the forecast. The implication is that introducing such impossibly high resolution would increase the range of practical predictability by only a few hours. As a corollary, it appears that coming improvements in forecasting may have to come from better numerical representations of the structures that are supposedly already resolved, or better formulations of some of the physical processes. The apparent drop in returns with continued increases in resolution has led some forecasters to propose that the anticipated additional computer power in the middle nineties can be more advantageously used to carry out some Monte Carlo procedure.

Ed Lorenz, The Essence of Chaos, 1993

So, what else could account for the Eta ability to overcome [compensate for] the inflow of [the] less accurate BCs ?

The Eta components that deserve attention in this respect:

Arakawa-style computational design features (which, by the way, do not rely on Taylor-series expansion):

The eta coordinate: avoids inconsistency in the two terms of the PGF: temperature on a sigma surface does not contain information which has gone into the calculation of the geopotential of the first term. Other advantages: grid box sizes, in horizontal, all of very similar size. No significant η vertical motion needed for horizontal motion;

A variety of efforts to avoid or minimize generation of computational modes (e.g., the B/E grid gravity wave coupling scheme, lateral boundary scheme, ...)

Conservation, on the E grid, of an enstrophy analog defined on the C grid (Janjic). Conservation of a number of other analogs;

Exact, in space differencing, conversion between the potential and the kinetic energy;

. . . . . .

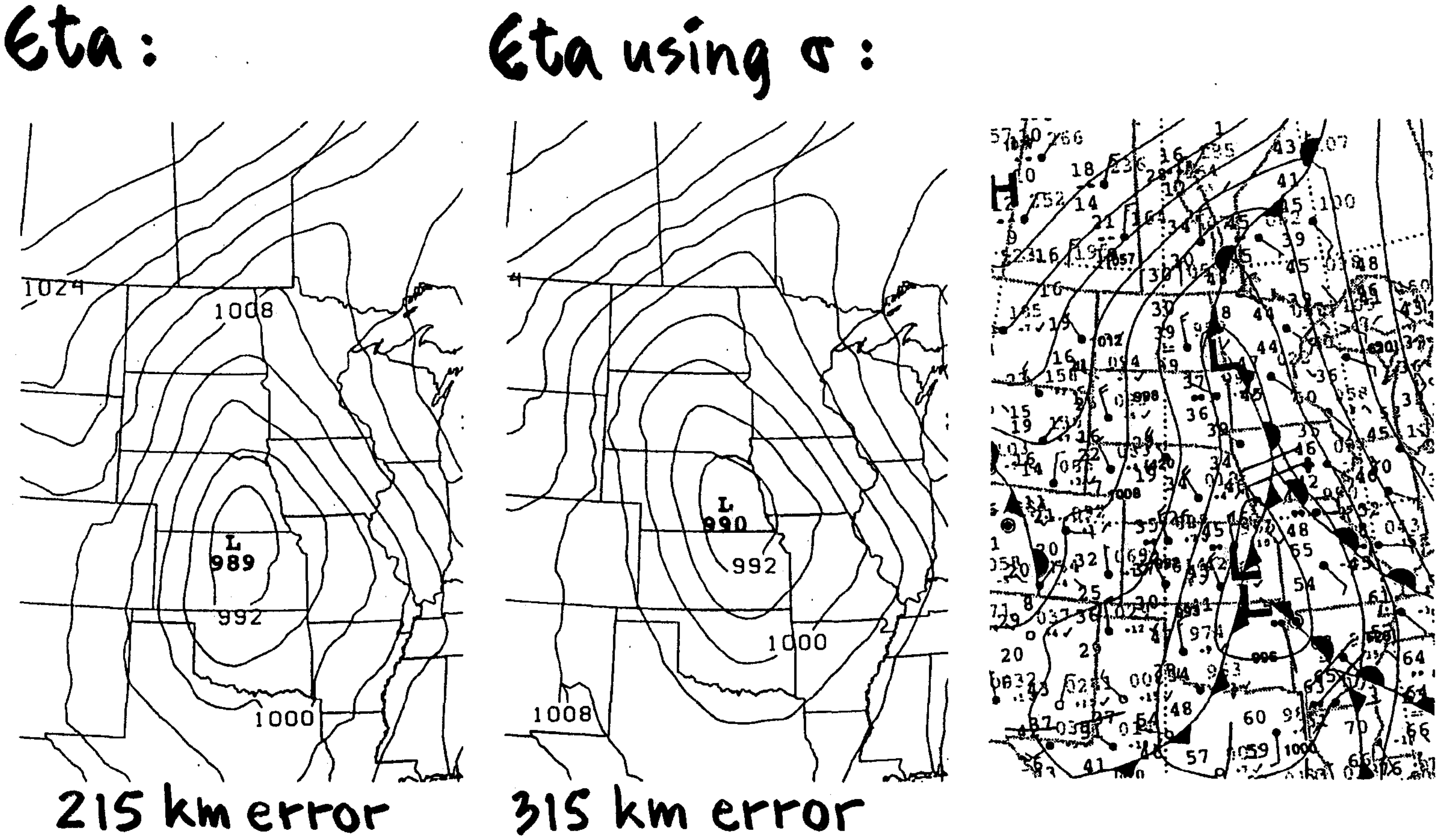


Fig. 2. The Eta Model 48 h forecasts valid 1200 UTC 6 November 2000, done using its operational eta code (left panel), same but run using the sigma coordinate (middle panel), and the HPC verification analysis (right panel). The position error of the low of the Eta forecast is 215 km, and that of the Eta sigma coordinate forecast 315 km (Hui-ya Chuang).

Symp. on Obs. Data Assim. and Probab. Pred., Orl. 2002

5. CONCLUDING COMMENTS

Inspecting rms fits to raobs of the Eta and the Avn at extended forecast times in spring and summer 2001 we find little evidence of the Eta accuracy relative to Avn's falling behind due to the

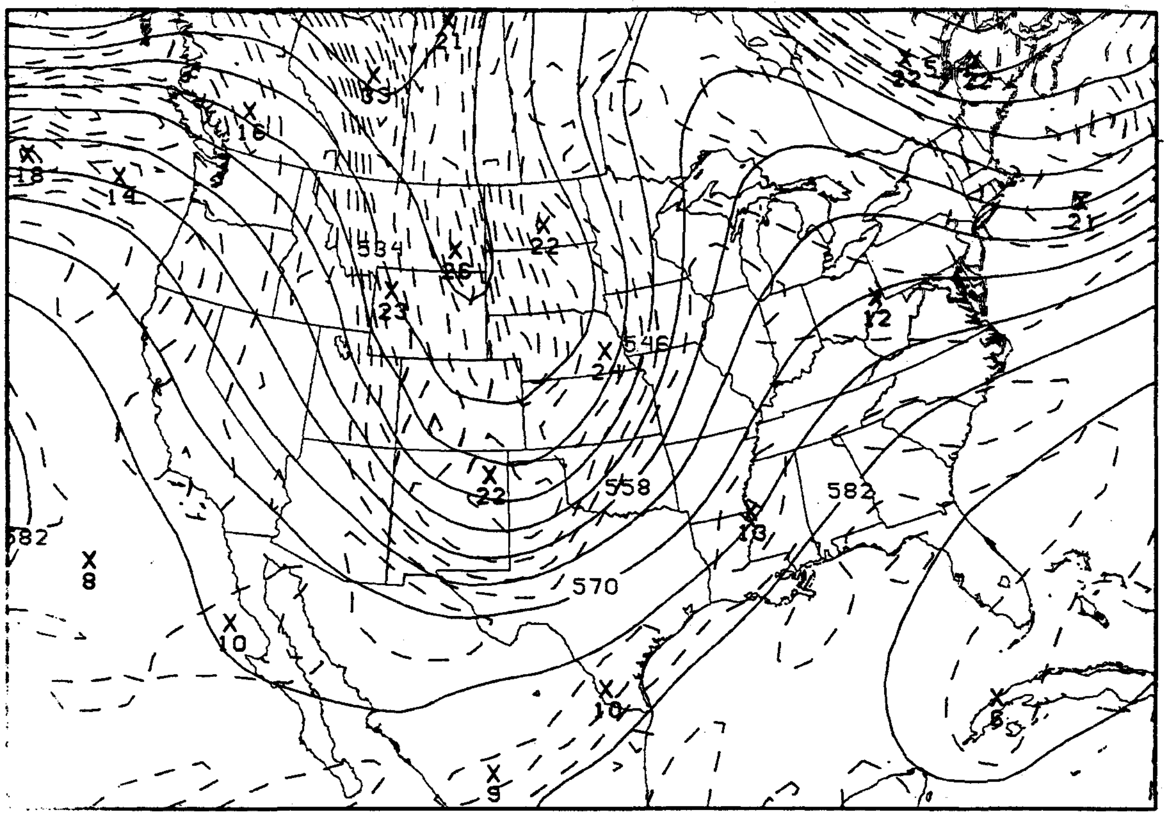
References

Anthes, R. A., Y.-H. Kuo, D. P. Baumhefner, R. M. Errico, and T. W. Bettge, 1985: Predictability of mesoscale atmospheric motions. *Adv. Geophys.*, **28**, Part B, 159-202.

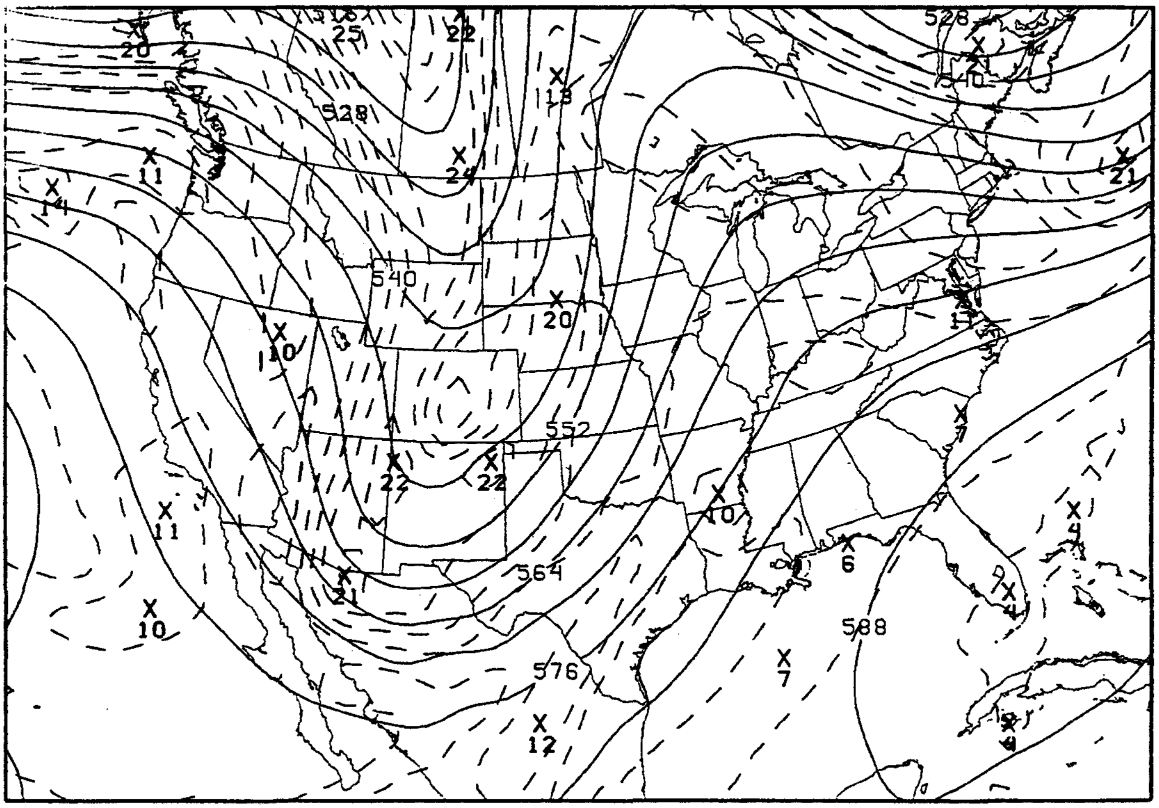
• Considerable advantage of the Eta over the Avn in placing surface lows in the winter 2000-2001 east of the Continental Divide, at 60 h, makes us challenge the notion of "downscaling" by LAMs. Given that the placement of these lows is largely governed by the large-scale mid-tropospheric flow, we find that "upscaling" by a LAM, the Eta in our case, can take place and play an important role just as well.

LAM can improve upon all scales that its domain size can accommodate

Example (60h fcsts, Avn, Eta)



011216/0000V060 500 MB HGHT & VORT -- AVN



011216/0000V060 500 MB HGHT & VORT -- ETA

much more accurate! (The trough actualy had a still greater negative tilt)

Concluding comments/

Taylor series accuracy:

Numerous extensive tests that failed to demonstrate benefit:

- Eta, 2nd order / NGM (4th order)
- Eta ... / RSM ("infinite" order)
- UK Met (Cullen et al.: "sensitivity ... to the choice ... has been slight")
- RAMS (Bill Cotton, personal communication)

⋮

None that, in my view, and as far as I am aware, did demonstrate benefit

Why?

("There is benefit in "test problems)

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diffusion coefficient is lower than that given by the monotone scheme. The unified model scheme requires a time step much lower than that required for linear stability. However, when the scheme is used in the complete model, dispersion of noise by gravity waves allows the full expected time step to be used and there is no evidence that the performance is significantly improved by reducing the time step below the value needed for stability. The use of the fourth order Heun scheme is essential to obtain results of this quality in the test problem. However, the sensitivity of the complete model to the choice between second and fourth order schemes at forecast resolutions (grid lengths less than 100 km) has been slight.

A recent experiment in which the Eta vertical coordinate was switched to sigma indicates that the eta quasi-horizontal coordinate is a significant contributor to the Eta skill in this sense.

Little evidence at hand, if any, that indicates that increasing resolution beyond 10-20 km, and increasing formal Taylor-series accuracy for grid-point models, should result in a major contribution to the improvement of atmospheric GCMs. However, the results summarized may indicate that the inconsistency between the way numerics and physical parameterizations are treated in NWP and climate models is an important obstacle in this sense. In numerics, grid point values are considered to represent point samples of smooth functions. This is the basis of Taylor expansion used in finite difference schemes, and even more in spectral models. In parameterizations, grid point values are handled as averages over grid-box volumes. As a result, grid-point to grid-point noise is created by parameterizations. Removal of this inconsistency is possible, and in my view deserves a high priority in designing next generation NWP and climate models.

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Concluding points (computational issues)

- In spite of using consistent schemes,
increasing resolution and Taylor-series type accuracy do not necessarily help, and can even hurt / increse the error
(e.g. PGF with sloping coordinate surfaces);

- It might be that our greatest obstacle to improving NWP/GCM skill is the inconsistent treatment of dynamics and "physics", point values/box averages.
(How else can one explain no benefit - to speak of - of "high accuracy" schemes in NWP models?)

points by physical parameterizations creates discontinuities. I see the favorable results of the Eta in comparison with the fourth-order accurate NGM at the Eta's early times, and against the Regional Spectral Model (RSM) later, consistent with this view. Namely, they could indicate the advantage of the ARAKAWA approach of the avoidance of computational modes and of other physically-based efforts of minimizing errors over that of the Taylor-series based formal accuracy, as long as parameterizations at individual grid points are in place. Use of finite-volume methods, such as the piecewise-polynomial approach, is one option for the removal of this conflict. Moving toward parameterization schemes which work on groups as opposed to individual grid points is another.

Mesinger 2001, in 50th Anniv. of NWP Symp., EMS