The Eta Model: Design, History, Performance, What Lessons have we Learned?

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ABSTRACT

A summary is given of the design approach, and challenges the Eta Model was facing during more than a decade and a half of its history at NMC and then NCEP/EMC. The model's Arakawa approach in emphasizing maintenance of the analogs of chosen features of the continuous system, and the avoidance of computational modes, is consistent with current physics parameterization methods; the former because it is using the box-average treatment as do the parameterization schemes, and the latter because it minimizes the impact of grid-point to grid-point noise resulting from parameterizations. In addition, the eta coordinate is addressing the pressure gradient force problem.

While it is next to impossible to be certain about conclusions from various model comparison results, the Eta performance over the years has given strong indications regarding the relevance or impact in comprehensive NWP models of high formal accuracy schemes, treatment of topography, the domain size vs resolution issue, and what value added a limited area model can achieve. As to this last point, a strong showing of the Eta relative to its driver GFS model at extended forecast times, in particular in winter, begs for a better understanding. Finally, work in progress in refining the eta discretization so as to allow for sloping steps and remove the Eta downslope windstorm problem is outlined.

1. Introduction: Early history and design

Eta Model history goes back to an effort started at the University of Belgrade, now Serbia and Montenegro, in the early seventies. Design of the very first Eta ancestor code, the dynamical core in today's terminology, was done with the aim to follow the Arakawa approach. This first code I wrote mostly during the one-month academic break January-February 1973. This was the time just after the pioneering efforts of Arakawa during the sixties and the beginning of seventies, at the dawn of the atmospheric primitive equation modeling. For example, and quite incidentally, precisely during that same time period, on 7 February 1973 (NWS 1973), for the first time forecast boundary conditions were incorporated in the NMC's first operational primitive equations limited area model, the venerable LFM (Limited-

area Fine-mesh Model). Of a number of principles introduced or emphasized by Arakawa foremost are maintenance of chosen integral properties of the continuous equations, in particular of enstrophy and kinetic energy for horizontal nondivergent flow; and the avoidance of computational modes. See Arakawa (2000a) and Mesinger (2000a) for more comprehensive reviews.

One feature of this first code that has withstood the test of time is the choice of the horizontal grid and the specification of the lateral boundary conditions. This is well reflected in the title of the first model report in English, emphasizing the noise issue as it relates to the specification of the lateral boundary conditions (Mesinger and Janjic 1974). I chose the Arakawa E-grid as opposed to B because it has all of the variables defined along a single outer line of grid points, for traditional east-west oriented rectangular domains. Lateral boundary conditions were and are today in the Eta prescribed or extrapolated along this single boundary line. This clearly is the way it should be according to the mathematical nature of the

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problem; I find it strange that most models prescribe boundary conditions differently (e.g., McDonald 1997). The specification of the outer line values in the Eta is followed by a "buffer" row of points of four-point averaging (Mesinger 1977). The four-point averaging achieves coupling of the boundary conditions of the two C-subgrids of the E-grid.

Use of the gravity-wave coupling scheme of Mesinger (1973, 1974) in a two-time level, split-explicit framework, followed quickly thereafter, and is reported on also in the first note cited above. This is a major feature of the Eta code today as well, minimizing spurious noise generation and achieving economy in time differencing.

In the original early 1973 code maintenance of various integral quantities was limited to the vertical advection; the Arakawa horizontal advection scheme on the B (or E) grid not yet having been arrived at the time. Maintenance of the E-grid enstrophy and energy in horizontal advection was achieved by Janjic (1977), a few years later. At the same time, Janjic has worked out a scheme conserving energy in transformations between the kinetic and the potential energy in space differencing.

The Janjic (1984) Arakawa horizontal momentum advection scheme, conserving C-grid defined enstrophy for horizontal nondivergent flow on the model's E-grid, and a number of other quantities, was a considerable improvement over his 1977 scheme. This has prevented a spurious systematic energy cascade in horizontal advection toward smaller scales, as nicely illustrated by a schematic of the Charney energy scale analogs shown as Fig. 3.12 in Janjic and Mesinger (1984). Such spurious cascade was not in fact prevented by the 1977 scheme, in spite of the conservation of enstrophy and energy.

Having convinced myself (Mesinger 1982) that the pressure gradient force problem of the terrain-following (sigma) system may not have a good solution, and that the errors could well tend to increase with increased resolution (error table in Mesinger 1982, corrected in Mesinger and Janjic

1985), I felt that quasi-horizontal coordinate surfaces were the most promising way to proceed. The eta coordinate (Mesinger 1984) step-mountain discretization I arrived at was a generalization of the Simmons, Burridge (1981) hybrid coordinate schemes, expanded, in 2D case, to include throughout also the horizontal differencing. I have kept their notation (eta) which has led to some confusion at times.

The 2D scheme to conserve energy in transformations between the kinetic and the potential energy in space differencing of Mesinger (1984) was generalized to 3D case by Dusanka (Dushka) Gavrilov, today Zupanski (Appendix of Mesinger et al. 1988).

With the assistance of Dushka, I have rewritten the then so-called HIBU (Hydrometeorological Institute and Belgrade University) code to use the eta during a visit to GFDL in 1984. Some of the real-data experiments were done at GFDL, and one subsequently at the then NMC, with the assistance of Dennis Deaven. Of the experiments performed, one in which a switch was used to run the code also using sigma coordinate revealed significant noise when the model was run as sigma (Fig. 6 in Mesinger et al. 1988). This I felt offered evidence of the sigma system pressure-gradient force errors, avoided when using the eta.

A comprehensive physics package was added to the eta dynamical core at the then NMC by Janjic (1990) and Black (e.g., Black 1988). This was done benefiting from gracious assistance of authors or coauthors of several physics routines as they existed at the time, primarily the Mellor-Yamada 2.5 turbulence, Betts-Miller convection, and Harshvardhan radiation (references in Janjic 1990, and Black 1988), modified some as felt desirable; and by writing the remaining code, notably the land-surface code (Janjic 1990).

Tests with real data followed. One feature of several of these early Eta experimental forecasts, run using about the same resolution (80 km) as that of the NMC's then relatively new Nested Grid Model (NGM), was increased and apparently rather realistic spatial detail of forecasts of

complex storms (examples in Black 1988). Another which just as well must have increased the respect of the Eta was a 13-forecasts experiment in which the Eta showed much less of a cold bias than that of the NGM, in spite of using the same radiation scheme. But when the Eta was switched to sigma, cold bias, a nagging NGM problem at the time, increased considerably (shown also in Black 1988).

The first open literature report on tests with the Eta Model that included this comprehensive physics package appeared at the time of this writing 16 years ago, in an NWP preprints book (Black and Janjic 1988). Understandably, this first physics package offered ample possibilities for refinements, and also included problems that had to be improved upon. Some of the refinements made until and including 1990, e.g. introduction of an explicit parameterization of the molecular sublayer over water, are described in Janjic (1994). The most critical of the problems was that of its surface fluxes scheme, which was replaced in 1991 (Mesinger and Lobocki 1991). Various additional refinements have of course also been made in these pre-operational Eta times, too numerous to be specifically mentioned here. For a description of the OI analysis system used, see Rogers et al. (1995). Following an extended period of real-time running, the Eta, at 80 km/38 layer resolution, was implemented as a replacement of the LFM as of 12z 8 June 1993.

For this to take place, and subsequently, the Eta faced a number of challenges in the form of comparisons with results of other models. In addition, different Eta setups in terms of domain size and resolution have been run for extended periods. Some of the ensuing comparison results are recalled and reported here, including those on the Eta performance beyond two days that became available in more recent times following the Eta operational extensions to 60 and then 84 h. The goal is to emphasize implications that offer guidance in attempts to improve NWP skill still further in the years to come. The paper will end with a result of and comments on work in progress in refining the eta discretization so as to remove

the problem the Eta had shown with downstream windstorms, a problem that has much affected the mainstream thinking on the suitability of vertical coordinates.

2. Comparisons against the NGM and the RSM

Eta comparison vs the NGM was of course attracting considerable interest at the end of the eighties. Efforts to improve the NGM at the time culminated with implementation of a fourth-order accuracy scheme in December 1990. Even so, the model and its analysis system were frozen already in August 1991. QPF verification was and remains the highest priority EMC statistical verification tool. It became available for three NCEP operational models, Eta, Avn/MRF, and the NGM as of September 1993. Following some physics improvements but no resolution increase during the early nineties, the Eta has shown a very substantial QPF advantage over the NGM across all of the thresholds monitored. Equitable threat and bias scores of the three models for the first 24 months of the availability of three model scores are shown in Fig. 1. A strong case can be made that the eta coordinate, and its Arakawa approach, were the primary contributors to this advantage of the Eta (Mesinger 2000a, and references therein).

Extensive comparison of the Eta against the formally "infinite accuracy" Regional Spectral Model (RSM) took place in the mid-nineties. According to published NMC Development Division plans of as early as 1993, the RSM was looked upon as a contender to replace the Eta. Referring to the Eta and to October 1996, only 3-years time after the Eta was officially implemented and after these plans were made, "A comparison with Regional Spectral Model (RSM) will determine possible replacement by the RSM" states the paper coauthored by all of the then Development Division managers (Kalnay et al. 1993). The comparison ended by a two year parallel 1996-1997, at 50 km resolution, in which the Eta was significantly better. Precipitation threat and bias scores of this parallel test are shown in Fig. 2. The Eta is seen to have won all
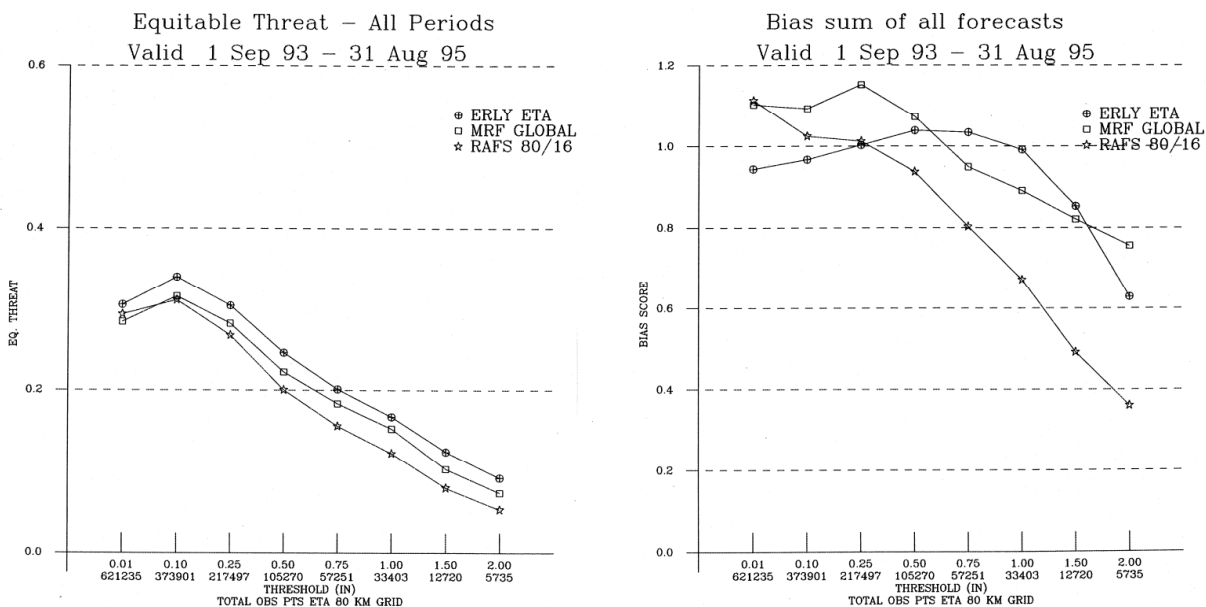
Fig. 1. Equitable precipitation threat scores (left panel) and bias scores (right panel), for the Eta 80-km Model (ERLY ETA), the Aviation/MRF Model (MRF GLOBAL) and NGM (RAFS), for the 24-month period September 1993-August 1995. The upper row of numbers along the two abscissas shows the precipitation thresholds, in inches/24 h and greater, which are verified. Scores are shown for a sample containing three verification periods, 0-24, 12-36, and 24-48 h. The sample contains 1,779 verifications by each of the three models.
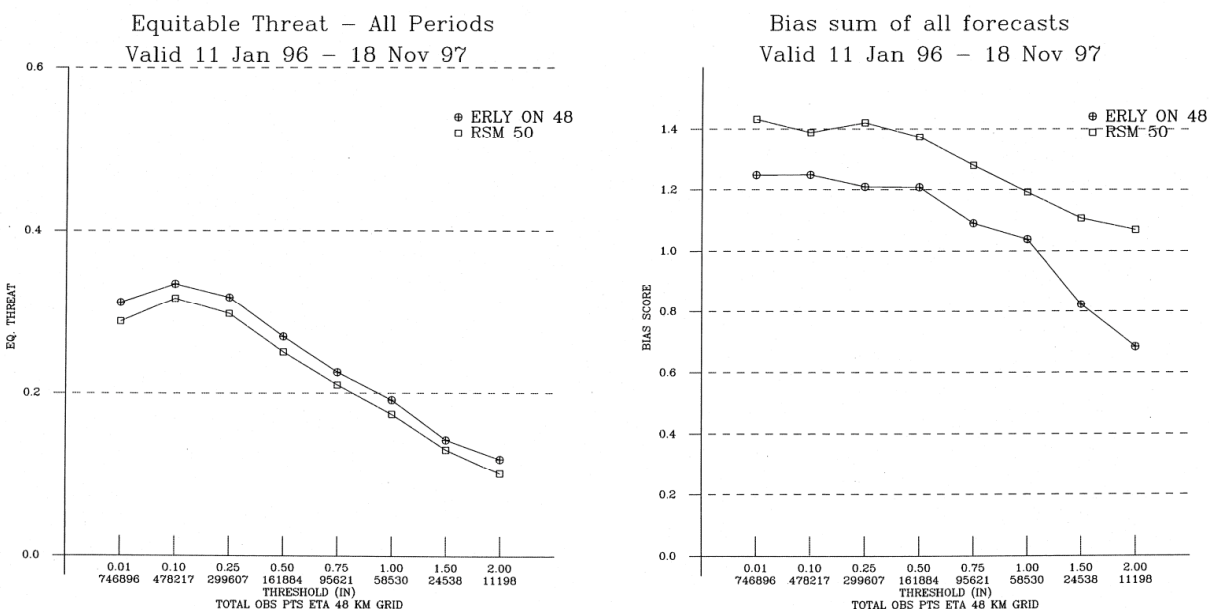

Fig. 2. The Eta ("ERLY") vs RSM precipitation threat (left panel) and bias scores (right panel), for 1996-1997. The upper row of numbers along the two abscissas shows the precipitation thresholds, in inches/24 h and greater, which are verified. Scores are shown for a sample containing three verification periods, 0-24, 12-36, and 24-48 h, and are verified on model grid boxes, 48 and 50 km, respectively. The sample contains 1,024 verifications by each of the two models. The Eta is using 12 h "old", while the RSM is using current Avn lateral boundary conditions.

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precipitation categories, in spite of being driven by 12-h "old" Avn lateral boundary conditions – compared to the current boundary conditions of the later-run RSM. Note that results for only the first 5 months of this 23 month parallel are shown in Fig. 5 of Juang et al. (1997).

3. The "Early" vs the "Meso" Eta

An unintended resolution/domain size experiment was initiated in 1995 and was in place for more than two years. "Meso" Eta runs were implemented, at 29 km/50 layer resolution, run later so that they used current Avn boundary condition, and also more data. To be able to afford higher resolution the 29 km domain was chosen smaller than that of the 48 km Eta; the two domains are shown in Fig. 3. A clear improvement was expected.

While some forecasts and certainly local detail were improved, as can be seen in Fig. 4 in statistical QPF sense in a two-year sample of 1245 forecasts no advantage of the 29 km model over the 48 km one was evident.

What was going on? The explanation hard to avoid is that the considerably larger domain of the 48-km Eta was of so much benefit as to more than compensate for the negative impact of its 12 h old lateral boundary data. For this, of the three major factors involved, resolution, accuracy of the lateral boundary condition, and the domain size, the domain size had to be the dominant one.

Note that this result, or explanation, is at odds with a rather widespread view of looking at nested models as "downscaling" tools, which are supposed to provide local detail but should not change the large scale fields of the driver model (e.g., Waldron et al. 1996; von Storch et al. 2000; Castro and Pielke 2004). The result of Fig. 4 suggests that a limited area model should be, and also indicates that it can be, able to improve not only on the local detail but on the largest scales it can accommodate as well. In other words, "upscaling" can take place, and it seems to me it should, unless the nested model has problems of some kind. Such problems could be due to the use of the Davis-type relaxation boundary condition, given that this is a feature common to many models but not present in the Eta.

I will return to this point of the apparent Eta strength in largest scales the model can accommodate at several places in the sections to follow.
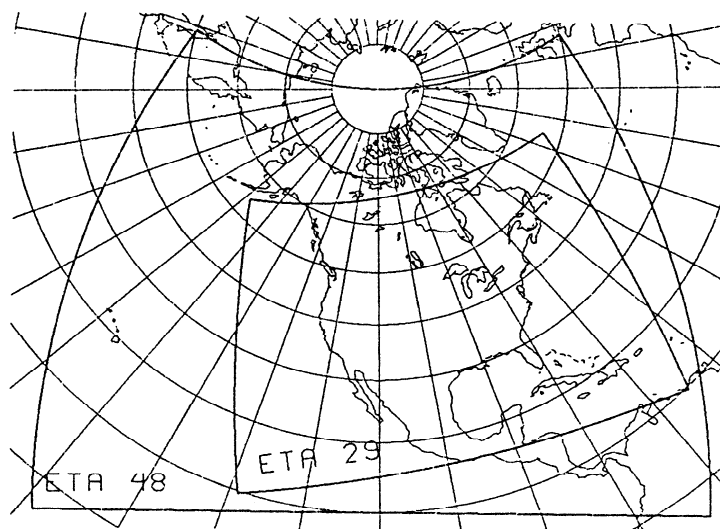

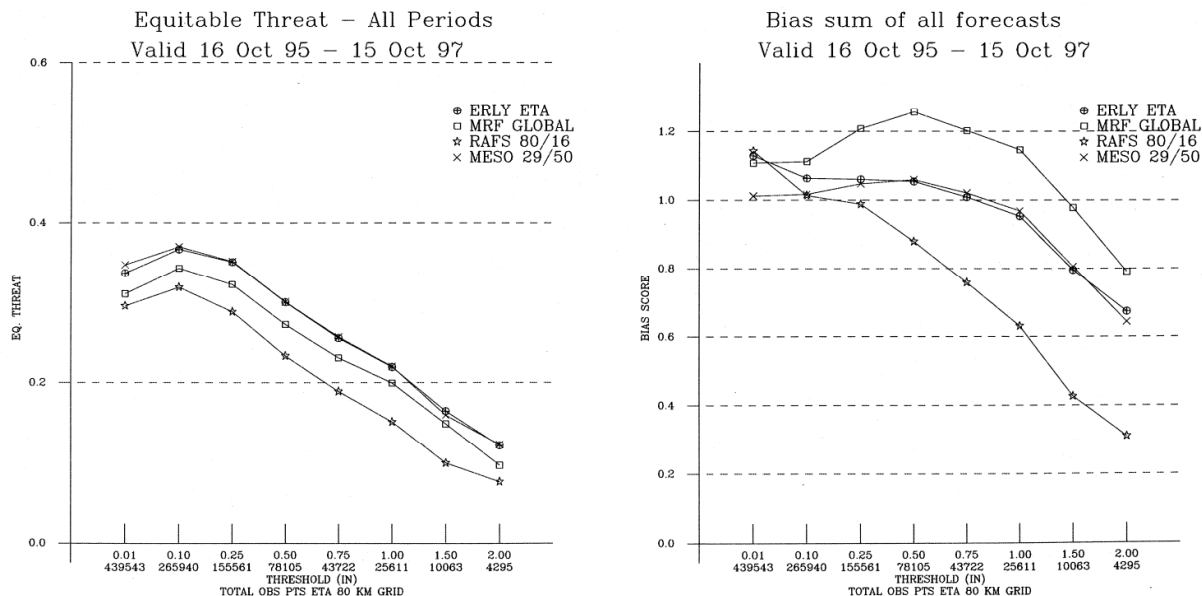Fig. 3. The domains of the Eta 48-km and of the Eta 29-km model.

Fig. 4. 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, left panel; bias scores for the same models and period, right panel. "All Periods" refers to two verification periods, 00-24 h, and 12-36 h; note that the 29-km model was run only 33 h ahead. It was initialized 3 h later than the remaining models. The sample contains 1,245 forecasts by each of the four models; 618 of them verifying at 24 h, and 627 verifying at 36 h.

4. The Eta vs the Avn/GFS

Comparing results of a nested regional model against those of its driver global model, numerous questions may come to mind. First of all, what is the objective of running the nested model? Clearly, it must be value added, hopefully increased or additional skill, of some kind. Deciding what this hoped for increased skill is, one will normally ask if is it being achieved. If it is, why is yet another question; how long can it be maintained one more. A less ambitious goal, more in tune with the present-day thinking would be: increased skill at least some of the time.

The "dry" eta code came to NMC the very same year, 1984, when the daily real-time forecasts using the NGM (RAFS) were started. Thus, one may wonder, is there any record of what the objective of the NGM was thought to be? In the conference paper summarizing results from the first year of real-time forecasting Hoke et al. (1985) state that the NGM was implemented "with the

fundamental goal of improving operational forecasts of heavy precipitation out to 48 hours".

Fig. 1 has shown that the Eta in its first 24 months of three-model precipitation scores was achieving this goal comfortably, for all precipitation thresholds, in spite of absorbing the very real handicap of being run first, using 12-h old Avn boundary conditions, and also a shorter data cut-off.

Even so, not a very bright future for the "early" Eta, the one run before the global model, was expected at the time. This was the period of perhaps a widespread enthusiasm with the success of the European Centre, and global spectral models in general. Thus, the NMC Development Division management plans of 1993 (Kalnay et al. 1993) foresee that already in October 1996 the early Eta was going to be "Phased out assuming AVN precipitation guidance 24-48 hour is comparable or better."

This did not happen. The advantage of the Eta

over the Avn in the second 24 months of three-model scores, September 1995-August 1997, Fig. 5, stayed about the same. Compared to the frozen NGM, both models have clearly improved, across of the thresholds monitored.
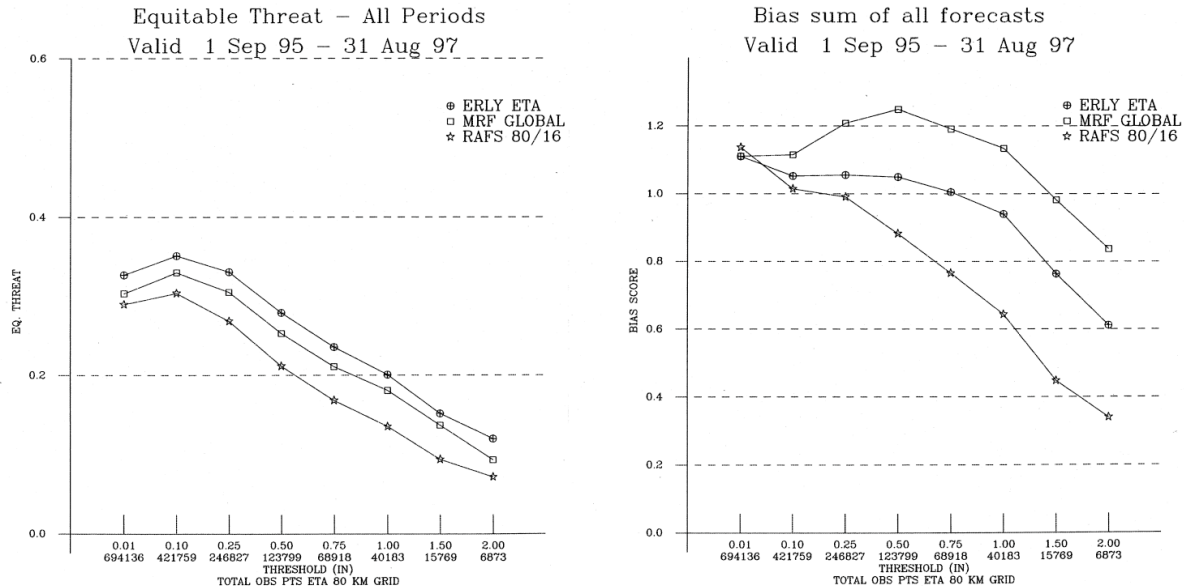

Fig. 5. Same as Fig. 1, except for the 24-month period September 1995-August 1997; and for the Eta being run at 48-km resolution during most of the period shown. The sample contains 1,970 verifications by each of the three models.

As for the Eta, a major set of model changes that have contributed to its improvement are those of the upgrade implemented on 12 October 1995 (Rogers et al. 1996; Mesinger 1996). These changes included a horizontal resolution increase, from 80 to 48 km; and a small increase in the domain size, from 105° x 75 10/26° to 106° x 80° of rotated longitude x latitude, same as the Eta domain used today.

Main model changes of October 1995 have all been tested separately, and convincing evidence was obtained of the resolution increase resulting in better scores (Rogers et al. 1995b). Two earlier resolution experiments gave similar results (Black 1994; Mesinger et al. 1997). Thus, implementation of the 29-km "Meso Eta", now using current Avn lateral boundary condition, was a logical step. Yet, results displayed in Fig. 4, from a very large sample, show no increase in scores. The reduced

domain size, as pointed out, seems the only credible explanation.

But one might still wonder: is the larger domain beneficial because of enabling the Eta to generate more accurate larger scales, as suggested in the preceding section, or perhaps by way of its moving the notorious "lateral boundary error" further away from the U.S. verification area?

Convincing evidence seems to exist that the mathematical error of the Eta lateral boundary scheme is not significant (e.g., Black et al. 1999). On the other hand, the rate of deterioration of skill with forecast time is considerable and is well documented. Presently the operational Eta is driven by the lateral boundary condition from the Avn (recently renamed GFS, Global Forecasting System) runs of 6 h ago. At the "on" times (00 and 12z) this is estimated to represent about an 8 h loss

in accuracy. Should one then not be able to notice, as this error is advected into the central Eta domain, that the Eta skill falls behind that of the Avn/GFS at extended forecast times?

This aspect is now particularly relevant given that as of April 2001 the Eta forecasts have been extended out to 84 h. Note that, just with reference to operational LAMs being nested within low-resolution global forecast models, Laprise et al. (2000) state 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, and in view of the "enhanced" contamination in case of the Eta and the Avn/GFS, what is that time range?

This issue has already been looked into by way of inspection of the Eta vs the Avn precipitation scores at later vs those at earlier forecast times, rms fits to raobs as functions of time, and accuracy of the placement of the centers of major lows by the two models at 60 h forecast time (Mesinger et al. 2002a; Mesinger et al. 2002b). These results will be updated and/or recalled here.

In Fig. 6 a year, May 2001-April 2002, of the Eta and the Avn precipitation threat scores are shown, for the sample of 00-24, 12-36, and 24-48 h, upper panel, and that of the 36-60, 48-72, and 60-84 h forecasts, all verifying at 12z, lower panel. There are more than 800 24-h 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.

In the two cited Mesinger et al. (2002) conference papers rms fits to raobs of the Eta and the Avn 250 mb wind and 500 mb height were shown, as functions of forecast time, for four seasons: spring, summer, and fall of 2001, and winter of 2001-2002. No systematic tendency of the Eta error growth rate to increase relative to that of the Avn at later forecast times was evident. This series is here updated by showing in Fig. 7 250 mb wind and 500 mb height rms plots for the warm season (May through October) of 2003, and the cold season (November through April) of 2003-

2004. An impact of the advection of the GFS lateral boundary errors is not visible in any of the four plots shown.

As yet another attempt, the accuracy of the Eta and the Avn in placing the centers of major lows, at 60 h forecast time, during the winter of 2000-2001, was documented and reported on in Mesinger at al. (2002a). Rules were set for identification of these lows on HPC's 00 and 12z analyses. Verification area was chosen east of the Continental Divide, to minimize the impact of the differences in the pressure reduction to sea level. 31 cases, coming from 12 events, qualified. Results are reproduced in Table 1. The Eta is seen to have been in numerous respects considerably more accurate than the Avn.

With these results on major challenges, unintended experiments, and tests the Eta has faced or has been involved with recalled or presented, I will now move to a more general discussion: what lessons have we learned? A "lesson" of course, can also be to have a good look into something most of us might have been taking for granted.

5. Discussion: Progress achieved by the Eta, order of accuracy, resolution, sigma vs eta

There can be little doubt that considerable progress in NWP skill has been made during the nineties. The starting point here is to assess how much this is evidenced by the results of the Eta, and how much the Eta may have contributed to this progress. NGM, frozen in 1991 and run until February 2000 with its analysis and initialization system also unchanged and independent of that of the Eta, served as a unique reference model to that end. Thus, in the left panel of Fig. 8 equitable threat scores are given of the Eta and the NGM (RAFS) 24 h accumulated precipitation forecasts for all of 1998. In the right panel, the 24-h NGM threat score plot is reproduced along with that of the Eta 24-48 h forecasts. For all eight categories the Eta 48 h scores are higher than those of the NGM's 24 h ones, albeit at five of them the difference is barely visible. Thus, in seven years,
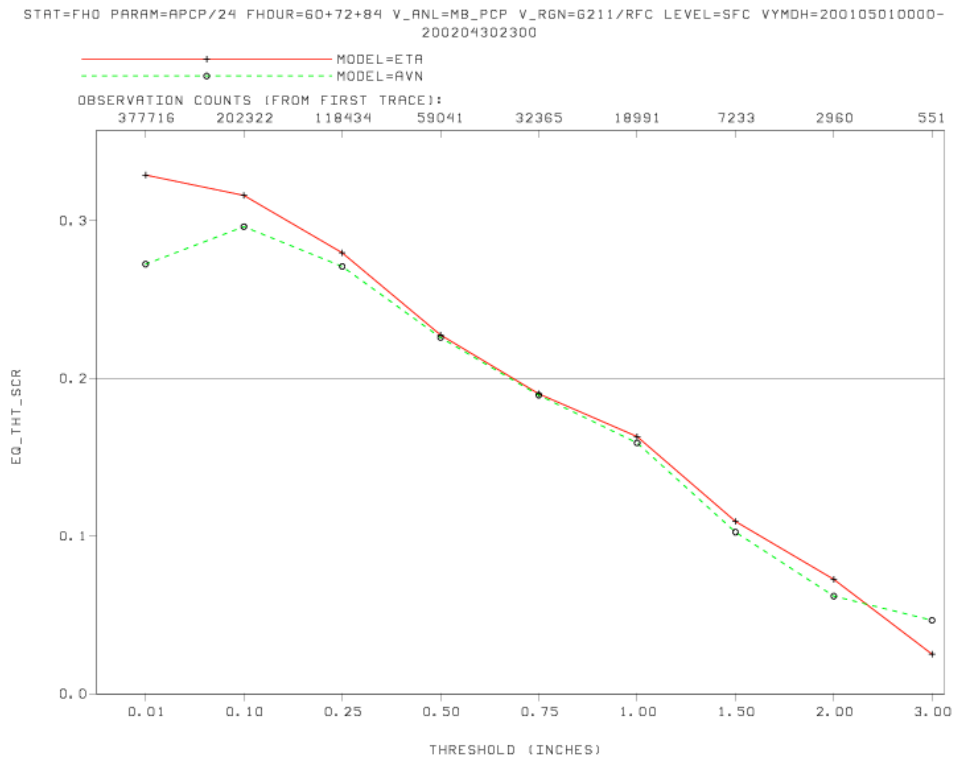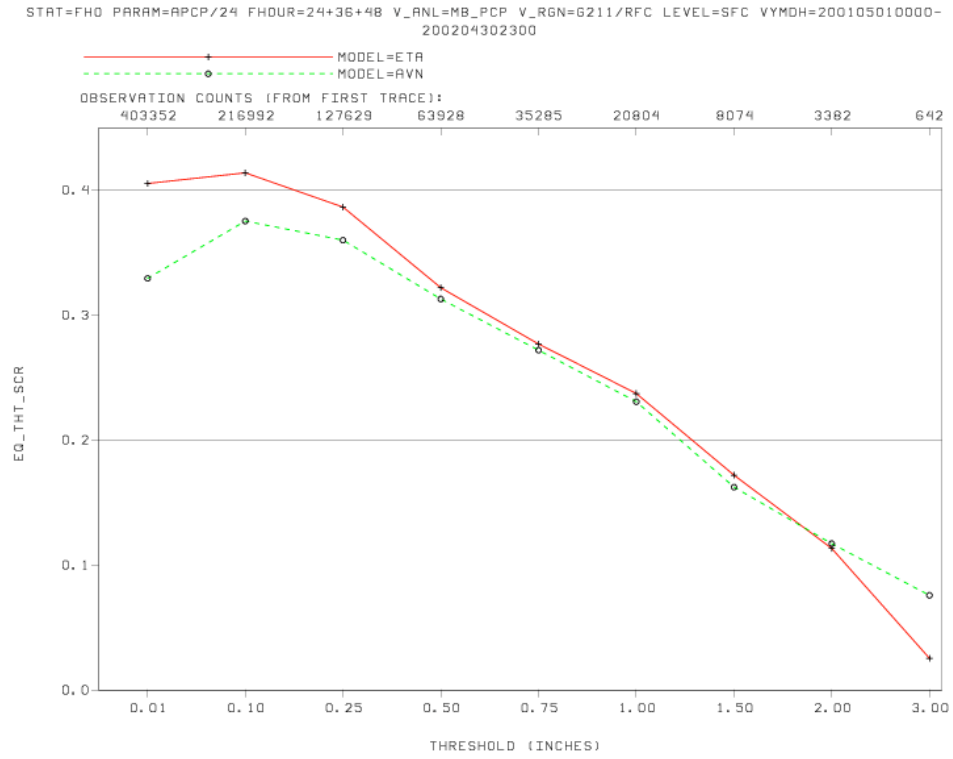
Fig. 6. Equitable precipitation threat scores of the Eta (solid) and the Avn (dashed lines), 00-24, 12-36, and 24-48 h forecasts, upper panel, and 36-60, 48-72, and 60-84 h forecasts, lower panel, May 2001-April 2002.
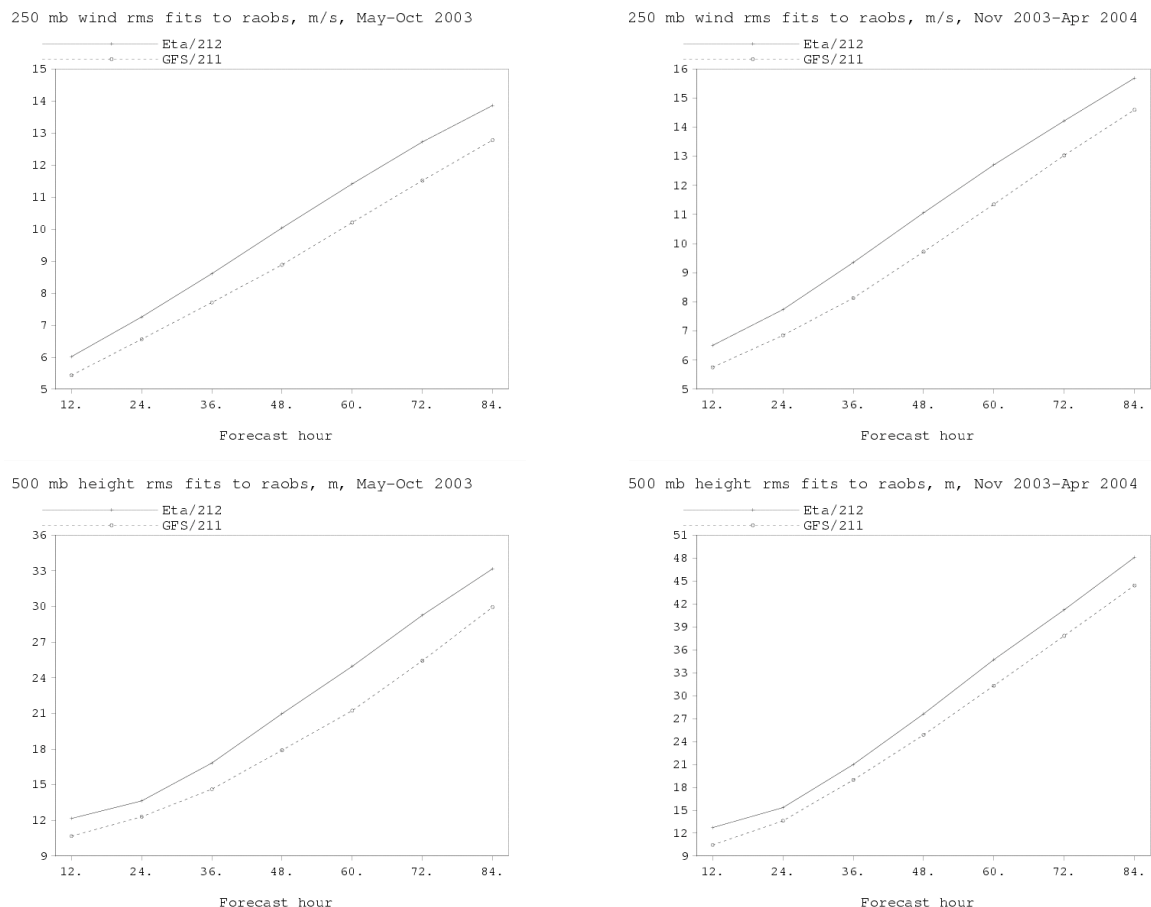
250 mb wind rms fits to raobs, m/s, May-Oct 2003

Eta/212
GFS/211

Forecast hour

250 mb wind rms fits to raobs, m/s, Nov 2003-Apr 2004

Eta/212
GFS/211

Forecast hour

500 mb height rms fits to raobs, m, May-Oct 2003

Eta/212
GFS/211

Forecast hour

500 mb height rms fits to raobs, m, Nov 2003-Apr 2004

Eta/212
GFS/211

Forecast hour

Fig. 7. RMS fits to raobs of the operational forecasts of the Eta (solid) and of the GFS (dashed lines), in the "warm season" of 2003 (left panels) and in the "cold season" of 2003-2004 (right panels); for 250 mb vector winds (upper panels), and 500 mb heights (lower panels), as functions of forecast time. The Eta is verified after being output to a 40-km grid ("grid 212"), and the GFS after being output to an 80-km grid ("grid 211")

a full day extension of the validity of NCEP's "official" QPFs has been achieved.

But how much of this progress, if any, is due to the Eta itself, and how much merely to increased resolution enabled by more computing power? Attempting to assess what the answer might be comparisons of Section 2 of the Eta against the NGM and the RSM come to mind, being done with models run at about the same resolution, and having physics packages of roughly similar complexity.

Considerable advantage of the Eta against both of these models has been evidenced. What

message, if any, does this imply? NWP is an imprecise science, in the sense that clean experiments are virtually impossible. Yet, if enough evidence accumulates, and if a physical understanding seems plausible, credibility of the evidence becomes hard to deny. In this respect, a common feature of the NGM and the RSM of having a higher formal (Taylor series based) accuracy compared to the 2nd-order accurate Eta is worth recalling. If higher accuracy were helpful to the NGM and to the RSM, this help clearly was not too significant. The 29 km Eta of Section 3 was also formally more accurate than the 48 km one, and the help, if any, was not too significant either. At

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Table 1. Position forecast errors, at 60 h, of "major lows"
east of the Rockies and over land,
December 2000 - February 2001

Valid at	Avn error	Eta error
00z 12 Dec.	125 km	275 km
12z 12 Dec.	325 km	150 km
00z 17 Dec.	475 km	125 km
12z 17 Dec.	175 km	425 km
00z 18 Dec.	450 km	575 km
12z 18 Dec.	75 km	100 km
00z 20 Dec.	250 km	350 km
12z 20 Dec.	175 km	175 km
00z 5 Jan.	400 km	350 km
12z 5 Jan.	125 km	350 km
12z 6 Jan.	1,175 km	500 km
12z 10 Jan.	325 km	150 km
00z 11 Jan.	425 km	75 km
12z 13 Jan.	475 km	150 km
00z 14 Jan.	50 km	350 km
12z 14 Jan.	175 km	150 km
00z 15 Jan.	350 km	300 km
12z 15 Jan.	225 km	175 km
00z 16 Jan.	225 km	275 km
00z 30 Jan.	175 km	350 km
12z 30 Jan.	300 km	275 km
00z 9 Feb.	350 km	325 km
00z 10 Feb.	150 km	175 km
12z 10 Feb.	225 km	200 km
12z 21 Feb.	575 km	325 km
00z 24 Feb.	325 km	100 km
12z 24 Feb.	300 km	100 km
00z 25 Feb.	275 km	150 km
12z 25 Feb.	325 km	300 km
00z 26 Feb.	475 km	75 km
12z 26 Feb.	575 km	175 km
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Average error	324 km	244 km
Median error	300 km	200 km

least one other relatively recent effort to benefit from higher-order differencing in a major NWP model has also failed to lead to increased skill. Thus, Cullen et al. (1997) state that "the sensitivity of the complete model to the choice between second and fourth order schemes ... has been slight".

I have repeatedly hypothesized earlier (e.g., Mesinger 2001) that this could be due to the inconsistency in the treatment of dynamics and physics in NWP models: in dynamics smooth fields are assumed, and grid point values are considered valid at points; in physics, noise is produced by changing individual grid columns, and grid point values are considered to represent averages over the grid boxes. In no physics experiments ("test problem" of Cullen et al. 1997) benefits from higher order are universally present. Introduction of the physics "noise" in complete models works against the Taylor series smoothness view. This inconsistency being to a smaller degree detrimental in the Eta due to a variety of its Arakawa-style finite-volume features, and – unless compact schemes are used – also due to its only 2nd-order formal accuracy, could have significantly contributed to the Eta performance as reviewed above.

How can this conundrum be resolved? One possibility, making sense also from a physical point of view (Arakawa 2000b) is to move away from single-column parameterizations. Another is to refine numerical discretizations, so as to try to abandon completely the treatment of grid point values as point samples of smooth functions. Piecewise-polynomial methods offer such possibilities.

The lack of evidence of the Avn (or, GFS) lateral boundary error affecting the relative skill of the Eta at extended forecast times is another issue begging for understanding. A number of implications can be made. Note first that for the Eta skill relative to the Avn not to be visibly affected by the inflow of the less accurate Avn/GFS boundary data beyond about two days, component(s) are needed in the Eta able to compensate for this inflow. Furthermore, the impact of this(these) component(s) ought to increase with time.

The higher Eta resolution seems a weak candidate for this role; recall the experiment of Section 3. Impressive benefits of high resolution are well-known for more local events and at shorter range, such as in the notorious 10-km Eta forecast of very heavy rains over California coastal ranges in February 1998 (e.g., Wu 1999). With no deterioration of synoptic-scale skill, this alone
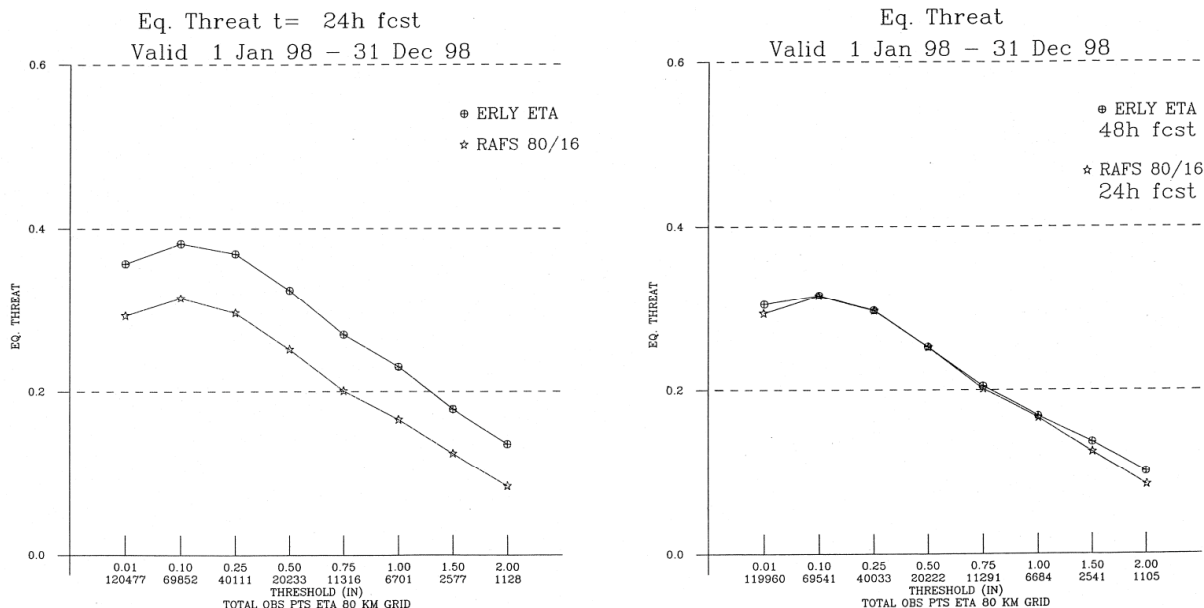
Fig. 8. Equitable precipitation threat scores, for 1998, of the Eta (ERLY ETA) and of the NGM/RAFS for 00-24 h forecasts, left panel. The sample contains 319 verifications by each of the two models. Scores of the 24-48 h Eta shown against the 00-24 h NGM/RAFS scores, right panel.

justifies increases in resolution, and the increases in resolution of the operational Eta have indeed regularly followed increases in available computing power. From the original 48 km/38 lyr, its resolution was increased to 48 km/38 lyr on 12 October 1995; to 32 km/45 lyr on 9 February 1998; to 22 km/50 lyr on 26 September 2000; and finally to 12 km/60 lyr on 27 November 2001.

But the attention at this moment is on the resilience of the Eta to demonstrate the impact of the inflow of the Avn/GFS boundary errors at extended forecast times. Error statistics looked at are of the types reflecting the accuracy of the placement of synoptic systems, and there is to my knowledge not much if any evidence that the increase of resolution beyond about 20-30 km is in statistical sense of much help, with NWP systems in place today. But more importantly, the notion that the benefit from increased resolution should increase with time seems hard to support. In fact, views to the contrary have been advanced (e.g., Toth et al. 2002, and references therein).

The eta coordinate looks like a stronger candidate, given that time is needed for systems to get organized as they are crossing the Rockies and entering the main verification domain of the continental United States. An experiment done with the 22-km Eta (Hui-ya Chuang, personal communication) supports this possibility. It was done on 48-h forecasts verifying 1200 UTC 6 November 2000. At that time a low was analyzed centered in eastern Kansas, with the sea level pressure of the main center of 992 mb, Fig. 9 right panel. The operational Eta placed the low 215 km northwest of its analyzed position, left panel. The Eta Model forecast with all parameters same except that the model was switched to use the sigma coordinate, placed the low still further to the north, with the position error increased to 315 km, the middle panel. Compared to the two earlier experiments, done with the then 80-km operational Eta (e.g., Fig. 7 in Mesinger and Black, 1992) the experiment of Fig. 9 shows little if any reduction in the magnitude of the impact, in spite of the very substantial increase in the resolution of the model.
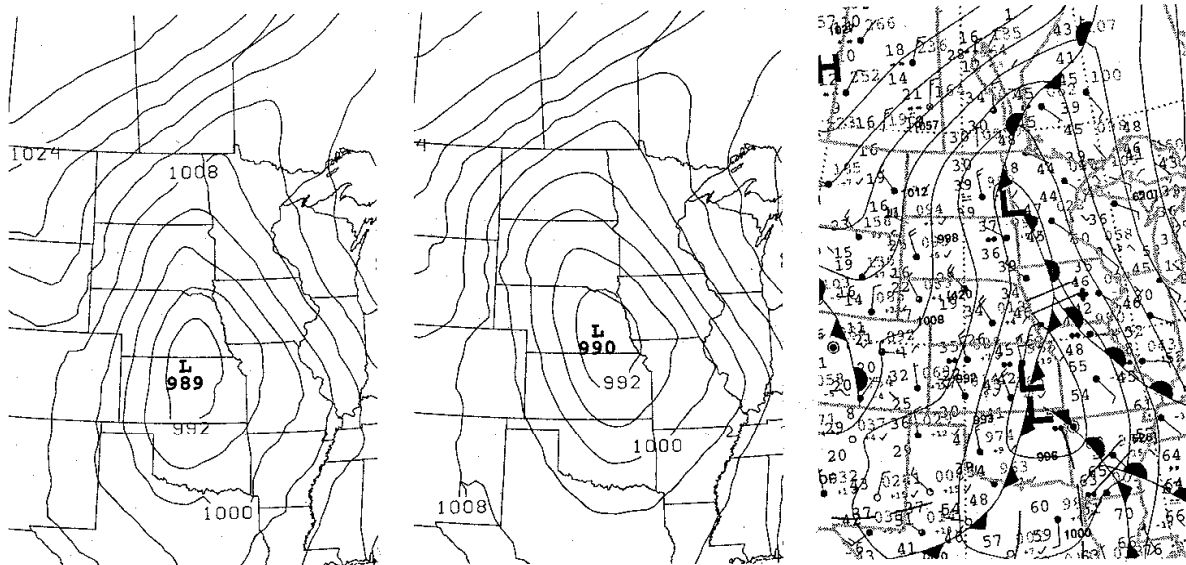
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Fig. 9. The Eta Model 48 h forecasts valid 1200 UTC 6 November 2000, done using its operational eta code (left panel), same but run using the sigma coordinate (middle panel), and the HPC verification analysis (right panel). The position error of the low of the Eta forecast is 215 km, and that of the Eta sigma coordinate forecast 315 km.

There are other indications suggesting the beneficial impact of the eta coordinate in obtaining a more realistic large-scale flow resulting from the impact of the Rocky Mountain topography. Note that the effect of the topographic barrier on the flow in the verification region here of most interest, the contiguous United States, should be expected to be the largest in winter, because the jet stream is then furthest to the south, at predominantly the contiguous U.S. latitudes. Inspection of rms plots such as those of Fig. 7 shows that the Eta in relative terms, compared to the Avn/GFS, does best in winter. This is just the opposite of what one might expect on account of the lateral boundary error propagating then into the main verification area the fastest.

Similarly, extensive comparisons have been made of the accuracy of the just completed 25-year North American Regional Reanalysis (RR, Mesinger et al. 2004), done using the Eta, compared to that of the NCEP/NCAR Global Reanalysis (GR, Kalnay et al. 1996). Contrary to what I think most people would expect on account of the higher resolution of the Eta and thus improved topographic and land-surface realism,

the greatest advantage of the RR over the GR is apparently in winds, in winter, at jet stream levels.

But in the late nineties, before these results became available, considerable concern had arisen as a result of a failure of a quasi-operational 10-km Eta to perform well in forecasting an intense downslope windstorm in the lee of the Wasatch mountain (McDonald et al. 1998), while the sigma system MM5 for the same case did well. This was followed by 2D experiments of Gallus and Klemp (2000), in which an eta code in a flow up and down a bell-shaped mountain failed to bring the strongest winds close to the ground on the lee side, as should have occurred according to a linear solution. Instead, a flow separation developed in the lee of the mountain. In addition, in Gallus and Klemp (2000) various scale- and resolution-related arguments were made.

As a result, the eta has lost much of its original respect and the opinion now seems to be quite widespread in the NWP community that the eta coordinate system is "ill suited for high resolution prediction models" (e.g., Schär et al. 2002; Janjic 2003; Steppeler et al. 2003; Mass et al. 2003; Zängl 2003). Various authors expressing that view have

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used and/or advocated sigma or modified sigma systems. It would seem thus that it is also considered that as the resolution of NWP models is being increased the performance of the terrain following coordinates will increasingly improve, so that an alternative rather complex system of "shaved cells" (Adcroft et al. 1999) is not cost-beneficial. Yet another option, of an eta-like system but with partial steps (Tripoli, personal communication) seems not to be attracting much interest. Thus, for example, all three major WRF dynamical core development efforts are based on various versions of the terrain-following coordinates.

Results of the first 12 months of comparison of precipitation scores of three NCEP operational models, Global Forecasting System (GFS), 12-km Eta, and 8-km Nonhydrostatic Mesoscale Model (NMM) are however at variance with this view. These 12 months are of particular interest since they have included the el Niño winter of 2002-2003, when during the November and December 2002 five events are on record of very heavy rains over the mountainous western United States with HPC analyzed precipitation of over 4 inches/24 hours, and typically 2 and 3 inches/24 hour patterns over individual mountain ranges that are clearly an extraordinary challenge to forecast well in terms of precipitation scores. A summary of these 12 month results, in form of equitable threat scores normalized to unit bias using Keith Brill's odds ratio method (Mesinger and Brill 2004) is shown in Fig. 10. These results also raise additional concerns regarding the expectation of improved skill with increased resolution. Over the roughly eastern half of the United States, with no major topography ("East"), the Eta and the NMM had about the same skill; if anything, the lower resolution Eta did slightly better. The GFS was clearly better than the two. Over the mountainous western half, "West", it was the Eta that had clearly the best scores, with the sigma system NMM second, and the GFS third.
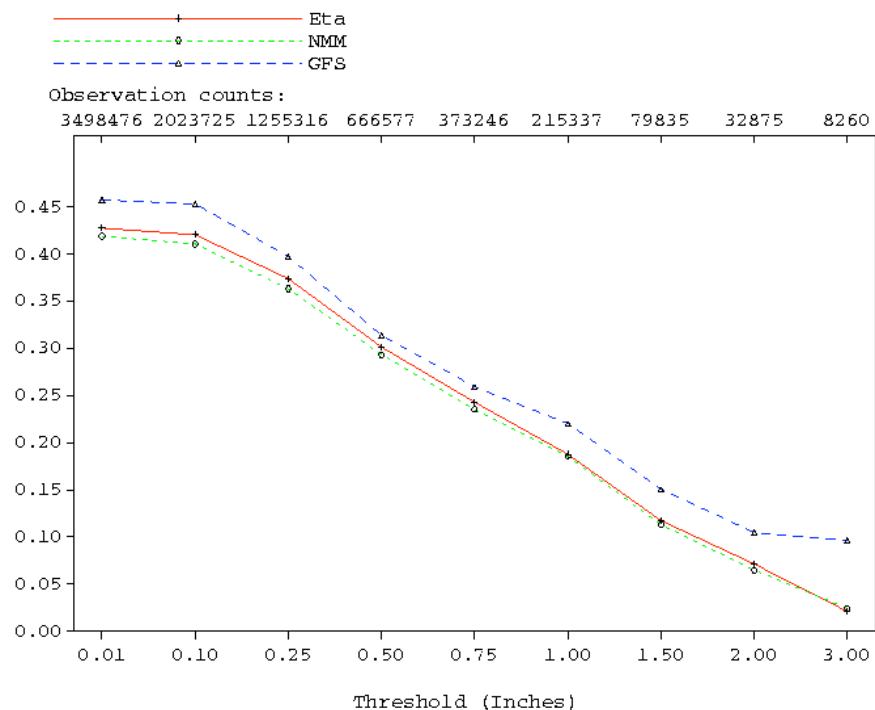
How is that possible? Explanation of the eta downslope windstorm problem has been

suggested in Mesinger (2004). The problem, absence of slantwise flow between neighboring eta layers, should not much affect the performance of the eta on the upslope side, and therefore the performance of the Eta for the mentioned very heavy el Niño rains over the West was excellent, much better than that of the sigma system models, NMM and also GFS. Over the East, the impact of topography was not dominant, and the Eta and the NMM performed similarly.

In an effort in progress (Mesinger and Jovic) we have refined the eta code so as to account for slopes replacing the flat tops of the current step-topography Eta discretization. Accordingly, the eta vertical velocity next to the ground is not required to be zero. Of the eta governing equations, this affects only the pressure tendency equation (Mesinger 2000b). With our current approach, topography slopes are defined at velocity points, and are defined at squares bounded by four neighboring height points. A preliminary result we have with this approach at the time of this writing is shown in Fig. 11. Its left panel shows our emulation of the Gallus-Klemp experiment, their Fig. 6(a). We have obtained this result using a full 3D Eta code, dynamics only, running a square domain, with variables prescribed not to change along one of its diagonals. Flow separation in the lee as seen in this panel was considered by Gallus and Klemp illustration of the Eta downslope windstorm problem; just as in their plot, a velocity of only between 1 and 2 m/s is seen in our left panel plot immediately behind the obstacle next to the ground. In the right panel, obtained using our sloping steps discretization, an add-on to the current eta code, a considerably greater velocity is seen next to the ground just behind the obstacle, of between 7 and 8 m/s. In addition, the noisy contour pattern at the upslope side is replaced by a considerably smoother pattern.

I consider this very preliminary result a demonstration that the eta downslope windstorm problem should not be too hard to remedy by an add-on to the current eta code. The precipitation

OddsR BN Eq Threat, Eastern Nest, Sep 2002-Aug 2003

Eta
NMM
GFS

Observation counts:
3498476 2023725 1255316 666577 373246 215337 79835 32875 8260

Threshold (Inches)

OddsR BN Eq Threat, Western Nest, Sep 2002-Aug 2003

Eta
NMM
GFS

Observation counts:
2958107 1180387 532073 205652 100148 55514 21158 10132 3134
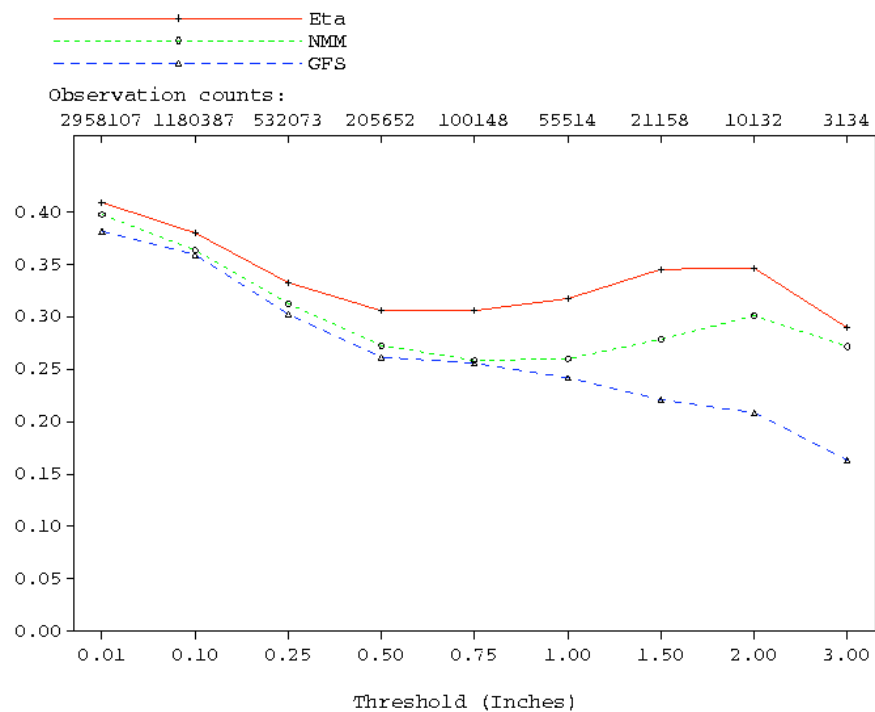
Threshold (Inches)

Fig. 10. Equitable threat scores of three NCEP operational models, the Eta, NMM, and GFS, normalized to unit bias using Keith Brill's odds ratio method, for the first 12 months of the availability of these three-model scores. NMM's "East" domain upper panel, "West" domain lower panel. See text for further detail.
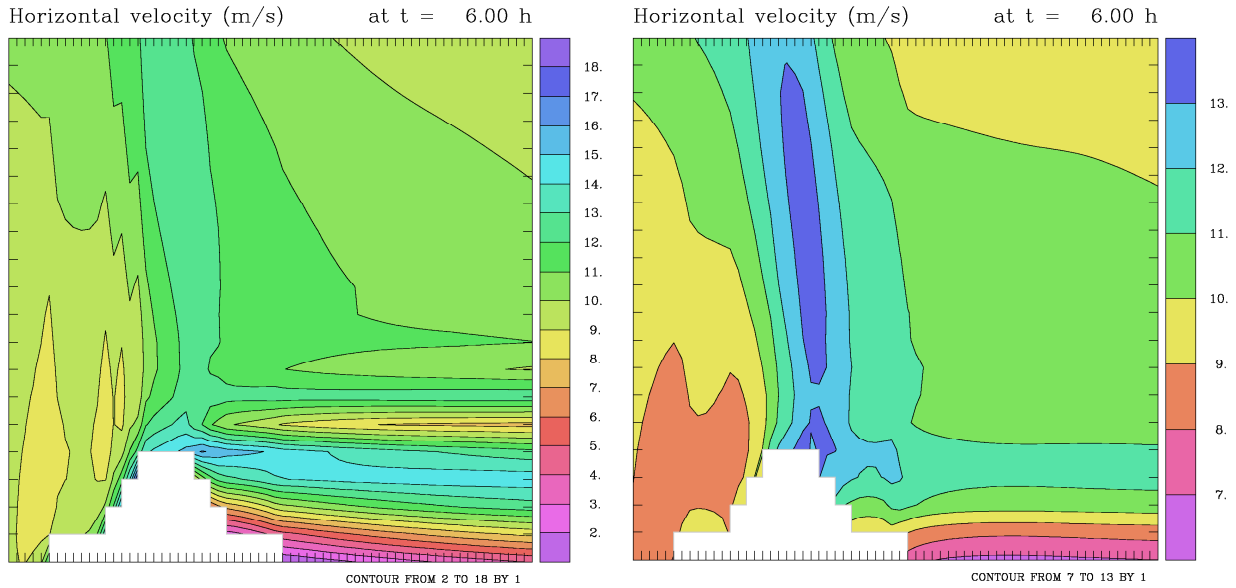
Fig. 11. Gallus-Klemp experiment, with parameters chosen so as to mimic the result shown in Gallus-Klemp (2000) Fig. 6(a). Control, left panel; eta code modified so as to account for sloping steps and resulting slantwise transports of mass, momentum, and temperature, right panel.

results of Fig. 10, on the other hand, with a striking difference between the "East" and the "West", I find strongly suggestive of the problems of the terrain-following coordinates. As argued in Mesinger (2004), it is to be expected that these problems should only become more serious as the resolution is increased. That could have been the main reason for the NMM, in spite of its better information on topography, not having done all that well in the West compared to the Eta.

6. Concluding comments

In the preceding discussion I have suggested that various Eta results are supportive of dynamical core approaches and views not universally embraced by the NWP community, or are not what might generally be expected, and thus deserve attention. In addition, a preliminary result on a refined eta discretization has been shown. Points that particularly should be noted may be the following.

• High Taylor-series type accuracy models, NGM and RSM, have failed to do well in comparisons with the Eta; and there are other "complete model"

results pointing to difficulties in benefiting from increased formal accuracy. I have repeatedly suggested that "noise" due to physics forcing at individual grid boxes or columns may be the likely reason;

• In comparisons with its driver global model, Avn, now GFS, the Eta has repeatedly shown to be quite competitive at extended forecast times, out to 3.5 days. No loss of skill relative to that of the GFS has been detected, in spite of the advection of the very real GFS lateral boundary error;

• There is evidence indicating that higher Eta resolution is not a good candidate to explain this resiliency to the effect of the advection of the boundary error;

• The eta coordinate, on the other hand, is a strong candidate in this sense, given that its impact could well be expected to initially increase with time, and that the Eta relative strength over the contiguous United States area seems to be the greatest in winter;

• The recent first 12 months of three-model, Eta, NMM and GFS, precipitation scores are highly favorable to the Eta, in the sense of suggesting that

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the benefit from its vertical coordinate in events of very strong precipitation in the "West" was sufficient to overcome the handicaps of old boundary conditions compared to the GFS, and less information on complex topography compared to the higher resolution NMM;

• This is strongly indicative of the sigma system pressure gradient force problem not being alleviated with increased resolution, but instead the opposite taking place, as argued in Mesinger (2004) and earlier one should expect. Recall that of the numerous attempts to address the problem, as reviewed in Mesinger and Janjic (1985), none really remove it;

• The Eta problem with downslope windstorms as evidenced by the Gallus-Klemp experiment, on the other hand, seems not hard to successfully address. The emulation of the Gallus-Klemp experiment shown here along with a preliminary result obtained using a refined eta discretization, an add-on to the current Eta code, is not far from a demonstration that this in fact had already been done.

Acknowledgements. The "dry" eta code came to the then NMC as a result of an NMC/GFDL cooperation effort, put in place by the directors of the two institutions, for which as I understand Bill Bonner, then NMC Director, was the driving force. The code and the associated message were clearly well received, not only by Bill who did his best to make my one-year visit pleasant as well as useful; but by the then Development Division staff just as well. This being an appropriate opportunity, I have asked Tom Black, who in a way took over looking after the code at NMC [and very early put together this wonderful model documentation, still indispensable, Black (1988)], to recollect the events following my one year visit 1984-1985. I'll quote the main body of Tom's reply:

"Here is what I can say about Ron [McPherson] as well as Joe Gerrity in the early days given my less than stellar memory. … I assume that the work you had done with Dennis Deaven

and others with the "dry" version of the Eta (the material for the '88 paper) had sufficiently impressed Ron that he definitely wanted to pursue its development. I don't remember exactly what Ron had to say but I believe that he already knew I was enthusiastic about the model ever since you gave a seminar in 209 on the pressure gradient problem in '85 or '86 so as soon as I finished my postdoc and was hired by NMC, he asked me to look into incorporating the GFDL physics into the model since the lack of physics was the glaring inadequacy at that time. Of course that effort was set aside when Zavisa [Janjic] brought Betts and Mellor-Yamada. As on offshoot of Ron's asking me to do that, I know it wasn't too long after going up to Princeton that I was showing something at a branch meeting about that GFDL code when I kept referring to it as the eta model since I was used to referring to a model by its vertical coordinate (I called the model used for my PhD work at Wisconsin the isentropic model). … I assume everyone else soon started using that name too solely due to its simplicity as opposed to using HIBU or step mountain for the name. Probably not long after that time Joe asked (told) me to write a documentation of the model since no one other than you or Zavisa was at all familiar with it; to me this strongly indicates that he was a supporter too. I know Joe liked all the finite difference equations I put into that documentation; he enjoyed checking them for symmetry and he subsequently volunteered to type up the entire document since we didn't have workstations yet. I got the definite impression he was eager to learn about how the model worked. After that things seemed to just flow naturally as I helped you and Zavisa so I have no other pivotal memories of other contributors before Eugenia announced that the Eta was going to replace the LFM."

Going now on just briefly beyond the earliest NMC times, results shown here obtained using the Eta were made possible only due to efforts of numerous people who have contributed to the design of the model, some by generously providing codes as mentioned in Section 1, and yet others by developing the model's data assimilation

system; and last but definitely not least, kept seeing to it that various systems are maintained. Tom Black and Eric Rogers, overseeing the smooth operation of the system during about a decade and a half addressed, should particularly be mentioned. The beginnings of the EMC precipitation verification system have been put in place by John Ward, the system was then further developed and maintained by Mike Baldwin, and for quite a few years now is developed still more and maintained by Ying Lin. Various scores as well as rms plots shown were obtained using the NCEP forecast verification system maintained by Keith Brill. And last but once again not least, enthusiastic support of Eugenia Kalnay, head of the NMC Development Division in charge of the operational implementation of the Eta in 1993, should be recalled.

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