Chapter 5

Limited Area Modeling: Beginnings, state of the art, outlook

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Abstract

For some time a standard situation in major numerical weather prediction centers is that of the existence of at least two groups, one for global/medium range, and another for limited area, or regional/mesoscale, prediction. Yet, what this limited area, or regional modeling, subdiscipline of NWP actually is, takes some effort in being defined. Major milestones of the emergence of the limited area NWP modeling are reviewed, emphasizing operational implementations.

The variety of approaches favored by various groups today testifies to the vitality of the field. A brief review of options pursued by major centers is made. The approach of the Eta Model is summarized. Several central issues, among them boundary conditions, numerical approach, including the choice of the vertical coordinate, and the choice of resolution vs the domain size, are commented upon. Inferences from the Eta Model results are made regarding the apparent considerable benefit from a relatively large domain size, covering close to one-fifth of the globe; value added skill as a function of time, and the progress made during the last decade.

Overview-type questions are raised, such as what the world of limited area modeling looks like, and will limited area models remain with us or will they eventually disappear? A number of outstanding problems or issues are stressed, and comments on the outlook made. It is suggested that 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, favorable to the Eta, could indicate the advantage of the ARAKAWA approach of the avoidance of computational modes and other physically-based efforts of minimizing errors over that of the Taylor-series based formal accuracy, as long as parameterizations are performed at individual grid points as this is done today.

1 Introduction: What is limited area modeling?

Nowadays, the term limited area modeling would seem to hardly require an explanation; in just about every major atmospheric modeling center there exist at least two groups, one for global and the other for limited area modeling. The name used for the limited area modeling may differ: regional, or mesoscale, are popular names as well, the meaning however is the same. Yet, in spite of the widespread use, some words on what is meant are appropriate. Recall that, in a literal sense, the celebrated very first effort at numerical forecasting, of Lewis Fry RICHARDSON (1922), was one performed over a "limited area". But at the time any attempt at global or even hemispheric modeling was clearly inconceivable, and no need for a term distinguishing between a larger domain modeling and one aiming at doing better over a chosen smaller area existed.

It was only once NWP had started its rapid ascent, at the end of the sixties and in the early seventies, that the idea of benefiting from larger area forecasts to obtain smaller area, higher quality forecasts, using lateral boundary conditions derived from the larger-area model became established. For this to become realized, the problem of the definition of the lateral boundary conditions had to be addressed. This was done quite early by the eminent, and, strangely, somewhat unrecognized work of CHARNEY (1962). CHARNEY analyzed solutions in terms of characteristics of the shallow-water equations and pointed out that, in the one-dimensional case, at least two conditions had to be specified at inflow points and one condition at outflow. He has also demonstrated the adverse effects of the overspecification of boundary conditions. Perhaps not surprisingly, CHARNEY had difficulties with a baroclinic case.

A very visible and early limited area effort of BUSHBY and TIMPSON (1967) saw the advent of smaller area, "fine-mesh" integrations as a dawn of a new era of forecasting actual weather, and specifically the "frontal rain". "One of the first attempts to predict weather, as distinct from pressure patterns and vertical velocity", writes BUSHBY on their thrust in his later review paper (1987). Interestingly, the technical problems of the boundary conditions were looked at by BUSHBY and TIMPSON more like a nuisance rather than as a problem they intended to deal with: "one is not so much trying to represent actual events at the boundary, but rather to prevent rapid amplification of spurious fast-moving waves near the boundary", they write.

But the obvious need to take advantage of forecast boundary conditions if any actual forecasting is to be done, left no room for the neglect of the boundary issues at hand. Thus, by the early seventies, one finds quite a few papers devoted to or at least partially dealing with the subject. For an extensive list of references of the time see, e.g., CHEN and MIYAKODA (1974). The question of whether the smaller area model should only be influenced by the larger area one, or whether it should also affect it, was one of considerable concern at the time; thus, "one-way" and "two-way" methods, respectively, came into being (e.g., PHILLIPS and SHUKLA, 1973). While many of these early efforts were in terms of the boundary conditions of a rather pragmatic nature, being aimed instead at simulation of tropical cyclones, in yet others theoretical understanding of the problem has been advanced (e.g., ELVIUS and SUNDSTRÖM, 1973; OLIGER and SUNDSTRÖM, 1978). The latter however led to somewhat of a lingering discomfort as it raised the issue of the well-posedness of the lateral boundary condition in hydrostatic primitive equations systems; specifically, in arriving at the result that "local pointwise boundary conditions cannot yield a well-posed problem for the hydrostatic equations". For an extensive review, see MCDONALD (1997).

But well prior to the appearance of these concerns, the enthusiasm over the dawn of the Global Atmospheric Research Programme (GARP) was a powerful incentive for vigorous efforts in limited area modeling as well; and reports of success in various experiments run using time-dependent boundary conditions started to appear. Thus, in the very first GARP "progress report" on numerical experimentation – reports nowadays widely known as "blue books" and at the time as yet unnumbered but dated

November 1972 – among 46 contributions one finds 7 devoted completely or partially to nested model integrations using time-dependent boundary conditions; with results being described all the way from “acceptable”, “reasonable”, “assez sensible” to that of “a marked improvement of the fine mesh forecasts”. Several of these report on efforts aimed at implementation of operational limited-area models run using forecast boundary conditions, our focus at this point.

2 Operational limited area forecasting: The beginnings

While various milestones of the implementation of operational NWP have been recorded in numerous papers including some of the contributions to this book, those referring specifically to limited area operational forecasting, curiously, left few if any marks in published papers. I have mounted considerable efforts to try to pinpoint the chronology of early operational limited area forecasting with a success less than I had hoped for.

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 be the first time that a nested model was “driven” by boundary conditions of another model; a standard practice of course today.

Yet another place of very early introduction of forecast boundary conditions for a limited area model is the then Météorologie Nationale, with November 1974 on record as the implementation time (ROUSSEAU, 1975). The effort led by ROUSSEAU emphasized high resolution with later even a three-tier coupling, numerical problems of topography, and precipitation verification. For the high resolution emphasis, continued later into the PÉRIDOT model time (e.g., ROUSSEAU et al., 1995) small domains of nested models were of course the price that had to be paid; a price considerably higher than it was understood at the time and it would seem generally also today; a topic to which I will return later.

Of course, in each of these places, the actual implementations typically followed years of developments and testing and had their own rich histories (note, e.g., the already referred to account of the various events in France regarding fine-mesh modeling, by ROUSSEAU et al., 1995). Moreover, then just as now, a formal implementation did not necessarily lead to a situation of peaceful enjoyment of the fruits of past labor; code errors and unforeseen problems were just as abundant as they are today. Thus, at the Meteorological Office, a serious error in the Assembler language coding of the boundary conditions scheme persisted through 1976 (F. HAYES, M. ATKINS, personal communications); and at NMC, implementation of the time-varying boundary condition had only aggravated what was referred to as the "pillow" problem, necessitating an ad-hoc remedy ("desloshing") to be developed for output purposes (NWS, 1973).

A timely WMO/IAMAP symposium held in Reading in May 1973 provides a telling glimpse at the limited area/fine mesh enthusiasm of the time by both its title "Dynamics of meso-scale systems and fine-mesh modelling" and its program, with 8 of the 35 lectures addressing "nesting and boundary problems". In its "symposium digest" WMO Commission for Atmospheric Science's Working Group on NWP writes: "It is clear that the nesting method is now being seriously studied by a large number of people. The wide acceptance of this approach in a relatively short time and the fact that nested models are already being used routinely at some forecasting centres ... shows that the anxiety expressed when nested grid methods were first proposed has now been replaced by cautious optimism."

Still, at remaining major NWP centers, a different emphasis was in place during the early and the mid-seventies – which in some of them included designs of movable mesh typhoon (Japan Meteorological Agency) and tropical cyclone models (the then U.S. Fleet Numerical Weather Central) – or the emphasis shifted to other efforts: the early work of ASSELIN (1972) at the Canadian Atmospheric Environment Service did not end in a model implementation, a pioneering effort at implementing a global spectral model taking precedence instead. Thus, at these and other major NWP centers, the implementation of limited area NWP models occurred some years later, for example, at the Deutscher Wetterdienst in November 1981.

With widening access in the mid-seventies to at least marginally adequate computer resources, the multifaceted rewards of limited area modeling – in particular for centers not engaged in hemispheric or global operational activities – became more appreciated and within reach of an ever increasing number of groups. Even if one might not be confident of achieving resolution higher than that used by major centers, a more successful design, in particular regarding aspects or special regional significance, could be expected to lead to better forecasts some of the time and hopefully when it really mattered; real-time access to in-house NWP data offered numerous application prospects superior to those if only access to an outside center were to be relied upon; and last but certainly not least, availability of an in-house NWP-type model had obvious appeal as a research and educational tool. As a result, more and more groups embarked on research and subsequently operational limited area modeling work, including centers in countries with very modest computing resources. For example, operational running of a primitive equation model using boundary conditions forecast by an outside center started in Yugoslavia in January 1978, following of course research and development work initiated some years earlier (MESINGER, 1973; MESINGER and JANJIĆ, 1974). For the then HIBU (Hydrometeorological Institute and Belgrade University) model, boundary conditions were manually prepared off the forecast Deutscher Wetterdienst charts. This may have been the first time forecast boundary conditions were taken from a model run by a different center, a widespread practice today.

3 Approaches used

With its 30-year history, limited area – or mesoscale – modeling is almost the same age as the modern-era primitive equations NWP. The progress has been steady and the number of models, and also model users, has been constantly increasing. Thus, an impressive number of models has been designed, with many of them downloadable on the Web with few if any conditions for their use. For example, the manuscript of the second edition of Roger PIELKE's textbook (PIELKE, 2001) at the time of this writing contains an appendix with detailed information about 10 mesoscale models, and references for 15 models more. Table 1 in DOYLE et al. (2000) lists 11 models, with perhaps four of them not having been included among the preceding 15. While not all of these models can be considered to be fully-developed NWP LAMs and have probably not been intended to be, there are still others which certainly are, and have failed to be included (e.g., ALADIN, BUBNOVA et al., 1995; and GEM, C ÔTÉ et al., 1998).

The diversity of models in terms of their numerical design I find fascinating, and a testimony to the vigor of the field. It is perhaps the numerical design that is generally considered to characterize the approach taken, given that the "physics" of mesoscale models tends not to differ as much from that of the global models as the numerical design does; or that it can even to a large extent contain options for the user to choose from.

In trying to summarize the variety of approaches taken, the method that traditionally had been used – the division into the finite-difference, finite-element, and spectral models – is today hardly adequate. Namely, most limited area models are finite-difference, but they still differ substantially in priorities set forth in their formulations; and there are approaches which are best summarized using none of the three classes listed. Thus, I will only briefly describe a number of approaches, concentrating on those that appear to be the most diverging ones, in order to illustrate the widely opposing views held and hopefully stimulate further consideration of the issues thereby raised.

The Eta model uses the ARAKAWA approach. While the maintenance of the difference analogs of chosen integral constraints of the continuous atmosphere is the best known feature of the approach, emphasis was placed by ARAKAWA, and by others, on reproducing numerous other properties of physical importance of the fluid dynamical system addressed. Avoidance of computational modes, dispersion and phase speed properties, and avoidance of false instabilities are typical examples; see, e.g., ARAKAWA (1997) and references therein, and MESINGER (2000b). Given the variety of objectives listed, there is clearly a lot of room for an adherent of the approach to exercise his or her judgment in choosing which ones to give the most weight. Since the Eta model results will be used to make a variety of points later on, a more detailed description of the Eta will be included in the subsequent section.

An essential characteristic of the ARAKAWA approach is a determination to understand the reason of any numerical noise encountered, and make an effort to remedy the cause of the problem as opposed to using artificial diffusion or filtering of small scales to remove its consequences. Moreover, a high emphasis is placed on choosing schemes with no damping characteristics, or at least as small a number of schemes with some damping and then as small an intensity of damping as found possible. This to me appears highly appealing given that at present forcing by physical parameterizations is done at single grid points, and that damping and/or filtering at small scales could well be expected to remove a significant fraction of the effect, which we have worked so hard to create and presumably have good reasons for having done so.

Striving to achieve goals of the outlined type, increasing the order of accuracy of the schemes used tends not to help (e.g., ARAKAWA, 1997). Thus, the Eta schemes, for example, those for which the Taylor series based definition of accuracy is applicable, are never of an order of accuracy higher than the second. Increasing the resolution, which for consistent schemes also increases the formal accuracy, may not help either. Note the examples of errors of two well-known pressure gradient force schemes in MESINGER (1982), reproduced, with an error corrected, in MESINGER and JANJIĆ (1985, Table 1): increasing the vertical resolution had no effect on the error in one case, and was leading to an increase of the error in another.

Choosing a right emphasis, assuming there is one, of course does not necessarily guarantee success; one can make wrong decisions in attempting to achieve the right goal. That aside, there is certainly no lack of finite-difference mesoscale models with radically different emphases. Thus, presenting efforts on the HIRLAM model, GUSTAFSSON and MCDONALD (1996) write 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. ... 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. ... it was found that a filter that damps only the two grid waves was not sufficient to bring the noise under control ..."

As to the computational modes/accuracy, looking at the information on 10 models that as stated are described in some detail in the manuscript of PIELKE (2001), one does get a strong impression that at least as far as the choice of the horizontal grid is concerned there is a definite movement toward grids that avoid, or largely avoid, the spatial computational mode problem. Of the eight models that did give information on the horizontal grid chosen, five use the C grid, and two the B/E grid. But relatively recent decisions in favor of the nonstaggered grid, and of high formal accuracy, can be found too. For example, PURI et al. (1997), summarizing the new Bureau of Meteorology Research Centre's (BAMS) LAM state: "model equations are formulated on a latitude-longitude ARAKAWA A-grid ... The lack of accuracy associated with the A-grid is regained by using higher order differencing (simpler to implement on the A-grid), and the mode-splitting is overcome by incorporating corrective terms."

This is just one possible cross-section of the extraordinary diversity of the approaches used. For a full measure of diversity regarding the choice of the horizontal grid, the unstructured grid of the OMEGA model may be mentioned. In a triangular grid, grid points are added or removed (!) to achieve the resolution deemed appropriate (BACON et al., 2000). Carrying movable nested grids (e.g., KURIHARA et al., 1998) is another method of achieving higher resolution in regions where it is considered needed. Semi-Lagrangian models can be added as yet another class, as opposed to Eulerian models referred to so far; for pros and cons, see STANIFORTH (this volume), and MESINGER (1997). A regional spectral model was introduced in Japan in 1988, TATSUMI (1987); a different version of the approach had or has a prominent place in the HIRLAM community (GUSTAFSSON and MCDONALD, 1996). Yet another member of the limited area spectral family is the ALADIN model (BUBNOVA et al., 1995). A perturbation regional spectral model has been introduced by JUANG (1992), and has led to a number of versions and is seeing widespread use (e.g., JUANG et al., 1997). Should variable resolution models be included here? It would seem not if they are intrinsically global models such as the ARPEGE (e.g., BUBNOVA et al., 1995) and have their own regional system; but a qualified yes if they are conceived, when applied to a region, as an alternative to driving a limited area model with another model's boundary conditions (the so-called Global Environmental Multiscale, GEM, model, CÔTÉ et al., 1998).

For a quite different point of view, the system of equations used can be listed. With continued increases in computing power and consequently also resolutions, nonhydrostatic formulations are of course increasingly chosen and/or considered necessary. A listing of approaches to that end would involve not only the issues raised so far, but also new ones, as typically approximations are made in choosing formulations more general than that of the standard primitive equations. Options are numerous; for some of them, see, e.g., the review of MESINGER (1997), JANJIĆ et al., (2001), and the appendix of PIELKE (2001).

4 The Eta model and some results

I will summarize here the Eta model as an example of the state of the art LAM; and also to introduce presentation of a number of results relevant to limited area modeling. The Eta history goes back to the effort already referred to, started at the University of Belgrade in the early seventies (e.g., MESINGER and JANJIĆ 1974); with many subsequent milestones, e.g., MESINGER et al. (1988), BLACK and JANJIĆ (1988), JANJIĆ (1990), and, during the nineties, too numerous to list here.

It is the model numerical formulation, or dynamics, that is the main focus here; as stated, in its dynamics the Eta is using the ARAKAWA approach. The Eta dynamics features that I find deserve the most mention are the following:

- The step-mountain ("eta") vertical coordinate (MESINGER, 1984; sea also MESINGER et al., 1988);
- The JANJIĆ (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;
- Gravity-wave coupling scheme of MESINGER (1973, 1974), used in a two-time level, split-explicit framework;
- Energy conservation in transformations between the kinetic and the potential energy in space differencing (MESINGER, 1984; MESINGER et al., 1988);
- Lateral boundary conditions prescribed or extrapolated along a single outer boundary line, 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.

All of these features are aimed at avoiding or reducing some kind of a physical (as opposed to a mathematical) error (e.g., the eta coordinate), and/or at avoiding various computational modes. A comprehensive "physics package" is in place, with turbulence kinetic energy (MELLOR and YAMADA, 1982) and cloud water/ice (e.g., ZHAO et al., 1997) as additional physics prognostic variables. In recent years at NCEP increasingly comprehensive land-surface parameterizations have been included (e.g., CHEN and MITCHELL, 1999). For more information on these and other model components, see, e.g., JANJIĆ (1994), and MESINGER (2000b). The Eta data assimilation system at NCEP has its own history, with the most recent information on the current 3D-Var system available in ROGERS et al. (2000).

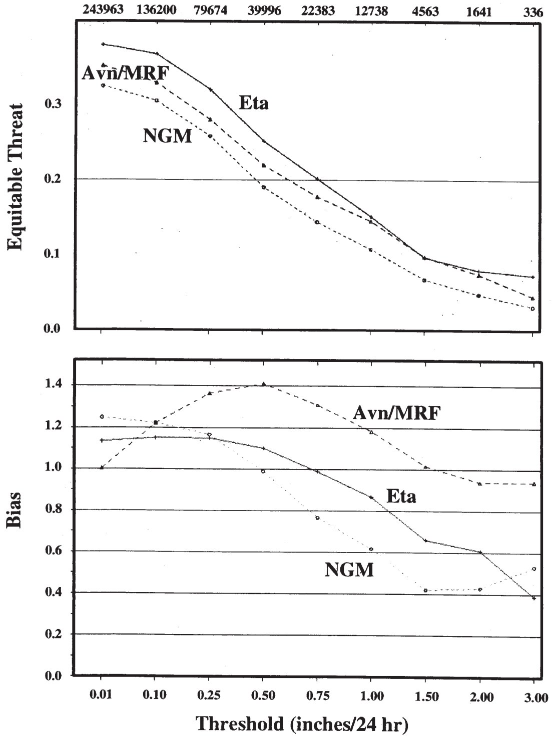


Figure 1: Equitable precipitation threat scores (top panel) and bias sores (bottom panel) for 1999, for the Eta model, the Aviation/MRF Model (Avn/MRF) and the NGM. The equitable threat score is equal to (H-E)/(F+O-H-E), where H is the number of "hits", E=FO/N is the number of hits in a random forecast, F is the number of forecast points, O is the number of "observed" points, and N is the total number of points verified. The bias score is equal to F/O. The numbers below the abscissa of the lower plot show the precipitation thresholds, in inches/24 h, which are verified. The numbers above the upper plot show the total number of the 80-km verification boxes which were "observed". Scores are for a sample containing three verification periods, 0–24, 12–36, and 24–48 h, of all the forecasts that were recorded by the system for each of the three models.

As surely is also the case with other models, the history of the Eta illustrates much of the perhaps unique nature of the world of atmospheric modeling; moreover, some of its results offer insight into a number of basic questions of the limited area approach. Namely, with so many options followed as enumerated in the preceding section, there clearly is no consensus which is the right way to go. How then do the models come to the center stage and supersede other models? Does this having taken place lead to a generally accepted opinion as to the attractiveness or even a superiority of an approach? Focusing on results and specifically on the limited area approach, what is the benefit, or value added, of running an operational LAM? Several points of this nature were discussed in MESINGER (2000b); I will here revisit two of the issues just addressed, and will return to additional ones in later sections. Results more recent than in MESINGER (2000b) will be given if available.

In its early period at the then NMC, in the late eighties, the Eta has achieved considerable prestige by two of its results, or features of its results. One was its average geopotential height error, or cold bias: with the same radiation package as that of the then recently implemented Nested Grid Model (NGM), and about the same resolution, the Eta had overall a much smaller cold bias than the NGM (BLACK and JANJIĆ, 1988, Fig. 6; or BLACK, 1988). For a sample of 13 48-h forecasts, the Eta cold bias was increasing until about half a day at a rate similar to that of the NGM, but then it stopped growing, while that of the NGM continued to grow. When switched to run using sigma coordinate, the Eta cold bias also constantly kept growing, albeit at a rate smaller than that of the NGM.

At the time this seemed impressive in view of the high-visibility of the NGM's cold bias problem, attracting so much attention so that eventually a "fix" was put in place to keep the zonally averaged temperatures constant. No connection was obvious to the earliest eta/sigma experiment demonstrating noise when the model was switched from eta to sigma (MESINGER et al., 1988, Fig. 6; the experiment was performed in 1984 though). It was only recently that the connection of the two became apparent as a result of JOHNSON's (1997) analysis of the "general coldness of climate models", strongly suggesting "aphysical entropy sources", for the most part numerical errors, to be the root cause of the problem (see also EGGER, 1999; JOHNSON, 2000).

The second feature of the early Eta results referred to above, of the late eighties, was significantly more mesoscale detail in forecasting lows with multiple centers (BLACK, 1988), achieved with just about the same horizontal as well as vertical resolution, and use of computer resources.

Hopes that in relative terms the NGM's results will significantly improve with its accuracy increased to fourth order (JUANG and HOKE, 1992) have proven disappointing. Implementation of a three-model precipitation verification system, including the Eta, the NGM, and the global spectral model (Aviation, "Avn", or Medium Range Forecast model, "MRF"), in 1993, has revealed a clear advantage of the Eta over the NGM (e.g., MESINGER, 2000b, Fig. 7). Consequently, no efforts to further improve the NGM or its analysis system have been made since August 1991 (DIMEGO et al., 1992).

I have argued (MESINGER, 2000b) that this strongly suggests an advantage of the Eta ARAKAWA approach over that of the NGM, of high formal accuracy and periodic application of a fourth-order filter (JUANG and HOKE, 1992); at least as long as the model "physics" is done at individual grid points as it is done today. Note that Taylor expansion essentially expects fields to be smooth. There are other reports of little if any benefit from fourth-order schemes: CULLEN et al. (1997) state that "the sensitivity of the complete model to the choice between second and fourth order schemes ... has been slight". Yet, the high-order approach seems not to have lost much of its appeal (e.g., as referred to already, PURI et al., 1997; also PURI et al., 1998; as well as item (3) at http://wrf-model.org/WG1/wg1_main.html).

A less controversial conclusion from the three-model scores is that of the benefit of the Eta over its driver Avn/MRF model. Over the years, the Eta has consistently had higher scores across all of the precipitation categories than the Avn/MRF, in spite of using the lateral boundary condition of the Avn's previous, until recently 12-h "old" run, and having a shorter data cutoff time. The scores for the year prior to this writing, 1999, are shown in Fig. 1.

Needless to say, the advantage of the Eta over the Avn/MRF model demonstrates the value-added achieved by the limited area approach, in a statistical sense, for the region and models addressed. Surely, for various events and also a variety of models, many other specific benefits have been demonstrated; what I find as the special appeal of plots such as that of Fig. 1 is that precipitation threat scores for the most part illustrate the model skill in placing precipitation systems, a skill which is more of a large scale than of a mesoscale nature. I will return to this point later.

A serious challenge to the mesoscale center stage of the Eta at NMC has been mounted at the mid-nineties by the so-called Regional Spectral Model (RSM) mentioned earlier (JUANG, 1992; JUANG et al., 1997). According to NMC's modeling plans for “Mesoscale ETA” of 1993, as put together by all of the then NMC’s Development Division managers (KALNAY et al., 1993) – the very same year the Eta was officially implemented – in only three-years time, in October 1996 “A comparison with Regional Spectral Model (RSM) will determine possible replacement by RSM”.

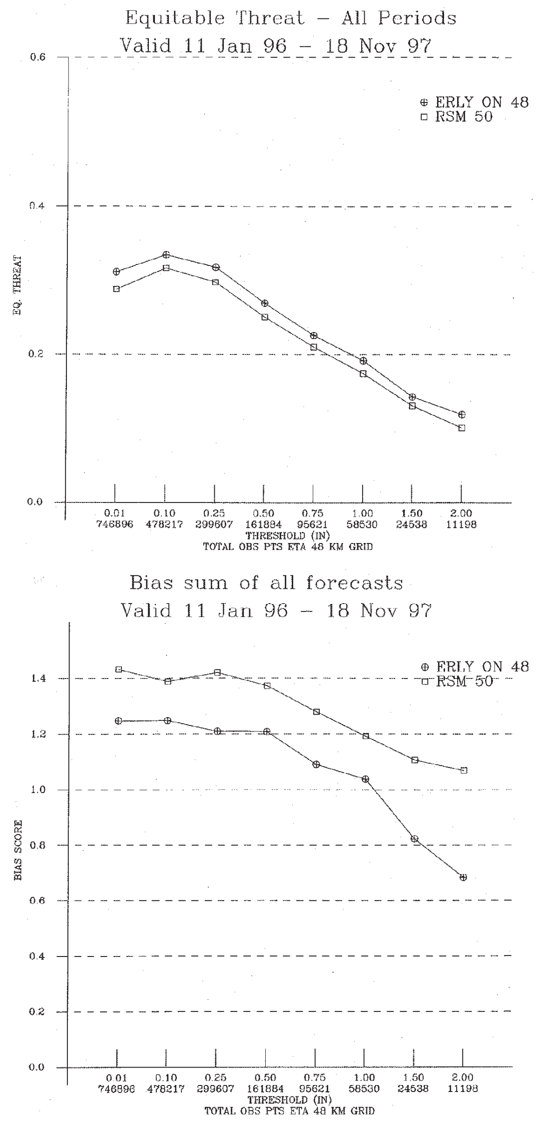


Figure 2: The Eta (“ERLY”) vs RSM precipitation threat (top panel) and bias scores (bottom panel), for 1996–1997. The upper row of numbers along the two abscissas shows the precipitation thresholds, in inches/24 h and greater, which are verified. Scores are shown for a sample containing three verification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

Indeed, when both models 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). Subsequently, the RSM 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 small role as well. And, needless to say, in all of those, events that happen by chance, serendipity (?), have a hand too. The problem is of course that clean tests which would compare the success of various approaches are practically impossible. Thus, it is a combination of the results of various experiences and tests, partly the shear volume of tests, and largely an opinion arrived at in a variety of ways as listed, that makes the field move in various directions as it does.

5 Choice of the vertical coordinate

The choice of the vertical coordinate is a model feature which vividly illustrates the situation just outlined. Quite a few options have been advocated and are in use.

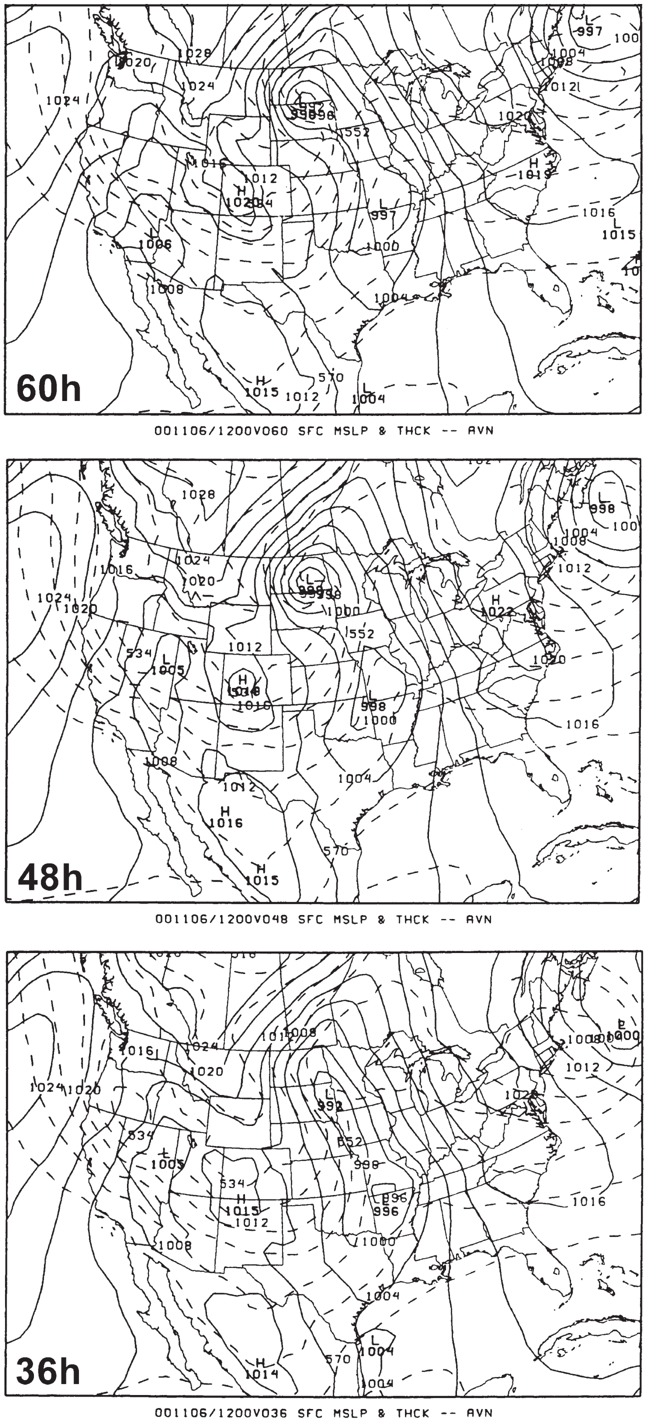
The discovery of the "sigma", terrain-following, system by Norman PHILLIPS (1957) had made the problem of the representation of topography in numerical models seem solved. Numerical modelers did not have to struggle with the unwieldy situation of the pressure system representation any more! Yet, at the end of the sixties, it became increasingly recognized that the situation with the sigma system was not without difficulties either. Perhaps starting with the vertical interpolation of geopotential from sigma back to constant pressure surfaces of SMAGORINSKY et al. (1967), one after another methods were being proposed to deal with the pressure gradient force problem. The review of MESINGER and JANJIĆ (1985) lists at least five distinct methods of arriving at presumably an acceptable situation. Clearly, when informed – which was not always the case – inventors of new methods were not convinced that the preceding methods had removed the problem.

Having recognized the existence of a convergence problem as pointed out in section 3, it had seemed to me that the best prospects were offered by abandoning the terrain following coordinates in favor of the eta system with quasi-horizontal coordinate surfaces. Two very encouraging early eta vs sigma tests were already discussed in the preceding section. More have followed: in two samples, the Eta model run using the eta had achieved significantly higher precipitation scores than when it was run using the sigma coordinate. Perhaps still more convincingly, two well recognized mountain-related modeling problems, too slow southward movement of cold surges in the lee of the Rockies, and placing of the lows as they form in the lee of the Rockies well to the north of their observed positions, were absent or just about absent in the Eta. Yet, when the Eta was switched to sigma, these problems reappeared on the Eta! (MESINGER and BLACK, 1992; MESINGER et al., 1997).

Nevertheless, little if any conversion from the terrain following coordinates to the eta took place; and benefits of other choices have been pointed out and used. In particular, the merits of isentropic coordinates – with usually some approach to sigma near the surface – have long been recognized and advocated by numerous modelers (e.g., BLACK and BENJAMIN, 1993; and in particular the very recent in-depth reviews by ARAKAWA, 2000, and GALL and SHAPIRO, 2000, and references therein).

But as to the eta vs sigma issue, difficulties the quasi-operational 10-km Eta has had with a Wasatch Range downslope windstorm (MCDONALD et al., 1998), in comparison with the so-called MM5 sigma system model (e.g., DUDHIA, 1993) have been noted, and have received considerable attention (e.g., JANJIĆ et al., 2001). In idealized tests of flow over a small-scale bell mountain of GALLUS and KLEMP (2000), once again, the eta was apparently at a visible disadvantage compared to sigma.

There are reasons (MESINGER, 2000a) to expect that the eta can be refined so as not to suffer from the disadvantages listed, including generalizations to partial steps or "shaved cells" of ADCROFT et al. (1997). However, is that necessary – will the sigma perform just as well as the eta for larger-scale topographic phenomena mentioned above, once the resolution is high enough? Perhaps most modelers believe it will.

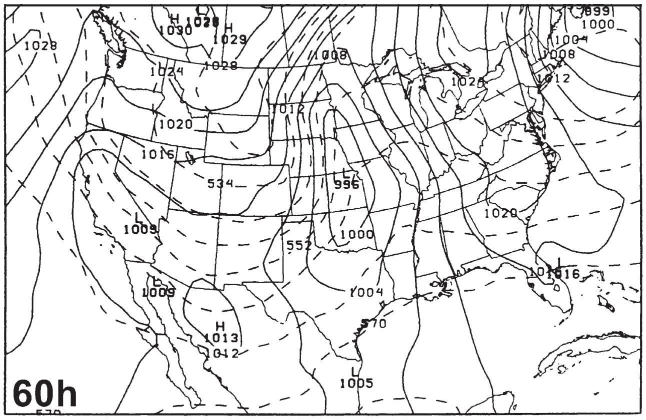


001106/1200V060 SFC MSLP & THCK -- AVN

001106/1200V048 SFC MSLP & THCK -- AVN

001106/1200V036 SFC MSLP & THCK -- AVN

Figure 3a : Sections of the 60-h (top panel), 48-h (middle panel), and 36-h (bottom panel) sea level pressure and 1000-500-mb thickness forecasts by the Avn; verifying at 1200 UTC 6 November 2000. Isobars (solid) are marked in millibars, and thickness lines (dashed) in decameters.



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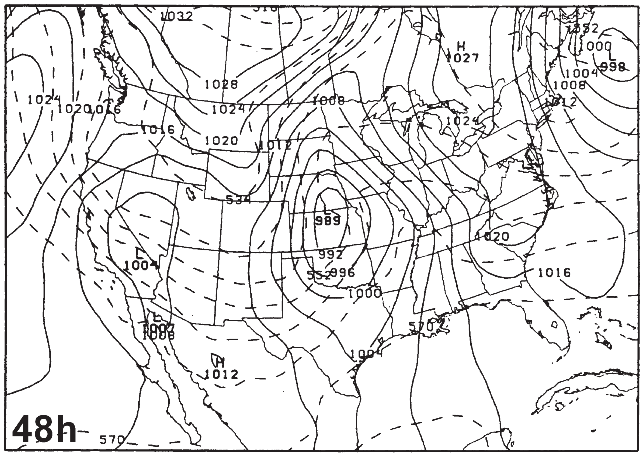

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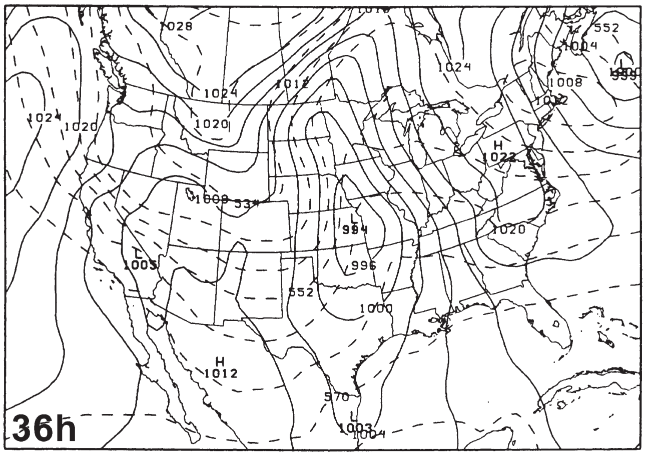

001106/1200V036 SFC MSLP & THCK -- ETA

Figure 3b: As in Figure 3a, but for the Eta model forecast.

However, this does remain to be seen.

I will conclude this section by showing forecasts for one case of a low in the lee of the Rockies that illustrates the issue. In Fig. 3a and b sea level pressure and 1000–500 mb thickness forecasts are shown, by the Avn model (a) and by the Eta model (b), all verifying at 1200 UTC 6 November 2000. The top panels show 60 h, the central panels 48 h, and the bottom panels 36 h forecasts, respectively. These are the operational NCEP forecasts of the time.

Note that both the NCEP global model and the Eta have increased their resolutions in 2000, the Avn/MRF model in January from T126L28 (estimated corresponding to about 105 km; 28 layers) to T170L42, estimated at about 75 km. The operational Eta resolution as of the end of September 2000 is 22 km/50 layers. One may wonder, with increased resolution of the global model, are there signs of improvement in its skill in placing lows in the lee of the Rockies? Recall that in a statistical study of MESINGER et al. (1996) that included 15 cases of lee lows with central pressures of 1000 mb or less, at 48 h the Avn had placed all 15 north of their analyzed positions, with errors ranging from 50 km to as much as, in two cases, 500 km.

Considerable difference is seen in the two top panels between the forecasts of the two models, with the Avn placing a deep low over the Dakotas, with central pressure of 990 mb; and a secondary low over the Missouri-Arkansas border. The Eta is forecasting one low, centered over the northeastern Kansas, and not nearly as deep. The forecasts are essentially the same 48-h ahead, central panels, except that the Eta low is deeper. Even at 36 h, the bottom panels, the Avn still insists on having the main low over the Dakotas, albeit it is not having that northern low as deep any more.

The NCEP verifying analysis is shown in Fig 3c. Not going into the subtleties of hand-placed Ls, a single low is seen, very much as forecast by the Eta in the three

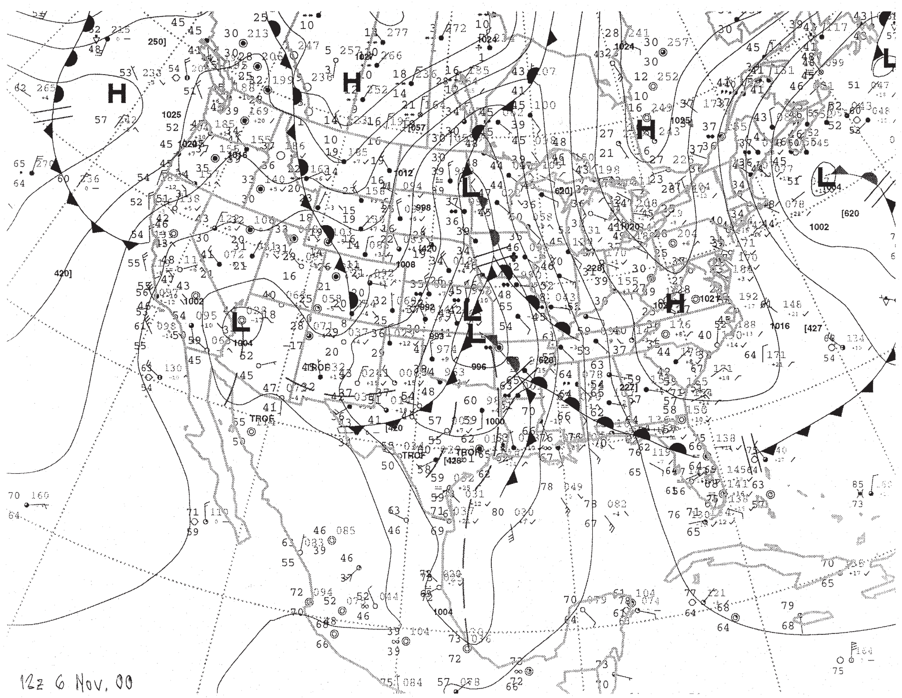

Figure 3c : A section of the NCEP's surface analysis, valid at 1200 UTC 6 November 2000.

panels of Fig. 3b. The case shown certainly offers no indication of an improvement in the NCEP's global, sigma system, model's tendency to forecast the Rockies lee lows too far to the north and have them too deep.

6 Lateral boundary conditions, and limited area vs variable resolution approach

The issue of the lateral boundary conditions is clearly central to the limited area modeling approach, and, as summarized in the introductory section, was understandably much in focus at the time of the emergence of the early LAMs. While overall a very large number of schemes have been proposed and at times also used, eventually a "flow relaxation" scheme of DAVIES (1976) became almost universally used. The scheme overspecifies, that is, prescribes the values of all fields at the boundary, but then relaxes the interior fields toward those of the driver model in a zone close to the boundary. The zone can be up to 8 lines wide, and a large number of efforts was made aimed at finding an optimum profile of the relaxation coefficient, analyses of attendant problems, and the like; see, e.g., the already cited review of MCDONALD (1997).

Why this has happened is not entirely clear and is I find unfortunate. While the scheme does have an attractive feature ("no changes are made to the limited area model solution when its field is in agreement with the field of the host model", MCDONALD, 1997) the scheme clearly has somewhat of a brute force character given that all variables are prescribed at the outflow points which is in conflict with the basic understanding of the problem, arrived at as early as in CHARNEY (1962). Perhaps the widespread use of the B grid, with the mass and velocity fields carried at lateral boundaries that are half a grid distance away from each other, had contributed to this trend.

Be that as it may, the existence of the relaxation zone, and other difficulties or unattractive features of the flow relaxation scheme, may have repeatedly led to not too complimentary statements as to the lateral boundary situation of the limited area models. Thus, CÔTÉ et al. (1998) cite as many as ten papers stating that they "all indicate that lateral boundary condition error can, depending upon the meteorological situation, importantly contribute to the total error." This assessment seems to have played a crucial role in their favoring a global variable resolution as opposed to a limited-area strategy. FOX-RABINOVITZ et al. (2000), also advocating a variable resolution approach, claim that "noise damping" is "required in nested-grid models to control severe computational noise arising from the application of lateral boundary conditions." The title of WARNER et al. (1997) "A tutorial on lateral boundary conditions *as a basic and potentially serious limitation to regional numerical weather prediction*" (emphasis mine) certainly does not help dispel the idea that the problem indeed may be quite grave and not amenable to an acceptable treatment.

For what I feel will be a better balance, I wish to call attention to results of the experiments of BLACK et al. (1999), showing the situation in a more positive light. The experiments have been done using the Eta model scheme, one of the two that in MCDONALD's (1997) terminology were categorized as "fairly well-posed" schemes. In the scheme (MESINGER, 1977), at the inflow points all prognostic variables are prescribed on the single outermost line of grid points. At outflow points all prognostic variables are prescribed except the velocities tangential to the boundary. They are extrapolated from the interior of the domain. This is one of the boundary formulations suggested by SUNDSTRÖM (1973). On the model's E grid, at the second outermost line of points variables are four-point averaged, thus being an average of the prescribed or extrapolated values on the outermost line, and values on the third outermost line of points, which are predicted. Note that this averaging couples the external gravity waves on two C-subgrids of the E grid, thus preventing generation of boundary noise via the lattice-separation mechanism. For simplicity of the extrapolation, as well as of the averaging, at present no mountains are permitted in the two outermost lines of points. A four-point quasi-Lagrangian (or, upstream) horizontal advection scheme is used for the points on the third, fourth and fifth outermost lines of points.

The experiments mentioned were aimed at looking into the feasibility of "parallel" runs on a domain smaller than the operational domain. Could a section of the forecast over the complete domain be reproduced without being significantly affected by the reduction in the domain size? To answer that question, two experiments were done testing the impact of the Eta boundary scheme. Operational runs on the "full" domain of the 32-km Eta of the time were used to supply boundary conditions for forecasts over a nested subdomain defined on the same grid and centered at the same point, but of the size of only about 36% of the full domain. The same model code was used. Control run values along the nested domain boundary were saved at one hour intervals and interpolated in time to define the boundary conditions. The "errors" of the test runs thus consisted of those due to the boundary scheme, and those due to the time interpolation.

48-h sea level pressure forecasts of one of the parallel integrations, for the case in which greater differences were noticed, are shown in Fig. 4. The control forecast is shown in the top panel, and the test forecast is shown in the bottom panel. Artifacts apparently due to the removal of mountains along the two boundary rows are seen over the Mexican and over the Greenland sections of the "mini" domain boundary. Additional spurious features appear in the form of kinks in the isobars next to the boundary at places, in particular near the southwestern corner of the reduced domain. Inside the reduced domain only minor differences are seen, the greatest perhaps being the depth of the low center at the Minnesota-Wisconsin boundary.

From the point of view of the boundary scheme errors, I find the small impact of the boundary scheme noteworthy. Specifically, no reduction in amplitude of the sea level pressure field in the nested integration is apparent; if anything, the amplitude could be declared a little greater in the nested run shown. Note that in view of the three rows of points having used the upstream horizontal advection, a reduction in the amplitude could have been anticipated. The damping feature of the upstream advection next to the boundary it would appear has had little impact because of the continuous updating of the inflow boundary values.

I see these experiments as largely a demonstration that well-behaved treatment of the lateral boundary condition is possible, even without the penalties of the relaxation zone and extra diffusion next to the boundary. Note, by the way, that the scheme, or one similar to the scheme described, is applicable also in case of the B grid, if the domain boundary is chosen so that it runs along both mass and velocity points. The simplest such choice obviously is a square domain with its diagonals oriented in the zonal and in the meridional direction.

As to the warning of the WARNER et al. title, indeed, there is a lateral boundary conditions limitation to regional numerical weather prediction. But I find that a more fortunate formulation would have been one stating that "near inflow boundaries, a limited area model cannot do better – it can only do worse – than its driver model." Recall that the purpose of a limited area model is to do better than its driver model. To do that, it not only needs higher resolution and perhaps also other additional information, it also needs space. It can develop its hopefully more accurate flow features only at some distance inside the lateral boundary.

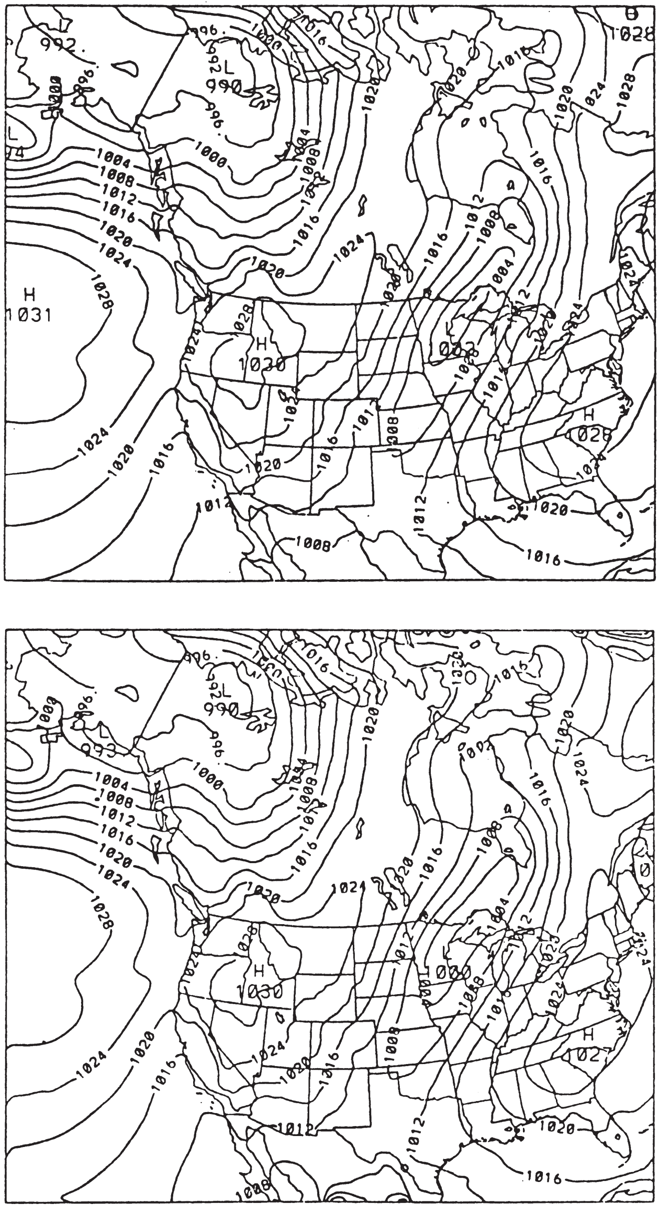

Figure 4: A section of the then operational 32-km Eta 48-h sea level pressure forecast, valid at 1200 UTC 17 October 1998, top panel; same except for a run over a smaller domain, done using the operational forecast to supply its boundary conditions, bottom panel. Boundaries of the plots shown are the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

Regarding the choice between the driven limited area vs the global variable resolution approach, some of the relevant points are of a management character – such as in an NWP environment the availability of a in-house global run, and scheduling of runs. Beyond that, I find that it is just about exclusively the accuracy of the lateral boundary data, or that of the forecast at an "equivalent" boundary of a variable resolution model, which will decide which one will do better. I will not be surprised, as I assume most readers as well, if both approaches stay with us for a while.

7 Resolution vs domain size, and homogeneous resolution vs adaptive grids/multiple nesting

That increased forecast accuracy ought to come with increased resolution is entirely logical to expect. Topography is better resolved, various motion scales are better resolved, and so on. There are of course problems as one is entering new territory; but presumably, the sooner we face these problems the better. There are also quite spectacular examples of actual benefits from increased resolution. For example, an Eta-10 excellent forecast of huge rains over southern California coastal ranges (MARTIN, 1998, at http://www.wrh.noaa.gov/wrhq/98TAs/9836/index.html) has become known beyond the NWP field (WU, 1999). Additional examples showing impressive results obtained using the ARPS model run at 6 km, the MM5 model run at 3 km, and the COAMPS model run at 5 km have been shown by GALL and SHAPIRO (2000).

The benefits of a larger domain size are less appreciated and perhaps even controversial. An Eta effort set up in October 1995 to take advantage in fact of a possibility to increase resolution for a reduced domain of interest, has unintentionally offered evidence regarding the impact of the domain size. For more than two years, the Eta was run twice a day at two resolutions, under the names of "early Eta", and "meso Eta". The meso, or 29-km Eta, differed from the early Eta as follows.

- 29 km/50 layers resolution, vs 48 km/38 layers of the early Eta;
- 3:25 h data cutoff and use of this late cutoff for initializations at 0300 and 1500 UTC, vs the only 1:15 h cutoff of the early Eta;
- "Current" vs 12-h old Avn lateral boundary conditions;
- A 3-h "mini" data assimilation vs the 12-h assimilation of the early Eta; and
- Smaller domain size. The 48-km Eta domain was 106×80 deg, while the 29-km domain was 70×50 deg of rotated longitude×latitude, respectively. Thus, the 29-km domain was by a factor of about 2.5 smaller than that of the 48-km Eta.

In spite of what would appear an overwhelming advantage of the 29-km Eta, in precipitation threat scores comparison for the first two years, including 1245 forecasts, in which in fact the 21-h and 33-h meso Eta forecasts were compared against the 24-h and 36-h forecasts of the early Eta, respectively, the two models performed about equally (MESINGER, 2000b, section VIII). There have certainly been many local features forced by the more detailed topography of the 29-km Eta that it had captured while the 48-km Eta did not; but the placement of synoptic-scale systems primarily responsible for precipitation skill, such as storms and fronts, was overall not improved.

The only reasonable explanation I see for this result is that the much larger domain size of the 48-km Eta had enabled it to develop more accurate *larger* scales of motion compared to what it would have been able to do had it been run on a smaller domain. The impact had to be of a sufficient magnitude to compensate for the significantly less accurate lateral boundary condition it was using, coming from the 12-h older Avn forecast.

This view is consistent with the Eta model excellent record in forecasting tracks of major tropical cyclones. A review of various results over the years, up to and including 1996, has been made in MESINGER (2000b). Of these, let me recall the four-model comparison of forecasts for each of the two most intense Atlantic hurricanes of the 1996 season, Bertha and Fran. For each of them, 48-h position errors were evaluated for the six latest initial positions, at 12-h intervals, still over water prior to landfall. For these 12 forecasts, the Eta median position error was considerably smaller not only than those of the Avn and the RSM 50-km model, but was also much smaller than that of the GFDL hurricane model. Note that the Eta has no vortex initialization effort, and at the time had used the 12-h old Avn lateral boundary condition.

I have done the same statistics for Hurricane Floyd of 1999, the most intense U.S. hurricane of the four hurricane seasons following 1996. As prior to landfall Floyd's movement was slower than those of Bertha and Fran, I have this time included eight latest initial positions over water in the statistics. For determination of the 48-h forecast positions I have now relied on the NCEP on-line track archive, recording forecast storm positions as identified by the "automated vortex tracker", maintained by Tim MARCHOK (NWS, 2000). Of four U.S. models included, NGM, Eta, Avn and GFDL, the Eta has once again had the smallest median error, 150 km; against GFDL's 250, Avn's 290, and the NGM's 310 km.

The Eta having in these two independent samples done in terms of track forecasts comparably and apparently even better then the official U.S. National Weather Service hurricane model, the GFDL, I find particularly noteworthy. Note that the GFDL model (KURIHARA et al., 1998) is a triply nested model, with the innermost mesh having a 1/6 deg resolution, much greater than the 48 km of the Eta in 1996 and 32 km in 1999. It has a refined vortex initialization scheme. However, it is using the nonstaggered, A grid, which can be considered to reduce the effective resolution; and points to a numerical design radically different from that of the Eta. The two nested meshes, of 1/6 and 1/3 deg resolution, move with the hurricane; the outermost mesh is however of only 1 deg resolution. The boundary conditions the GFDL model is using, once again, are of the current – same initial time – Avn run, as opposed to the Eta's "old" Avn run.

Accepting the general notion that the movement of tropical storms is governed by the "steering", that is, large scale, flow, I find these results consistent with and in fact supporting the idea that a limited area model, well designed and with a uniform resolution over a large domain, is capable of a significant improvements not only of mesoscale features, *but of the large scale features as well.* It could be that this view is gaining some ground, given that the approach of adaptive grids that has been more at the forefront some years ago, does not seem to be much advocated any more.

8 LAM value added skill as a function of time

Yet another issue confronting an NWP limited area modeler, and/or management of an operational center, is how long ahead to run a regional model. Not all that many years ago the enthusiasm created by the constantly improving skill of global spectral models such as that of the ECMWF might have made many people expect that the global models will be used for increasingly shorter range forecasts, replacing at these ranges regional models. For example, in 1993 the then NMC's Development Division management in their modeling plans had the "early Eta", at 80-km resolution, in 1996 "phased out assuming Avn precipitation guidance 24-48 hour is comparable or better", to be possibly survived by a higher resolution "mesoscale Eta" run only 36 h ahead (KALNAY et al., 1993).

In the same vein, perhaps it was generally expected that the advantage to be gained by a regional higher resolution over the global driver model should gradually disappear as the forecast range is increasing. This view is consistent with the frequently espoused idea that for a longer range forecast larger scales may be sufficient.

The trend regarding the Eta has gone the other way. For example, for a 24-month sample September 1995-August 1997, no reduction in the advantage of the Eta over the Avn model in precipitation threat scores could be seen in the 24–48 h compared to the 12–36 h scores (MESINGER, 2000b). For some time in recent years operational NWS forecasters using the Eta guidance have repeatedly asked for an extension of the time-range of the Eta. Once the computer resources and the code that took appropriate advantage of the current NCEP computer system's MPP architecture were available, in March 2000, the time-range of the Eta was extended to 60 h.

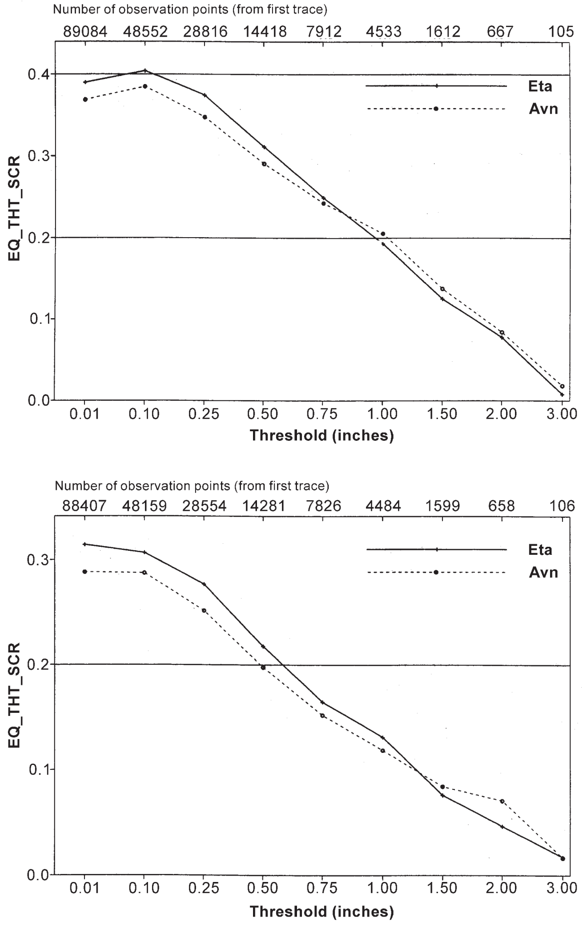

Figure 5: Equitable precipitation threat scores for the Eta model (full lines) and the Avn model (dashed lines), of 00–24 h (top panel) and 36–60 h (bottom panel) accumulated precipitation forecasts, April–November 2000, as functions of thresholds in inches/24 h. The numbers above the plots show the total number of the 80-km verification boxes which were "observed". There are 239 forecasts that are verified at 24 h, and 236 forecasts that are verified at 60 h, by each of the two models.

At the time of this writing eight months of scores are available at NCEP that include those of the Eta 36–60 h accumulated precipitation. One might wish to look for signs as to whether the relative standing of the two models as a function of time is any more conclusive now that the Eta range has been extended. To that end in Fig. 5 the Eta and the Avn equitable threat scores of 00–24 h, and of 36–60 h accumulated precipitation is shown, for the eight months mentioned, April–November 2000.

The advantage of the Eta over its driver Avn model at 24 h is this time quite modest: it is winning five categories and loosing four. The advantage at 60 h, overall, is a little more convincing, and certainly not less, the Eta is now winning the 1 inch/h category which it had lost at 24 h. Contrary to what probably was excepted by most people some years ago, the limited area model, the Eta in this case, is not achieving an advantage for a relatively short time only; even in this operational mode example where it is absorbing the disadvantage of having the previous global model's run boundary condition.

This, by the way, is entirely consistent with the now generally accepted idea of using regional models to "downscale" global model climate runs. Not only that the climate downscaling approach assumes the LAM advantage to be about constant with time; it is in fact assuming it to be increasing from zero to its constant value, depending of course on model accuracy, resolution, and various additional regional information it can draw upThis, by the way, is entirely consistent with the now generally accepted idea of using regional models to "downscale" global model climate runs. Not only that the climate downscaling approach assumes the LAM advantage to be about constant with time; it is in fact assuming it to be increasing from zero to its constant value, depending of course on model accuracy, resolution, and various additional regional information it can draw upon.

9 The progress made, concluding comments and outlook

For an overview of the state of the art and an attempt to look ahead a number of questions can come to mind. Some are: How far have we come? What do the typical operational LAMs look like, in terms of scope, resolution, etc.? The aspect emphasized in this review was model dynamics; does it really matter, and if it does, as the resolution increases, will it indeed matter less? The number of models, or "model families", both regional and "local" is considerable. How does this affect the field? Should one expect, with constantly increasing resolution of global models, that regional and even local models eventually disappear altogether? Or alternatively, do limited area models have a future?

Limited area and local models are of course at the cutting edge of efforts to take advantage of high resolution, to reproduce various mesoscale phenomena, and the like. Many success stories are continually published, and other reviews have recently been made, e.g., DOYLE et al. (2000) and GALL and SHAPIRO (2000). To express the progress in numbers, I will resort once again to precipitation scores: the Eta 24 h and 48 h vs the NGM 24 h scores, for 1997, have already been compared in MESINGER (2000b). The same plot, but for 1998, is shown in Fig. 6. In its top panel equitable threat scores of 00–24 h forecasts of the Eta and of the NGM (or, for the system, RAFS) are shown. As seen, considerable gain in the accuracy of 24-h forecasts is achieved by the Eta over the NGM, going from about 20% in terms of the threat scores for low precipitation categories to about 65% at the highest category then monitored of 2 inches/24 h and greater.

In the bottom panel of the figure 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 scores are higher than those of the NGM, albeit at five of them the difference is barely visible. The NGM, as stated previously, has been "frozen" in 1991; thus, since then the time validity of the NMC/NCEP model-produced quantitative precipitation forecasts (QPFs) has doubled. Alternatively, a full day extension of the validity of QPFs has been achieved.

What is currently at the forefront of efforts in operational regional NWP centers? The situation at NCEP is probably typical: with increasing availability of MPP architecture computers, possibilities for extraordinary increases in the size of the models run are at hand. As of September 2000 the operational Eta is run at 22 km/50 layers resolution, on the same domain as that of the previous 48-km model, of 106×80 deg of rotated longitude×latitude. This domain size is about 19% of the area of the globe. There are 196,021 height grid points in a layer, which, with 6 three-dimensional prognostic variables, amounts to a total of about 6×10^7 prognostic variables. 60 h forecast is done in about 60 minutes.

Plans for 2001 are to implement near the end of the year, on the same domain, a 12 km/60 layer model. Before that, the time range of the Eta is to be extended for another day, to 84 h. Also, a number of 10-km resolution nests are to be implemented over parts of the contiguous United States.

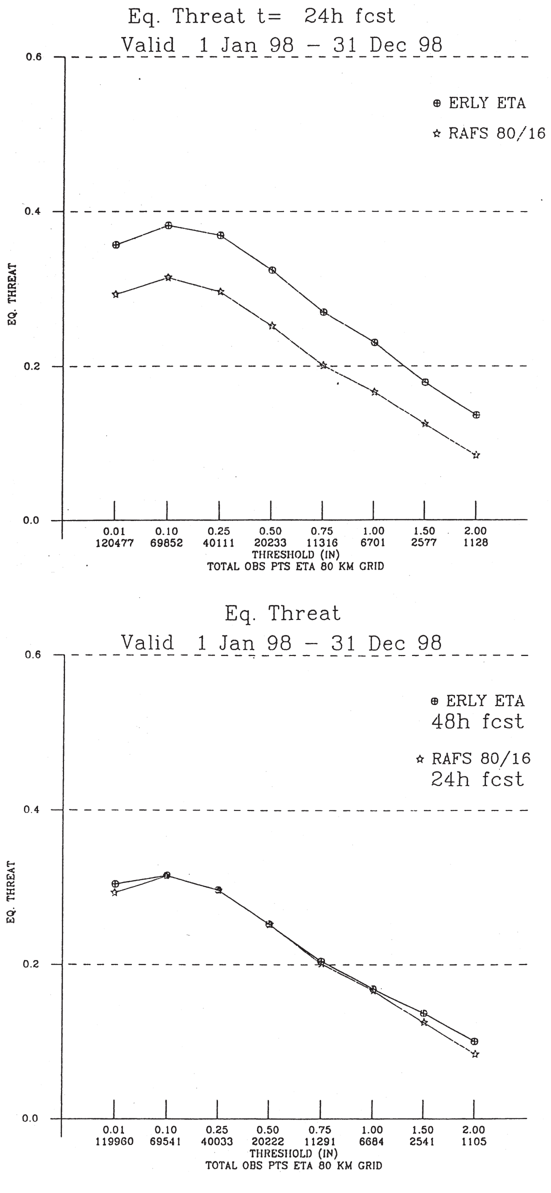

Figure 6: Equitable precipitation threat scores, for 1998, of the Eta and of the NGM/RAFS for 00–24 h forecasts, top panel. The sample contains 319 verifications by each of the two models. Scores of the 24–48 h Early Eta shown against the 00–24 h NGM/RAFS scores, bottom panel.

For support/illustrations of various points made, I have drawn primarily on results of one center, this being the center I am most familiar with. There are of course many other operational centers with their own perhaps similar stories. In some cases, communities of users have formed around a model. This is particularly the case with "research" limited area models, those developed at universities and/or research organizations; and is a characteristic of limited area modeling much more than of NWP modeling in general. The use of such "community models" is very extensive and probably growing: ANTHES (2000) estimates, as he says, "conservatively" that only three of them, MM5 (Penn State-NCAR), RAMS (Colorado State University), and ARPS (University of Oklahoma) are used "by more than 1,200 users at more than 600 institutions worldwide". Communities have formed around models that were developed primarily in operational environments too: ALADIN, Eta, and HIRLAM, for example. Thus, the Eta, in various versions, is run operationally by national weather services, regional weather services, or other organizations, in more than 10 countries. The numbers of operational centers using ALADIN, and HIRLAM, are similar.

As described earlier, various models tend to use quite different numerical designs, in many cases unique to a specific model. The situation is not too different with physics modules: in some cases a specific approach is used by more than one model

– convection schemes are an excellent example; but in other cases a module is unique to a given model. Thus, a significant portion of the research done is of a local interest to a model's community, and only some is of interest for a wider community.

What about the future? With constant increase of resolution of global models, will limited area models some day disappear?

A healthy future of the limited area modeling approach I find is guaranteed by two advantages it offers compared to global high resolution models:

- For a chosen region, and given computer resources, a limited area model can always achieve a higher resolution;

- A limited area model can take advantage of an optimal grid geometry; it does not have a pole problem.

Thrusts is progress provide insight as to where we are going. Along with efforts at increasing resolution pointed out already, development and/or improvement of nonhydrostatic models is taking place at numerous centers. Work on "Weather Research and Forecast (WRF) model" is but one example (e.g., DUDHIA et al., 1998; also http://www.mmm.ucar.edu/wrf/users/document.html). But the challenge ahead in eventually moving towards explicit simulation of convection in NWP-type limited area models should not be underestimated. This is a new territory, and I think it is reasonable to expect that it might take quite a few years before visible progress in day-to-day forecasting comes as a result.

But how much will it be possible to improve weather prediction, a few days ahead, with all the MPP computer resources that is coming our way, and thrusts in progress having well advanced? Two spectacular recent short range failures of major NWP models in forecasting the European "boxing day" storm and the "blizzard" over the Washington, D.C., area (see Tim PALMER's article in this volume) provided high-visibility demonstrations that the standard short range forecasting can still fail in a major way only one day ahead. While the ensemble approach in these cases was shown to be beneficial, it would seem that major synoptic-scale storms should be predictable at this short range by the purely deterministic approach. It is my opinion that refinement of assimilation methods and forecasting models, within the current operational resolutions (on the order of 20 km) and primitive equation formulations ought to enable our eventually doing well with major cases as mentioned within the one-day range.

It takes years, or better a decade or more, to refine a specific model. To go back to the Eta example, in spite of more than a decade of refinement, there are still quite a few specific steps well founded by understanding at hand which could be undertaken to improve the Eta further, within the current primitive equation formulation. I have listed several in an earlier review paper (MESINGER, 1997), and I can add more. Some of these are switching to the CHARNEY-PHILLIPS vertical grid, reversing the time order of integration of the continuity and momentum equation in its adjustment stage, and moving toward a more refined formulation of the eta coordinate to enable partial and/or sloping (shaved) steps.

Of opportunities that are not "local" to the Eta model, in my view the major challenge is addressing and hopefully removing the conflict that now exists between the numerical design of models and their physical parameterizations: the former assumes prognostic fields to be smooth functions of space, while forcing at individual grid 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.

The point of my referring to these issues is primarily to underscore the fact that possibilities of embarking on model refinement and promising new design efforts are many, and are not limited to the traditionally taken routes of increasing the resolution, moving to nonhydrostatic formulations, and "improvements of physics". A difficulty is that it is hard to judge beforehand which efforts will be the most rewarding, and the manpower available for projects of these types is limited. The progress achieved over the past 50 years has been extraordinary; yet, as put by ARAKAWA, the "great challenge" phase of atmospheric-oceanic-land surface modeling is still ahead of us. "The problem is of huge dimensions" just as stated by BJERKNES (1904) so many years ago (ARAKAWA, 2000). I have no doubts that during the 50 years that remain until the 100th NWP anniversary symposium, NWP including limited area modeling researchers will not run out of plenty of exciting work at their hands.

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