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THE ETA MODEL IN WEATHER AND CLIMATE: BACKGROUND, AND LESSONS LEARNED

Abstract: The idea of writing a limited area atmospheric model came following my several years stay at the University of California in Los Angeles, UCLA, at the end of the sixties. Exposed at UCLA to what I refer to as the Akio Arakawa approach, encouraged by my having an idea for a scheme that seemed an improvement to what Arakawa was using, and aware of the importance of topography for weather of the country I returned to, led to my writing in 1973 a limited area code that eventually became the Eta model. Refinements introduced in subsequent years including those of a collaborator I acquired, Zaviša Janjić, led to the code that when installed in 1984 at the then U. S. National Meteorological Center, attracted attention. It is the model's performance when compared to two competing candidate models that eventually led to it becoming in 1993 the primary U. S. operational regional weather prediction model. Some of the key events that enabled this to happen are recalled. Although the model after about a decade + eventually was replaced in this role, it continued to be used, such as for forecasts by the Brazilian National Institute for Space Sciences (INPE), as a Regional Climate Model (RCM) in numerous climate change studies, and as a tool for the North American Regional Reanalysis (NARR), run in near-real time by the U. S. National Centers for Environmental Prediction. Model refinements in this later period are summarized, including the introduction of the so-called cut-cell discretization of its representation of topography. More recently, using about the same resolution, the model showed ensemble skill mid-tropospheric jet-stream forecast accuracy superior to its highly acclaimed driver European Centre for Medium Range Forecasts (ECMWF) model.

Key words: *Eta model, cut-cell schemes, finite-volume schemes, topography representation*

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1. THE BEGINNINGS

The reason I enrolled to study meteorology was my reluctance to abandon either one of the basic sciences taught in high school, chemistry, mathematics, physics. Also, because it offered understanding of why events we see take place. It turned out however that no chemistry was taught to meteorology students, and that mathematics was what I found the most enjoyable. However, methods used for weather prediction, clearly the main practical purpose of meteorology, at the time were analyses of weather maps, something I was not at all comfortable with. But weather prediction using mathematics, or, to use more modest words, using computers, seemed on the horizon, and to me the only way to make progress that looked like real science.

Much of an encouragement I received from a book „Numerical Weather Analysis and Prediction“ (Thompson 1961) then I got hold of, and still more from my attendance of the „International symposium on numerical weather forecasting“, in Oslo, March 1963. Just about every one of the leading pioneers of the emerging numerical forecasting field was present, including Akio Arakawa, Jule Charney, Arnt Eliassen, Cecil (Chuck) Leith, Edward Lorenz, Aksel Wiin-Nielsen, more (Platzman 1963). But most of all, it included a report by Arakawa on his finite-difference horizontal advection scheme that via conservation of total kinetic energy and vorticity squared prevented the so-called nonlinear instability that Norman Phillips discovered some years earlier (Phillips 1959), and that looked like making a successful longer range numerical weather prediction (NWP) impossible. The NWP future looked bright!

At the time however there were no electronic computers in Belgrade, and in addition my education in the area needed improvement. I managed to spend some time at the National Center for Atmospheric Sciences (NCAR), Boulder, CO, some at the University of California at Los Angeles (UCLA), then some in Belgrade without a real job, and eventually at the end of the sixties at the best place possible for exposure to the at that time emerging developments in atmospheric numerical modeling, again at UCLA. This because of the ability to listen to numerical methods course of Akio Arakawa.

This was the time when people at the forefront of NWP efforts understood that for real progress one needed to move from integrating the vorticity equation to more complete so called „primitive“ equations, Navier-Stokes equations with hydrostatic approximation. These are equations which have the vertical velocity calculated using the two horizontal components. A new set of problems had to be given attention, and these were not problems one could learn about by looking at a textbook on numerical methods for solving differential equations, such as the highly respected textbook of the time by Richtmyer and Morton (1967).

There are at least two basic reasons for this. While we know the equations of motion we want to solve, they having been known now for more than 200 years, and while we also know they *are* initial-value equations, we do not really know the initial values. They are obtained via a variety of measurements and can only be approximate. And we are working with a system that does not have a solution in form of some analytic function. The solution is the atmospheric state that happens.

One of these new problems with no mathematical guidance is the distribution of variables in space. Arakawa, working with his graduate student Frank Winninghoff, had four possible square arrangements of variables of two-dimensional primitive equations analyzed (Winninghoff 1968). They are displayed in Fig. 1. The way this was done was to look at what happens when using simplest centered differences for space derivatives of linearized gravity and inertia terms when assuming wave solutions of these equations (e. g., Mesinger and Arakawa 1976, Ch. IV, Sec. 6; Arakawa and Lamb 1977, Ch. III, Sec. A). Examining the effect of the resulting space discretization error on the frequency Arakawa and Lamb (1977) conclude that except for some rare situations the fully staggered C grid gives the best result, this being important for the so-called geostrophic adjustment process. This is the establishment of approximate balance between the horizontal pressure gradient and the Coriolis force once this balance is perturbed, something that is nowadays understood to be constantly taking place in the atmosphere.

2. NWP PROGRESS, THE ETA AT NMC AND NCEP

This address of the impact of the choice of the horizontal grid via its adequacy for the numerical representation of the gravity-inertia terms at the end of the sixties might well mark the beginning of the soon to follow fast progress in the skill of the actual NWP models. Namely, the skill of operational NWP following its inception several years after the famous Charney, Fjørtoft, and von Neumann (1950) accomplishment was not impressive for quite some time. Change to more general primitive equations was one requirement, and the availability of more powerful computers they needed another. Both were gradually taking place only in early to mid-seventies.

Having returned to the then Yugoslavia in 1970, after several years dedicated mostly to preparing the courses taught, I wrote the original code of what eventually was going to become the Eta model. I decided to use the E-grid because this seemed to me best for the definition of lateral boundary conditions. Soon I was joined in this effort by Zaviša Janjić, senior year

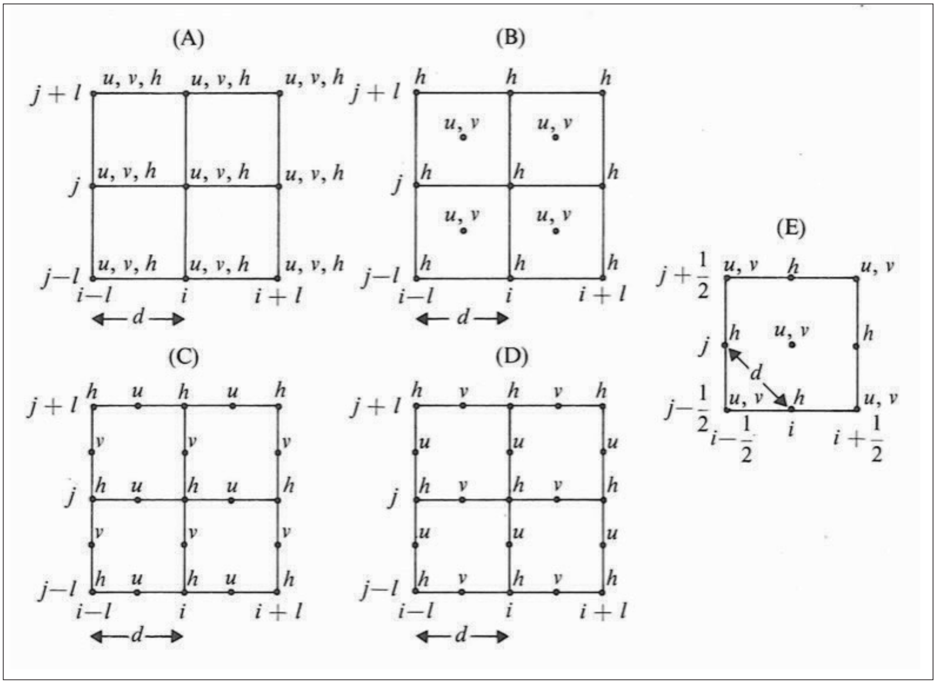

Fig. 1. Four possible distributions of horizontal velocity components *u, v* and height *h* for the so-called shallow water model, defined to have velocity components independent of height. For primitive equation models, surface pressure and temperatures are defined at the *h* points. Note that E is the same as B, except for being rotated by 45°. Thus, B and E grids at times are referred to as the B/E grid. From Mesinger and Arakawa (1976).

student when I returned to Belgrade, who made important contributions of his own. In the very first code there was one scheme directly taken from Arakawa, the vertical advection scheme, but various our contributions followed (e. g., Janjić 1977, Mesinger 1977). But those of most impact were surely these of the early eighties, with (Mesinger 1984) changing the vertical coordinate from the ubiquitous terrain-following to the terrain-intersecting step-topography eta (Fig. 2), and (Janjić 1984) discovering a way to convert the Arakawa and Lamb (1077) C-grid horizontal advection scheme to use the velocity components of the model's E-grid.

Having re-written the model code during my half a year 1984 visit to GFDL to use these upgrades I have brought the code to the then National Meteorological Center (NMC) in Camp Springs, MD, for another half a year visit. Dennis Deaven of NMC helped me install the code and run an experiment additional to those already done at GFDL (Mesinger et al. 1988).

A most distinguished person working at NMC during my 1984 visit was Norman Phillips, mentioned above for his discovery of the nonlinear

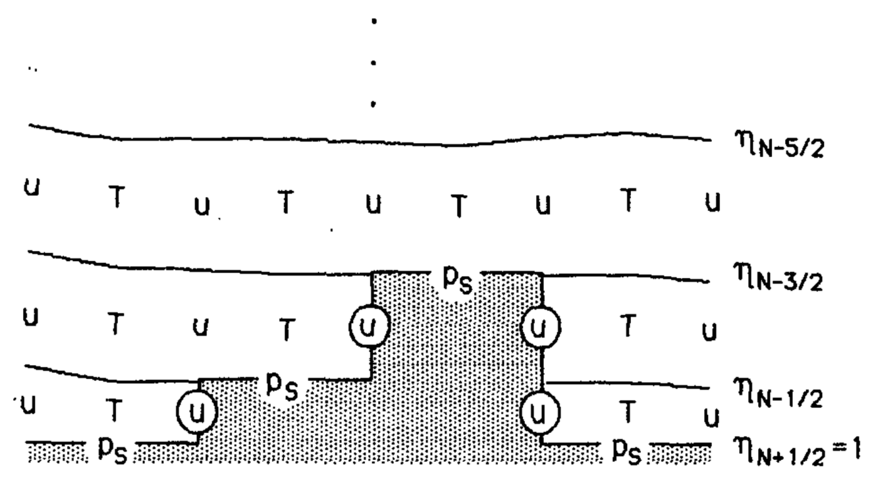

Fig. 2. Example of a 2D representation of topography using the eta vertical coordinate. *u* represents x-components of velocity, *T* temperature, and N the number of model layers. Quasi-horizontal lines are model layer interfaces with prescribed η values. From Janjić (1990).

instability. Phillips, one of the „pantheon of gods“ of atmospheric numerical modeling one might say (note, e. g., Fig. 1 in Mesinger et al. 2018) left in 1974 his position of the head of the Department of Meteorology at MIT (Massachusetts Institute of Technology) to pursue numerical prediction at NMC. With the assistance of Jim Hoke, he developed the so-called Nested Grid Model (NGM), that clearly NMC expected a lot from. But when I asked him in 1984 what horizontal grid he used in the NGM, A, B, C etc., he replied he did not know! Instead, he handed me a technical note on NGM, and told me something like „Here is our publication, so you can find out“. Of course, I looked into it, and found out he used the D grid, according to Arakawa the worst choice. Was it a different time with information not easily spread. Or?

The National Weather Service Director of the time, Ronald (Ron) McPherson saw to it that the model code (note yet referred to as Eta) is maintained, tested more (Black 1988), and further developed, see Tom Black's words in the Acknowledgements of Mesinger (2004). A crucial step in this further development was Zaviša Janjić's visit to NMC in 1987, during which he upgraded the „minimum physics“ package of the model primarily by adding the Mellor-Yamada level 2.5 turbulence, level 2 in the lowest layer, and the Betts-Miller convection scheme, both with various modifications (Janjić 1990).

Janjić's visit was followed by mine, with the attention divided between additional model developments and verification efforts, all of these with continued assistance of Tom Black. Model upgrades included addition of a viscous sublayer over water to the surface layer scheme, so-called piecewise linear vertical advection of moisture (Mesinger and Jovic 2002), and, in cooperation with Alan Betts, refinements of the Betts-Miller convection scheme. With the Eta, as spontaneously already referred to at that time, often showing results superior to those of the operational NGM, a three-way comparison of precipitation accuracy was done of the Eta vs. the NGM as run operationally, and the NGM using the Eta's Betts-Miller convection scheme. This by objective skill scores confirmed the Eta's notable improvement over the NGM in forecasting all heavier precipitation categories during the period used, regardless of the convection scheme used in the NGM (Mesinger et al. 1990).

Another Janjić's visit followed, with a considerable upgrade of the convection scheme, subsequently referred to as the Betts-Miller-Janjic (BMJ) scheme, as well as that of the viscous sublayer scheme, now different above land and water, and minor Mellor-Yamada (MY) changes (Janjić 1994). It should be noted however that the Janjić (1994) paper covers essentially only the material prior to the end of his just referred to visit, some time in 1990, with only brief mentions of the developments after 1990.

When in early 1991 I rejoined what used to be the NMC's Development Division, reorganized so that it became the National Centers for Environmental Prediction/ Environmental Modeling Center (NCEP/EMC), its Director Eugenia Kalnay told me about a problem of the then semi-operational Eta. During the past winter it exhibited a „mixed performance over warm water", occasional overdeepening of lows and widespread rain that did not verify. Looking into a sensitive case of a real development that did not verify, eventually I invented what I referred to as the „*l* bulk" scheme, replacing the finite-difference type specification of the length scale of the model's MY-2 (Mellor-Yamada level 2) lowest layer scheme. It very much removed the overdeepening problem, and performed even better than a standard Monin-Obukhov formulation (Mesinger and Lobocki 1991, summarized in Mesinger 2010).

Another problem was identified by chance (serendipity?). Adrian Marroquin running the Eta outside NCEP, complained about having no turbulence kinetic energy (TKE) above the planetary boundary layer (PBL). I checked at EMC and noticed reasonable values in the forecast I looked at. The difference had to be in the code: Marroquin was using an older version which did not have the MY master length scale values I specified throughout the model atmosphere and thus also above the PBL, advised by Mark Helfand to do so, these specifications addressing also other issues (Mesinger 1993b). But having a look at the right place, I noticed a major oversight on the part of apparently all previous users of the MY-2.5, that made it next to impossible for TKE to be generated above the PBL (Mesinger 1993a).

Eventually the Eta became officially the U. S. operational regional model on 8 June 1993. The NGM at the time was „frozen" since 1991, but continued to be run, thus, inter alia, serving as a benchmark that could be used to assess the progress made. Another model, so called Regional Spectral Model (RSM), developed by Henry Juang, was also run on a regular basis, and it the eyes of some certainly was a contender. Note the statement of all the Development Division managers of the same year as the official implementation of the Eta „A comparison with Regional Spectral Model (RSM) will determine possible replacement by the RSM" (Kalnay et al. 1993). It continued to be run until late 1997, with resolution about the same as that of the Eta, when in almost a 2-year comparison of more than a thousand forecasts the Eta demonstrated higher precipitation accuracy across all the intensity thresholds. This despite the RSM being run later with a 12-h more recent lateral boundary conditions (Mesinger 2004, Fig. 2).

Following a variety of enhancements and refinements made, in 1998 the operational Eta achieved precipitation accuracy scores of its 24–48 h forecasts across all intensity thresholds higher than the NGM's scores of the 00–24 h forecasts.

The Eta accuracy over its U. S. domain was higher than that of the U. S. global model as well, so in 1997 a proposal was made for a „regional reanalysis" project, by the Advisory Committee of an existing global reanalysis project. The idea of such reanalyses, at the time one already having been performed, is to use a fixed model system and process all the data available as of the beginning of satellite measurements, to obtain analyses of climate change not affected by the model and analysis changes. This proposal to perform regional reanalysis using the Eta has eventually been accepted, funded, and done for its initial 25-yr retrospective period, and continues to be performed in near-real time as we speak. Paper describing the method and reporting on these first 25 years of data, Mesinger et al. (2006), is frequently cited, so that in Google Scholar as this is being written has more than 3700 citations.

However, a problem with the Eta has been noticed at the end of the nineties. An experimental 10-km Eta failed to forecast an intense downslope windstorm in the lee of the Wasatch Mountain, while a sigma system MM5 model did well (McDonald et al. 1998). Following that, Gallus and Klemp (2000) reported on a nonhydrostatic eta code in simulating flow over a 2D bell-shaped topography exhibiting a flow separation off its top instead of a descent down the lee slope. This had a rather negative impact on the Eta reputation as it was by many expected to become more detrimental with higher resolutions. Consequently, when replacing the referred to 10-km Eta by an 8-km Nonhydrostatic Mesoscale Model (NMM) using terrain-following coordinate, an announcement was made that „This choice [of the vertical coordinate] will avoid the problems ... with strong downslope winds and will improve placement of precipitation in mountainous terrain" (Geoff DiMego, personal communication, 19 July 2002).

Accordingly, upgrades of the Eta at NCEP were discontinued, and in addition a more advanced data assimilation system has been developed for the NMM. Eventually in 2006 a so-called „parallel" was run, of four + months of forecasts of the operational Eta system, and the newly developed NMM system, at the same domains and resolution. The Eta performed clearly better with precipitation skill scores, the more so the longer-range forecasts were looked at (e. g., Mesinger and Veljovic 2017, Fig. 4). There was little else in terms of objective scores that would be favoring the NMM (DiMego 2006). Over higher topography western contiguous United States, the Eta remained more accurate in both 2-m temperatures and 10-m winds (Mesinger 2022). Nevertheless, perhaps understandably, decision was made to have the NMM be the next U. S. operational regional model.

3. THE ETA OUTSIDE NCEP

With the Eta demonstrating accuracy as summarized no wonder it was used in various ways in some countries outside the United States. In 1994–1998 it was the primary experimental tool of international summer schools organized in Krivaja, Bačka Topola, by the Federal Hydrometeorological Institute, Belgrade, sponsored and partly supported by WMO (World Meteorological Organization). It was used in three two-week workshops/conferences on regional modeling organized by the International Center for Theoretical Physics (ICTP) near Trieste, 2002, 2005, and 2008.

The most extensive use of the Eta outside NCEP was at CPTEC (Center for Weather Prediction and Climate Studies), Cachoeira Paulista, SP, Brazil. Two CPTEC people visited NMC in 1996 and have taken the Eta code to Brazil. One of them was Sin Chan Chou (pron. Shou) who continued using it and organized a dedicated group using the Eta for short range forecast and as a regional climate model (RCM). As this is written Chou had organized for the 7th time an Eta model workshop with participants being taught to run the model and make experiments. Twice it was the model of choice of an U. N. organization, CEPAL, covering Latin America and the Caribbean, for training workshops on climate change experiments, hosted by CPTEC.

CPTEC, an agency of INPE (National Institute for Space Sciences), as this is written only INPE, following NCEP's 2006 decision has become kind of a „primary home“ of the Eta, not only for hosting events but also in taking part in contributions to the further development of the model. Thus, the paper summarizing the design of the model as of 2011, Mesinger et al. (2012), of 11 coauthors includes 5 coauthors who are or were resident in Brazil.

But it is fitting to continue this presentation with summaries of some of the major model advancements following 2006. One resulted from another event due to chance. To address the „Gallus-Klemp problem“ of the Eta, I had a long-standing idea, as of 2002, on my „to do list“ what needs to be done. Since Gallus and Klemp ascribed the problem to the existence of step corners of the step topography Eta, as illustrated in the schematic of Fig. 2, I was going to change the discretization so that the velocity cells just above the corners have sloping bottoms, as illustrated in Fig. 3.

Only much later I realized that this in fact is a simple version of what originally was referred to a shaved cells method (Adcroft et al. 1997), and nowadays, perhaps as of Steppeler et al. (2011), a cut-cell scheme.

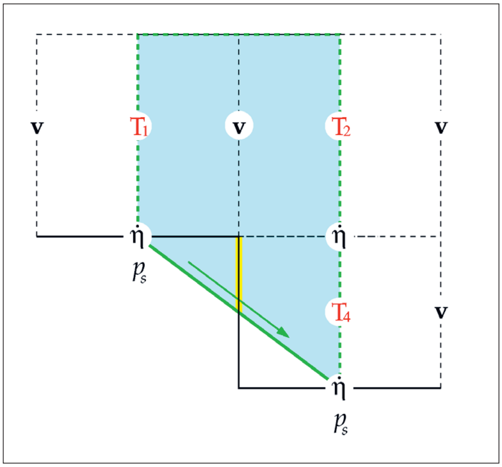

Fig. 3. 2D schematic illustrating the „sloping steps“ Eta discretization. The vertical topography side below the velocity (v) cell in the middle is replaced by a sloping side going from the left to the right surface pressure (*p*S) points. Symbols T denote temperature cells, η denotes the eta coordinate, with dot (˙) above a symbol standing for the time derivative. From Mesinger et al. (2012).

Once a version of the code using „sloping steps“ was put together a test was done using an 8-km/60-layer code over a domain of the western United States and running a 48-h forecast. Obtained temperatures of the lowest layer T cells are shown in Fig. 4. Two or three spots all in mountain basins are seen responsible for the choice of the NCAR graphics routine of the plotting interval of 10°K, one of them in southwestern Montana, with the temperatures below 180°K. Another in western Alberta, not much warmer than that.

Understanding what happened was obviously needed. It was not hard to get the idea that the finite-difference vertical advection scheme, used for slantwise temperature advection such as between cells T1 and T4 in Fig. 3, is a good candidate to be responsible.

The centered finite-difference scheme used for slantwise advection in calculating temperatures of Fig. 4 was

$$\frac{dT}{dt} = \cdots - \dot{\eta}\,\overline{\frac{\Delta T}{\Delta \eta}}^{\eta} \tag{1}$$

d/dt being the time derivative, the eta vertical velocities, $\dot{\eta}$, being defined at cell interfaces, the overbar standing for two-point averaging in the direction indicated, and Δ denoting the finite difference in the direction of the η.

Suppose the left half of the schematic of Fig. 2 were the exit region of a basin with predominant flow to the right and somewhat upward. According to (1) the temperature change due to vertical advection is the average of contributions from the top and the bottom sides of T cells. If a temperature inversion were to develop between the two leftmost and lower T cells, then the vertical advection contribution from their mutual interface would cool both cells, but for the lower of them would be the only contribution, thus tending to increase the inversion, amplifying its cooling, feeding on itself. An instability like mechanism would be established, for a physically wrong reason.

It was easy to avoid the problem. As we *know* the velocity across the half of what was a vertical step, yellow in the schematic of Fig. 3, we also know the mass of air moving in the time step from cell T1 to T4, so that it is straightforward to calculate the temperature changes due to the slantwise advection in a Lagrangian way. This was coded instead of the use of (1), and a realistic lowest cell temperature forecast was obtained instead of that in Fig. 4.

However, the scheme (1) was used not only for slantwise advection, but for the vertical advection of the main prognostic variables, v and *T*, as well. Being now aware of the scheme’s problem at the lowest cells, I have changed the vertical advection of v and *T* to the finite-volume scheme that the model

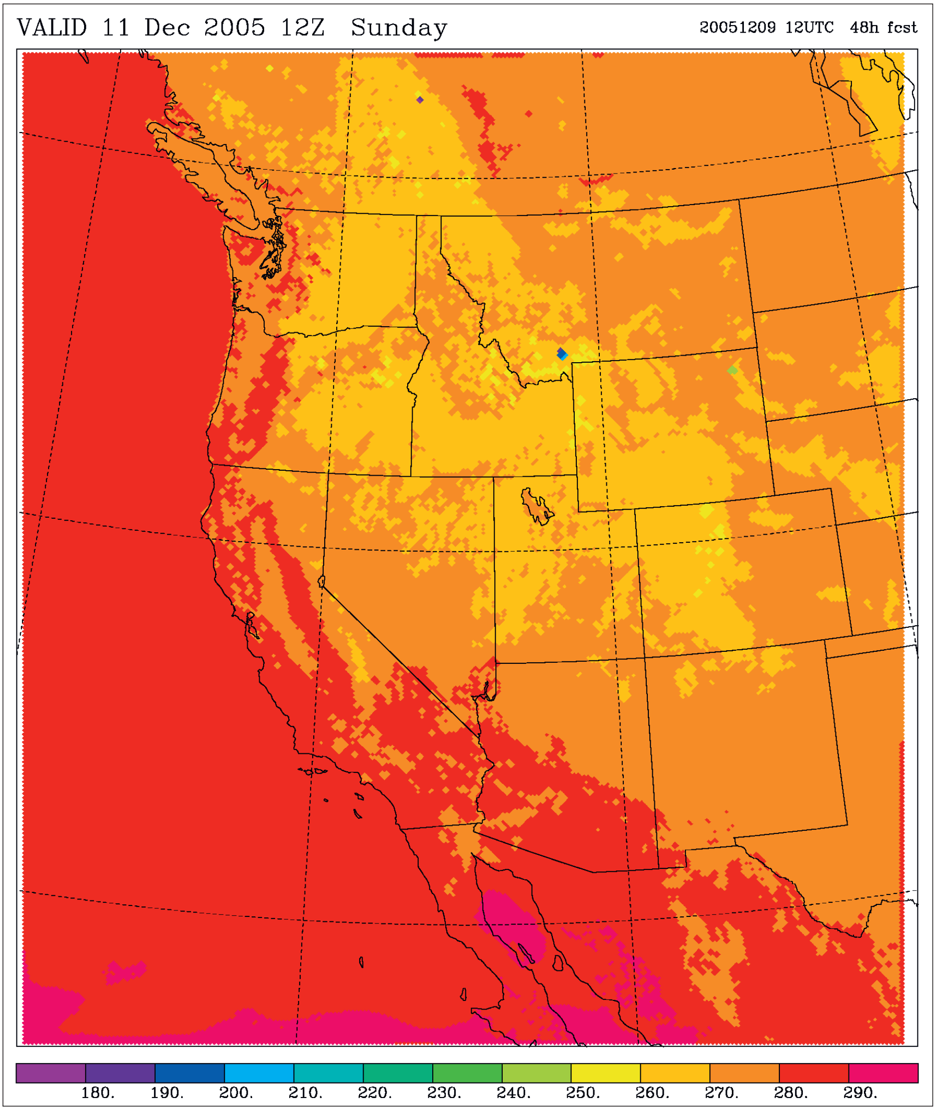

Fig. 4. Temperatures of the lowest temperature cells of a 48-h forecast with the „sloping steps“ Eta, when using a finite-difference „Lorenz-Arakawa“ centered slantwise temperature advection scheme.

was already using for moisture (Mesinger and Jovic 2002). It is a scheme that respecting the finite-volume meaning of prognostic values as cell averages, adjusts slopes inside cells toward values at the edges of neighboring cells, but without creating new minima or maxima and keeping them linear inside cells. Thus, the term „piecewise linear“ is often used. Advection can then be performed using velocities at cell boundaries.

An unexpected reward came from that change, in addressing the model's difficulty with downslope windstorms. When the change was made experiments were in progress with cases of intense downslope windstorms in the lee of the Andes. Two sections of synoptic maps illustrating one of these cases are shown in Fig. 5. The case is the same as that discussed in Section 9 of Mesinger et al. (2012). Warming of 24°C is seen at the station San Juan, about the middle of the maps. Warmings of that type are known in the Alpine region under the name „foehn", in the lee of the Andes their name is „zonda". The „reward" just referred to is illustrated by the two plots of Fig. 6. The one on the left shows the result of the forecast using (1) for the slantwise as well as for the vertical advection, while the one on the right shows the result with (1) replaced for both by the finite-volume advections. Warming in the zonda region is thereby seen increased by more than 4°K and occurs in one might say „the right place". But to get back to the total warming, compared to the 24 h forecast (not shown) the warming of Fig. 6 at San Juan is seen to be more than 20°K. Thus, notwithstanding the difference of 33 vs. 30 h, this zonda effort can be declared a success.

Be that as it may it is the flow separation issue pointed out by Gallus and Klemp (2000) that was quoted the most as the weakness warning people to stay away from the eta system, e. g., five citations listed in Mesinger (2004). Thus, it required attention, and it was on 9 March 2002 that I worked out a plan how to address it. I could look up this date because I recall I was then travelling on a ship from a meeting on „Awaji" island to Osaka. My

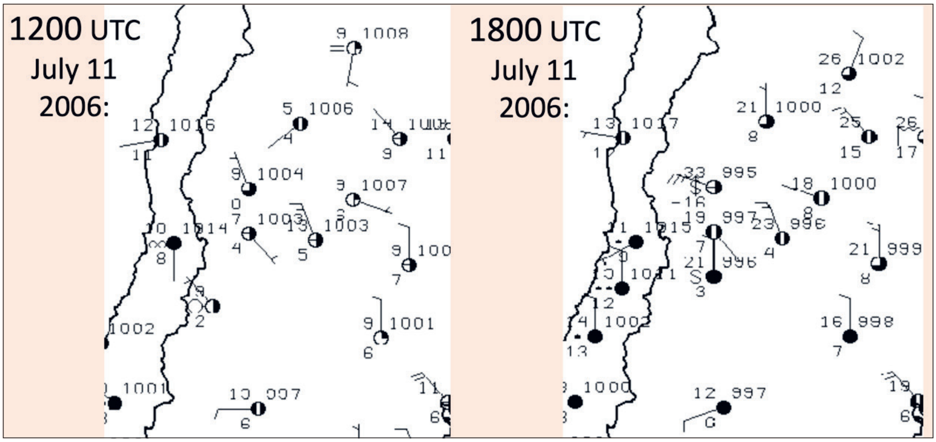

Fig. 5. Sections of surface synoptic maps illustrating a case of an intense „zonda" windstorm in the lee of the Andes. Warming from 9 to 33°C in 6 h is seen at the station San Juan, 630 m above sea level, close to the middle of the sections. Valid times are displayed in the top left corners of the maps.

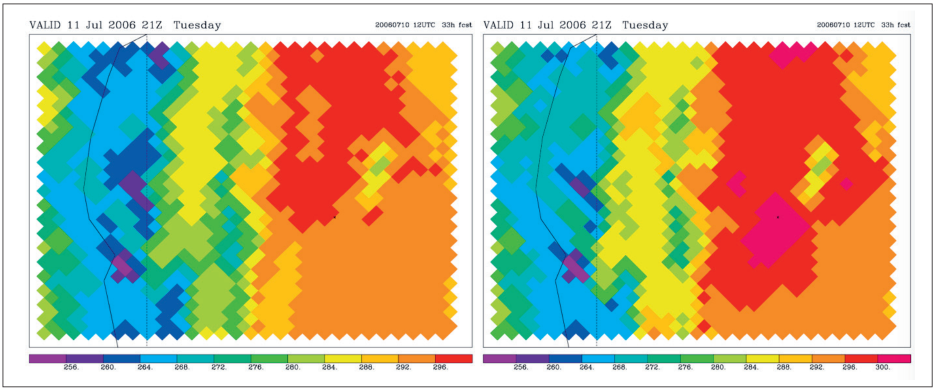

Fig. 6. Forecast lowest cell temperatures at 33 h of the case discussed in Section 9 of Mesinger et al. (2012). The left-hand plot shows the result obtained using (1) for both the slantwise and the vertical advection, while the right-hand plot shows the result with these advections replaced by the finite-volume versions. The roughly vertical line on the left sides of the plots is the Chile-Argentina border, while the straight line is the 70°W meridian. The dot to the right of the centers of plots shows the place of the San Juan station.

plan involved defining slopes at the bottoms of v cells, using the topography values of four surrounding *zS* points. Thereby the step corners of the eta topography according to Gallus and Klemp (2000) responsible for the flow separation would be eliminated, and presumably the Gallus-Klemp Eta problem as well.

Implementing the plan was not straightforward, assistance was needed in handling the code I wrote, and obtained from the Sin Chan Chou's group, primarily Jorge Gomes. My code bug produced in copying hand-written code lines to code statements was eventually discovered by Ivan Ristić of the „Weather2“ Belgrade company, and the code then seemed to work fine. But the flow separation in the Gallus-Klemp experiment of 2D bell-shaped topography, Mesinger et al. (2012, Fig. 3), while visibly improved, was not completely removed.

An unusual help came in 2013 from Sandra Morelli, of the University of Modena. Morelli informed me of noticing „something strange“ in the code of the so-called horizontal diffusion, code modelers use either to avoid unwanted noisiness of fields, or to simulate the impact of unresolved eddies, the latter in the case of the Eta. „Something strange“ was leftover code from a previous sigma version that was with the eta coordinate not active, but a look at the right place was enough to see a problem. Horizontal diffusion code was not made aware of the „sloping steps“ and was thus responsible for the remaining flow separation. This being addressed, flow over the 2D bell-shaped topography was obtained as in the right-hand plot of Fig. 7. Its left-hand plot is (c) of Fig. 6 of Gallus and Klemp (2000), which they obtained using artificial modification of the code to remove the impact of the step corners they found responsible for the flow separation problem.

The routine used for our right-hand plot of Fig. 7 did not allow for slopes, so they are not visible in the topography of the right-hand plot Fig. 7. Compared to the linear solution one could be concerned with the maximum on top of the mountain, but we are confident this could be improved with slopes over more than one cell if this were felt to be an issue of sufficient priority.

4. ETA AS RCM AND ITS LARGE-SCALE SKILL

While the Eta has been used as a global model on a cubed-sphere grid (Latinović et al. 2018), almost exclusively its use was as a limited area model (LAM), covered in two preceding sections. As stated earlier, as RCM it enjoyed extensive use for a variety of purposes mostly over South American domains (e. g., Chou et al. 2020, with references to many others).

One point can be stressed here. It is almost universally believed that the nested model should improve on smaller scales, while it should accept „large scales“ as they are in its driver global model. Consequently, so called Davies’ relaxation lateral boundary conditions are applied, forcing variables in some rows around the boundary to conform to the driver model values, completely at the boundary, and less and less toward the inside of the domain. Very often investigators also apply the so-called large scale or spectral nudging inside the domain, forcing the integration variables not to depart much from those of the driver model.

It is hard to see a scientific basis for these practices. While the global driver model might be equipped with components and feedbacks missing in a LAM or RCM, if we consider just the atmospheric motion, impact of these missing components can be received via the lateral boundary conditions but large scales inside the LAM domain could still be improved if the LAM has some advantage over its driver model. The advantage could be higher resolution but can also be a dynamical core better in some ways, or both, but hardly better parameterizations because global models require very considerable parameterization efforts.

As an example, in Fig. 8 top right, average wind speed at 250 hPa of an Eta 21-member ensemble is shown, driven by a European Centre for Medium-Range Weather Forecasts (ECMWF, or EC) ensemble, with its average wind speed at the same height at top left, both at 4.5 days lead time. Space resolution of the Eta ensemble was about the same as that of the driver EC ensemble. EC analysis valid at the same time is shown at the bottom left. Mesinger and Veljovic (2020) contains more detail.

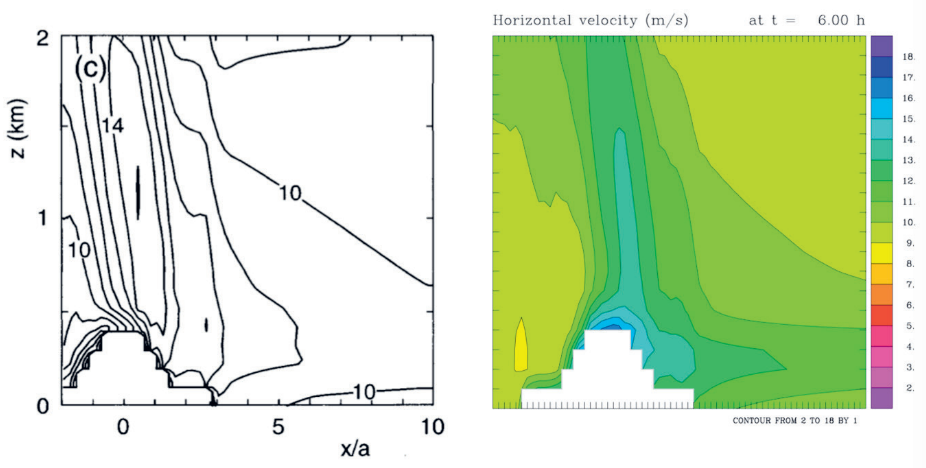

Fig. 7. Simulation of the Gallus-Klemp experiment with the Eta code, plot (c) of Fig. 6 of Gallus and Klemp (2000), left, using the sloping steps Eta code allowing for velocities at slopes in the horizontal diffusion scheme, right. From Mesinger and Veljovic (2017).

While visual impressions as those pointed out in the caption of Fig. 8 are crucial, results of models are normally assessed using some skill numbers, or scores. Three such verification scores have been used to assess the Eta skill vs. that of its driver EC model, and with each of them at 4.5-day lead time all 21 Eta members had better skill scores of 250 hPa wind speeds

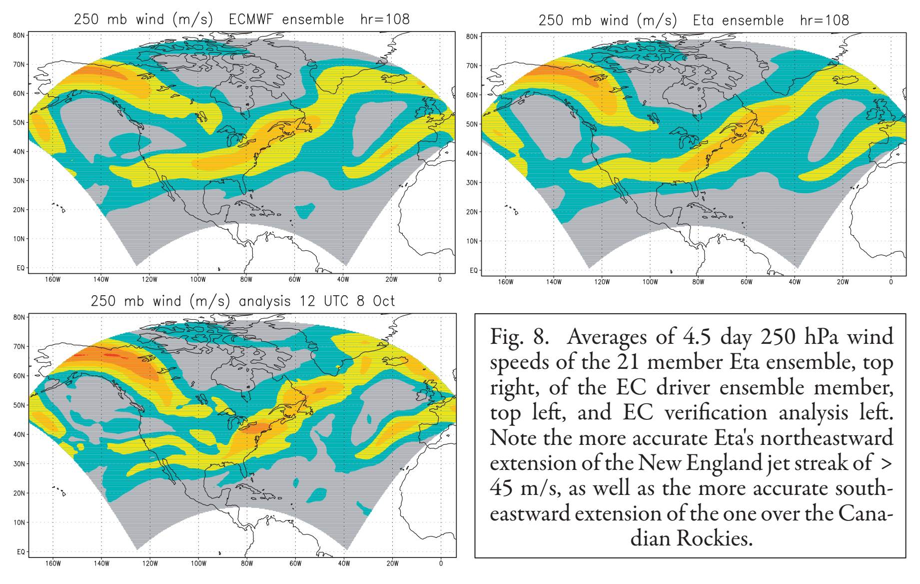

Fig. 8. Averages of 4.5 day 250 hPa wind speeds of the 21 member Eta ensemble, top right, of the EC driver ensemble member, top left, and EC verification analysis left. Note the more accurate Eta's northeastward extension of the New England jet streak of > 45 m/s, as well as the more accurate southeastward extension of the one over the Canadian Rockies.

than their driver EC members, and with two of them even more frequently (Mesinger and Veljovic 2017). Surprisingly, when switched to use the sigma coordinate the Eta also achieved better scores, although not that much better as the Eta.

5. CONCLUDING COMMENTS

Weather and climate models require many components and are nowadays never developed by a single person. But if a model that in terms of its dynamical core features was developed primarily by only two people achieves results at least comparable with a model of a major international institution, one might wonder why this has happened.

In this text two features have been listed that contributed to the Eta skill but are absent in the EC model. One is the Eta vertical coordinate resulting in quasi-horizontal coordinate surfaces, eliminating thus large pressure gradient force errors.

Another is the finite-volume slantwise and vertical advection. They not only avoided the false advection from below ground of the finite-difference scheme used previously and made a crucial contribution to the simulation of the zonda windstorm, but they also achieved consistency with the finite-volume property of the Eta Arakawa horizontal advection. This I believe has been essential for the successful performance of the Eta model as shown, including the skill of the Eta vs. the Eta using sigma.

ACKNOWLEDGEMENTS

Very many people in numerous ways enabled the today's existence and skill of the Eta model, its code and its results. To list only a few, Zaviša Janjić, Lazar Lazić, Tom Black, Eugenia Kalnay, Dušan Jović, Sin Chan Chou, Jorge Gomes, Sandra Morelli, Ivan Ristić, Katarina Veljović, too many more to mention individually, and to all of them goes my appreciation and heartfelt gratitude.

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