Eta vs sigma: Precipitation and placement of storms, Gallus-Klemp test, and 250 hPa wind skill compared to ECMWF in ensemble experiments

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Abstract. Over the years as many as five times documented tests were done comparing the Eta model against the same code but switched to use sigma and in all of them the eta version did better. Among these results, better precipitation scores, and more accurate placement of storms, stand out. A possibility that these results came because the Eta precipitation schemes were "tuned" to work best with the eta would seem to have been eliminated by the results of the parallel test comparing the Eta/EDAS system against the NMM-WRF/GSI system during the 5+ months of 2006. In this parallel the operational Eta although "frozen" for considerable time achieved better precipitation scores than the NMM-WRF that used more advanced data assimilation system, the more so the further one moved away from the data assimilation time. A weakness that received extraordinary notoriety of flow separation in the lee of the Witch of Agnesi topography, is shown to have been removed with the latest refinement of the sloping steps eta discretization. Among results presented in Veljovic et al. (Meteor. Z., 2010) were those of an experiment in which 26 Eta ensemble members driven by an ECMWF 32-day ensemble mostly had better scores in placing strong 250 hPa winds than their driver members. Trying to identify the primary cause of this perhaps surprising result 10 of the Eta members were driven by switching the vertical coordinate to sigma. While no obvious impact on 250 hPa wind scores stood out, a tendency was seen for more accurate tilt of the 250 hPa trough of the eta compared to sigma members. To test the sensitivity to resolution and also to check on the robustness of this Eta vs ECMWF result to the choice of the period a 10-member Eta experiment was rerun for a more recent ECMWF ensemble, one initialized 4 October 2012, when its resolution was higher than of that used previously. The advantage of the Eta members more frequently than not is seen again, even though this time the resolution of the Eta during the first 10 days of the experiment was about the same as that of the driver ECMWF members. Rerunning the Eta ensemble with the code switched to sigma this time however an advantage of the Eta/eta over the Eta/sigma is seen, quite considerable during the early 2-6 day period of the experiment when a deep upper-air trough was moving across the Rockies.

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1. Introduction

This paper intends to address three sets of results, all however in the context of the choice of the eta vs terrain-following or sigma coordinate. As the first, it will recall and summarize, in one place and in a journal as opposed to conference papers and internal documents, outcomes of as many as five efforts in which the Eta model was tested against its version switched to use the sigma coordinate. As in these tests precipitation scores and placement of storms received the most attention, several verifications of the same features against other sigma system models will also be pointed out as they are felt to reveal fingerprints of the eta advantages demonstrated in the eta vs sigma tests. These tests and model verifications will be summarized in the next section.

A recent removal of a sloping steps Eta weakness in flow over bell-shaped topography, or Witch of Agnesi, will be addressed in Section 3. The step-topography eta problem of flow separation in the lee of a bell-shaped topography pointed out by Gallus and Klemp (2000) was frequently cited as a demonstration of undesirability of the eta coordinate at high resolutions. This latest improvement to be addressed in the simulation of the Witch of Agnesi flow resulted from a discovery of an omission in making the horizontal diffusion code aware of the sloping steps refinement of the eta discretization. What prompted attention to the diffusion code were blow-ups of the 1-km runs in experiments over a very rough terrain, traced to numerical instability of the Eta's Smagorinsky-like nonlinear diffusion scheme. They were caused apparently by occasional too high diffusion coefficient values resulting from high values of velocity deformation at resolution and topography used. The modification addressing the problem will be summarized, leading in an unconditionally stable and monotonous Smagorinsky-like horizontal diffusion scheme. The emulation of the Witch of Agnesi flow obtained as a result will be shown and suggested to replicate to a high degree the lee flow of the Gallus-Klemp simulation they felt satisfactorily removed the flow separation they pointed out takes place with the step-topography discretization.

For our final set of experiments we shall revisit the effort we have undertaken earlier (Veljovic et al. 2010) of Eta integrations driven by ECMWF 32-day ensemble members. In these the Eta members absorbed unavoidable lateral boundary condition (LBC) errors and yet demonstrated overall a somewhat better upper tropospheric wind scores we looked into than their ECMWF driver members. We have presented this result in the framework of regional climate modeling, where many authors believe that regional climate models (RCMs) need to be subject to large-scale or spectral nudging (e.g., von Storch et al. 2000, among numerous others), to prevent their large scales from drifting to an undesirable degree with respect to those of the driver fields. But if the nested RCM is capable of even a small improvement in its large scales, more often than not so, then such large scale nudging will obviously not be helpful. Indications could be seen in the results of Veljovic et al. (2000) that the advantage of the Eta was visible particularly at a time when a deep upper-tropospheric trough was crossing the Rockies, this being reminiscent of situations in which the eta over sigma advantage stood out in several documented tests among those to be summarized in the next section. Therefore, we have redone 10 of these Eta member integrations running the Eta code switched to use sigma, and have looked at the impact. Furthermore, to check on the robustness of this Eta-favorable result, and also on the impact of resolution of the ECMWF ensemble, we have run another Eta ensemble driven by a more recent ECMWF ensemble, one initialized in October 2012, when the ECMWF ensemble was at a higher resolution than that we used earlier, of January 2009. This more recent Eta ensemble we have also rerun switching the Eta to use sigma, and have looked into the impact on 250 hPa wind scores. Finally, for more confidence on the impact of resolution, we have also rerun the same ensemble with the Eta at a lower resolution, same as that of the driver ECMWF one after 10 days. Results will be presented and implications discussed in Section 4.

The paper will end with a few concluding comments.

2. Precipitation and placement of storms

A useful feature of the eta coordinate is that with not much additional effort code can be written with a switch enabling runs using sigma coordinate. This was done and over the years a number of tests made checking on the impact of the coordinate, as follows.

In the very first test, when the Eta code with minimum physics was put together, in 1984, a run using sigma exhibited a visibly greater intensity of noise than the same run using the eta coordinate (Mesinger et al. 1988, Fig. 6). Once the Eta code was equipped with a fairly complete physics package, a test was made by Tom Black to address the then prominent systematic error of the U.S. NMC operational NGM model, a cold bias throughout the troposphere that was increasing with time. In a test including a week of twice daily forecasts the Eta showed a cold bias as well, but at 48 h only on the order of one third of that of the NGM. But when switched to sigma, the cold bias about doubled, to roughly two thirds that of the NGM (Black 1988).

In both Mesinger and Black (1992) and Mesinger et al. (1997) more accurate placements of storms, and much better precipitation scores of the eta compared to sigma runs were reported. Strong evidence pointed to both of these improvements deriving largely from storms that formed in the lee of complex Rocky mountains topography.

Thus, yet another test was run at higher resolution in 2001, on a complex low of multiple centers, shown in Fig. 1, right panel. At 1200 UTC 6 November 2000 a low was analyzed centered in eastern Kansas, with the sea level pressure of the main center at 992 hPa. An experiment was done on 48-h forecasts verifying at that time, when the 22-km operational Eta placed the low 215 km northwest of its analyzed position, left panel. The model was rerun switched to use sigma coordinate, with the result shown in the middle panel (Hui-ya Chuang, 2001, personal communication). The low is seen to have been placed still further to the north, with the position error increased to 315 km.

Prompted by this test and other forecasts of placements of prominent centers an analysis was done of position errors in placing the centers of major lows by the operational Eta and by the operational NCEP global (GFS, at the time referred to as "Aviation" or Avn) model, at 60-h lead time, during two consecutive winters, December 2000–February 2001, and December 2001–February 2002. We shall refer to these periods as "winter #1" and "winter #2," respectively, further down. Rules were set up for identification of "major" lows on NCEP

Hydrometeorological Prediction Center (HPC) 00 and 12z analyses, such as the one with its section shown in the right panel of Fig. 1, and for verification. One should note that the locations of centers such as those seen in the figure were done by human analysts, who sign their analyses, and use information if available beyond that which entered into the "machine" analysis that served as background. Verification area was chosen east of the Continental Divide, to minimize the impact of the differences in the pressure reduction to sea level; over land or inland waters, and inside hard copy forecast output maps of the two models that were routinely printed at the time. Results for the first of the two winters were displayed in two conference papers (e.g., Mesinger 2004a). Both the mean and the median position error showed a considerable advantage of the Eta.

Rules for identification of "major lows" and verification were revised prior to inclusion of the second of the two winters, since it was realized that they could be improved. The main weakness eliminated by the revision was the requirement for the depth below a given number, which was noted as not a good idea because it introduces a geographical preference into the selection process (Matt Barlow, personal communication, 2004; Bell and Bosart 1989). The rules set up, original as well as revised (Mesinger 2004b, p. 20) were such as to eliminate cases in which a small forecast error might have a model wrongly choose an alternate near-by center as the main one. For example, the deepest center of the right panel of Fig. 1 would not have qualified for inclusion, because an analyzed center between the first and the second closed isobar was not allowed.

With these revised rules, a total of 41 cases were identified in winter #1, and 38 in winter #2, respectively. In winter #1 the Avn average position error was 319 km and that of the Eta 259 km, respectively. Avn was more accurate 15 times, and the Eta 25; 1 case was a tie (with errors read off to a 25 km accuracy). Median errors of the two were the same, 275 km. In winter #2, in the same order, average errors were 330 and 324 km, and the number of wins 17 vs 19, with 2 ties. Median error of the Avn was 262.5 km, and that of the Eta 250 km. There are of course very many differences between the two models other than the vertical coordinate; but one that deserves to be mentioned looking at 2.5 day forecast errors, mostly over the continental United States, is that the Eta was using Avn forecast LBCs of 6 h earlier initial time, so that 60-h Eta results certainly had some impact of the resulting LBC error. Another point of interest is that the resolution of the Eta in winter #2 was higher than that in winter #1, 12 km/60 layers, vs 22 km/50 layers, respectively. Still, taking both winters together, the final point we wish to make is the geographical preference of the Eta "wins." Of the 44 wins of the Eta, 6 were for the centers analyzed in Colorado and Kansas, compared to only 1 for the Avn. In states sharing borders with these two, there happened to have been only 3 additional centers that qualified for inclusion, with 2 wins for the Eta and 1 for the Avn. One may note that this region of the considerable advantage of the Eta is precisely that were surface lows tend to form in front of deep upper-tropospheric troughs as they are crossing the Rockies. Southerly flow into these lows advecting moist air from the Gulf typically leads to cases of intense precipitation. An example of such a case, among others, is one analyzed in detail in Mesinger et al. (1997), with considerably better precipitation scores of the Eta compared to those of the Eta run using sigma, in spite of only a small improvement in the placement of the precipitation center.

In the light of the average and median errors just summarized the accuracy of the Eta shown in Fig. 1 is not exceptional; the case was chosen for a sigma test because of the consistently fairly accurate placement of the main center by the Eta, as opposed to very large errors of the Avn, which was placing the center as far north as between the two Dakotas at 60-h lead time, and even over North Dakota at the 48-h time (Mesinger 2001). For illustration of the Eta accuracy in its more successful cases in placing multiple centers over this area in the lee of the Rockies, in Fig. 2 we show the Eta 60-h forecast verifying at 1200 UTC 18 September 2002 (middle panel), along with the Avn 60-h forecast verifying at the same time (upper panel), and the HPC verification map (lower panel). In every subsequent forecast at 12 h intervals the Eta was showing the three centers in about the same locations, while the Avn kept forecasting a single center too far north, until the 12-h lead time, when it did place the center over South Dakota, along with one secondary center over the Ontario–Manitoba border (not shown).

In the summer of 2002, however, NCEP/EMC decided to move toward eventual implementation of the NMM (Nonhydrostatic Mesoscale Model) as its regional operational model, to be cast in the WRF (Weather Research and Forecasting) framework, as NMM-WRF. A NOAA-wide announcement at the time in support of the move for NMM, using terrain following coordinate, stated that "This choice [of the vertical coordinate] will avoid the problems . . . with strong downslope winds and will improve placement of precipitation in mountainous terrain." Consequently, development work on the operational Eta was discontinued, so that a single implementation after summer of 2003 was in land-surface, and cloud/radiation. The model was strictly "frozen" in spring of 2005, to the extent that even a "bug" discovered in land-surface after that time was not corrected.

In spite of all the NCEP/EMC mesoscale effort having been dedicated to the NMM at this stage, the 12-km Eta kept doing well in precipitation scores in comparison with the NMM that was run on the so-called "high resolution windows," at 8-km resolution. Precipitation scores of the two models, along with those of the GFS, for the last 12 months of the availability of three model scores, February 2004–January 2005, are shown in Mesinger (2008). It can be seen that the advantage of the Eta was particularly considerable in the western United States, so-called "Western Nest," where the Eta outperformed the other two models across all of the precipitation categories monitored, and very much so for the higher categories up to and including 2 in/24 hr. One could recall that the period referred to included several very heavy rain events in the U.S. West, such as that having led to the La Conchita, CA, catastrophic mudslide of January 2005.

A possibility cannot be excluded that the persistently better precipitation scores of the Eta referred to so far were a result of model precipitation schemes having been adjusted to perform best with the use of the eta coordinate. To this end perhaps a convincing information came once the NMM-WRF was considered ready for a comprehensive pre-implementation "parallel" test against the operational Eta, on the same large domain and resolution, in January 2006. Prior to that time, a new and more advanced data assimilation system, GSI, was developed for the NMM-WRF. As this parallel test of the two models with their data assimilation systems followed several years of full attention given exclusively to the NMM, presumably there was enough time to address the issue of precipitation schemes having been "tuned" to the eta, if so.

Yet, in about a five+ month parallel, as shown in Fig. 3, the Eta system still showed better precipitation scores than the NMM-WRF system, and increasingly so as one moved further away from the initial time when the different data assimilation systems should have had the most impact.

A paper by Russell (2007) is worth noticing regarding the topic addressed, as it comes to the same conclusion on the impact of the choice of the vertical coordinate but arrived at in a rather different model environment.

3. Gallus-Klemp / Witch of Agnesi test

Analysis and an experiment done by Gallus and Klemp (2000) on flow over a bell-shaped topography led to a widespread belief that the eta coordinate is "ill suited for high resolution prediction models" – as stated like this or in a similar way in quite a few papers. The problem Gallus and Klemp highlighted was separation of the flow in the lee, with very low speeds at the foot of the mountain. The sloping steps refinement of the eta discretization (e.g., Mesinger et al. 2012), led to a better result, but not to a degree as to more or less replicate the solution Gallus and Klemp obtained after presumably removing the problem.

Recently it was noted that what is referred to as horizontal diffusion (see however Mellor 1985) was not made aware of the sloping steps discretization upgrade. This was addressed and in addition the horizontal diffusion scheme was refined so as to be unconditionally stable and monotonic. Namely, blow-ups of the code's Smagorinsky-like scheme [similar to Janjić 1990, Eqs. (5.5)] run at 1-km resolution over a rough coastal topography of the state of Rio de Janeiro area have occurred, and were found to have been caused by the linear instability of the diffusion scheme. This was presumably due to a local too high value of the diffusion coefficient that resulted from high value of the velocity deformation. This is governed by the flow as it develops and so cannot be necessarily prevented by a choice of the numerical value of the coefficient used. A remedy was put in place by preventing the diffusion increment to change the sign of the five point Laplacian of the field being diffused, thus putting in place an unconditionally stable and monotonic horizontal diffusion scheme.

With these refinements of the code the Gallus-Klemp experiment was rerun, obtaining the result shown in the right hand plot of Fig. 4. For comparison, the result obtained by Gallus and Klemp using a nonhydrostatic Eta code of Gallus and Rancic in which they have modified advection schemes at points adjacent to the step corners using an assumed condition of the y-component vorticity being zero at the step corners, is shown in its left hand plot.

The alteration used by Gallus and Klemp in obtaining the left hand plot of the figure they felt has eliminated "most of the flow separation by diminishing or preventing vorticity generation at the step corners." There are no step corners in this experiment with the sloping steps discretization of the eta, and no artificial modification of schemes was used. Yet, a very high degree of resemblance of the velocity contours of the two plots can be seen, with the velocities in the lee of the obstacle of the right hand plot even somewhat greater than those of the left hand plot.

4. Added value at large scales in RCM runs

Is it possible in RCM runs to add value at large scales, or should one even attempt to achieve it, is a subject receiving considerable attention. Many authors consider that an RCM should have large scales unchanged compared to those of the driver model, and to that end even resort to "nudging" the RCM toward large scales of the driver model. However, what are large scales of the driver model and even more of an RCM is not all that clear. For a recent review of the subject see Diaconescu and Laprise (2013).

The situation is further clouded by numerous authors having run experiments using reanalysis LBCs, and even so making claims as to the ability or lack thereof of RCMs to add value at large scales. It is crucial to note that the purpose of RCMs is not to reproduce something we know, but to improve on climate integrations which are projecting changes into the future *that we do not know.* When driving an RCM with reanalysis derived LBCs the RCM has no opportunity to improve on large scales of the climate projection driver data, even though it might be able to do so. This is because such driver data have not been made a part of the experiment. Thus, a fair assessment of the optimal domain size, and the ability of an RCM to add value at different scales, is not possible.

This of course is not a problem with experiments using GCM generated LBCs, verified against analyses, e.g., such as reported by Veljovic et al. (2010); and also is not a problem with experiments of the "Imperfect Big-Brother (IBB)" type (Diaconescu et al. 2007; Diaconescu and Laprise 2013), where RCMs are driven by LBCs derived from high-resolution GCM runs after imposition of presumed errors, but verified against unmodified GCM results, mimicking real-world data.

With these issues in mind we have designed and run our experiments of Veljovic et al. (2010) which showed that most of the time Eta ensemble members had better 250 hPa wind scores than their driver ECMWF 32-day ensemble members. Main verification scores used were Bias adjusted Equitable Threat Scores (ETSa; Mesinger 2008, Brill and Mesinger 2009), reflecting placement accuracy of wind speeds greater than a chosen threshold, which we set at 45 m s^{-1}; and RMS difference between forecast winds and those of ECMWF analyses.

This result may be found surprising given that an LBC driven model has to absorb unavoidable errors coming from its LBCs, and the reputation of the ECMWF model. Looking for a major reason behind this results we ran 10 members of the 26 member Eta ensemble switched to use sigma coordinate, but no obvious advantage of one or the other coordinate could be seen in the two verification scores mentioned (not shown). However, of the 10 eta members 3 did display a visibly more accurate tilt of the 250 hPa wind speed contours at an apparently crucial 12-day time than their sigma system counterparts; one showed the opposite result. Wind speed contours of one of these 3 members with eta advantage are shown in Fig. 5, along with those of the corresponding sigma member, the driver forecast, and the ECMWF verification analysis. This situation with a major upper tropospheric trough moving across the Rockies, normally associated with formation of a surface low in front of the trough, is reminiscent of those which had a major positive impact on precipitation scores advantage of the Eta over various sigma system models (e.g., Mesinger 2004a).

While this does indicate an advantage of the eta, it seems not one of a magnitude that would be expected from a primary reason for the advantage of the Eta in 250 hPa wind scores over its driver ECMWF members reported in Veljovic et al. (2010). We have therefore continued looking into the impact of other factors. To test the sensitivity to resolution we have run a 10-member Eta experiment for a period more recent than that of Veljovic et al. (2010), initialized 0000 UTC 4 October 2012, when the ECMWF ensemble resolution was about 32 km the first 10 days, and about 63 km thereafter. The resolution of the Eta ensemble was unchanged, about 31 km. This at the same time tests the robustness of the result to the choice of the period, an issue of some interest given the impression of considerable influence of a specific synoptic event on the result reported in Veljovic et al. (2010).

The two verification scores referred to but obtained for the 10-member Eta ensemble of about October 2012 are shown in Fig. 6. Bias adjusted Equitable Threat Scores (ETSa) for wind speeds greater than 45 m s^{-1} are shown in its upper panel, and RMS wind difference in the lower panel, both at 250 hPa and verified against ECMWF analyses. Red lines refer to results of the driver ECMWF ensemble members, while blue lines refer to those of the Eta members. Although a lot of the time the values of the two sets of members are seen to be almost the same, just about always when there is a visible difference between the two it tends to be favoring the Eta. The advantage of the Eta members over its driver ECMWF members is perhaps about the same and certainly not smaller than what it was for the 26 member experiment of Veljovic et al. (2010). With the resolution difference now practically removed the first 10 days, and being reduced thereafter, it seems safe to conclude that the impact of the resolution advantage of the Eta in the results of Veljovic et al. (2010) was not significant. We shall return however to the resolution issue with more results later on here.

One feature standing out in the plots of Fig. 6 is the very visible advantage of the Eta members in placing the jet stream winds during days 2-6 of the experiment, reflected in ETSa scores of that time. For a look into the synoptic situation associated with this advantage of the Eta we show in Fig. 7 the plots of the ECMWF 250 hPa wind speed analyses at 0000 UTC 7 October 2012, upper panel, and of 1200 UTC 8 October 2012, lower panel. Note that the former of these two times, that of the upper panel, corresponds to the prominent spike at day 4 of the blue ETSa line of the plots of Fig. 6, while the latter, that of the lower panel, corresponds to the time of 12 hours following the peaks of both the blue and the red lines of the ETSa plots of the figure. We see that this situation of the visible advantage of the Eta is once again that of an intense upper level trough moving over the Rockies. Recall that this is the situation normally accompanied with formation of a surface low in the lee in front of the upper level trough. These lows tend to be associated with considerable precipitation, fed by the advection of moist air from the Gulf northward into the system as it is being developed.

Using the present ensemble result, based on ECMWF ensemble more recent and of higher resolution than that of Veljovic et al. (2010), we have renewed our efforts to identify candidate reasons for the advantage of the Eta. We have run two experiments. The first was to rerun the 10 Eta ensemble members but with the code switched to use sigma coordinate. The resulting scores, same as shown in Fig. 6 but with the scores of the 10 Eta/sigma members added in orange, are shown in Fig. 8. In contrast to the experiment done on the 2009 ensemble of Veljovic et al. (2010), this time the Eta/eta members do demonstrate an overall advantage. During days 2-6 of the considerable advantage of the Eta members over the ECMWF ones, the Eta/sigma members show higher ETSa scores than the driver members as well, but less so and during a shorter time period. The Eta/sigma members are having higher ETSa scores that the Eta/eta ones during about the days 8-13, but this advantage is overall somewhat smaller than that of the Eta/eta of the earlier period. As to the RMS scores, lower panel, they clearly confirm the advantage of the Eta/eta members during the earlier period, but not nearly so much the advantage of the Eta/sigma members during the later period.

As our second experiment we have rerun the 10 Eta members but using a lower resolution, of 63 km, about the same as that of the ECMWF members after 10 days. The results, same as in Fig. 6 but with the 63-km scores added in turquoise, are shown in Fig. 9. We see that, perhaps surprisingly, no clear benefit can be noticed from the higher resolution of the Eta 31-km experiment compared to that of the 63-km one – at least not to a degree that could be claimed to have significantly contributed to the advantage of the Eta over the driver ECMWF ensemble. We have no doubts that the higher resolution members had to show advantages at lower levels where the more detailed topography should have enabled some small-scale features to have developed more realistically than with the lower resolution, but at the 250 hPa elevation this impact – at least with the verification scores we are looking at – does not stand out. At most, one could claim a small advantage of the 31-km over the 63-km ensemble during the later part, around days 5-6, of the initial period of the very visible advantage of the Eta. Presumably scores from this earlier period, when the skill these ensemble runs have must be at a synoptically useful level, should be looked at with more significance than their skill at later times, at days around 20 and more, when the placing of jet stream level winds according the ETSa scores shown is not much if at all better than random.

5. Concluding comments

We find our ensemble results summarized and shown here to support the results of previous deterministic tests demonstrating the benefit from the choice of the eta vs sigma coordinate, although the degree of the advantage we have been pointing at might not be at a level that all readers will find convincing. While the advantage of the choice of the eta we feel did make in the results shown a visible contribution to the success of the Eta over the driver ECMWF ensemble, contributions of other aspects are required to explain the visible advantage of the Eta members shown in our Fig. 6.

Resolution must be generally the first candidate that comes to mind but judging from the results of our resolution experiment shown in Fig. 9 the resolution did not make a significant contribution. Thus, one is left wondering as to what are the features that along with its coordinate are enabling the Eta to absorb its LBC errors and yet do a little better than its ECMWF driver members.

We believe that it is the totality of the Eta dynamical core design, which we referred to as "finite-volume+" (Mesinger et al. 2012) that is primarily responsible for this performance. In addition to the eta coordinate, the components of this dynamical core include the Janjić (1984)

Arakawa scheme written for the B/E grid but conserving energy and enstrophy as defined on the C-grid, van Leer type finite-volume vertical advection of dynamical variables (Mesinger and Jovic 2002), and conservation of energy in space differencing in transformations between the kinetic and potential energy (Gavrilov, now Zupanski, in Mesinger et al. 1988).

A feature that also deserves to be listed is the Eta LBC scheme, which unlike the customary relaxation scheme of just about all other operational LAMs, and various RCMs, makes an effort to be consistent with the mathematical nature of the problem (e.g., Mesinger and Veljovic 2013). Last but not least, it should be noted that we have intentionally chosen our domain to be quite large compared to domain sizes typically used in RCM experiments, and to have it placed so as to have its central region in the lee of the major north-south topographic barrier, Rocky Mountains, being aware that this is an area where the Eta model has frequently had results more accurate than some of the other models.

One might wonder if a single general "take home" message might follow from the results reported on in the preceding section, relevant for groups working in RCM environments. We feel it is that if an RCM is found to require nudging of its large scales toward those of the driver model for satisfactory results, it is a good idea to try to find out why.

But as to the traditional NWP or more generally "seamless modeling" communities, we find that the totality of results of the preceding three sections strongly suggests that almost exclusive reliance by major modeling centers on terrain-following coordinates is unfortunate, as thereby a chance is being missed to use relatively simple dynamical cores that can handle arbitrarily steep topography at high resolutions, with results improved in ways that are not negligible.

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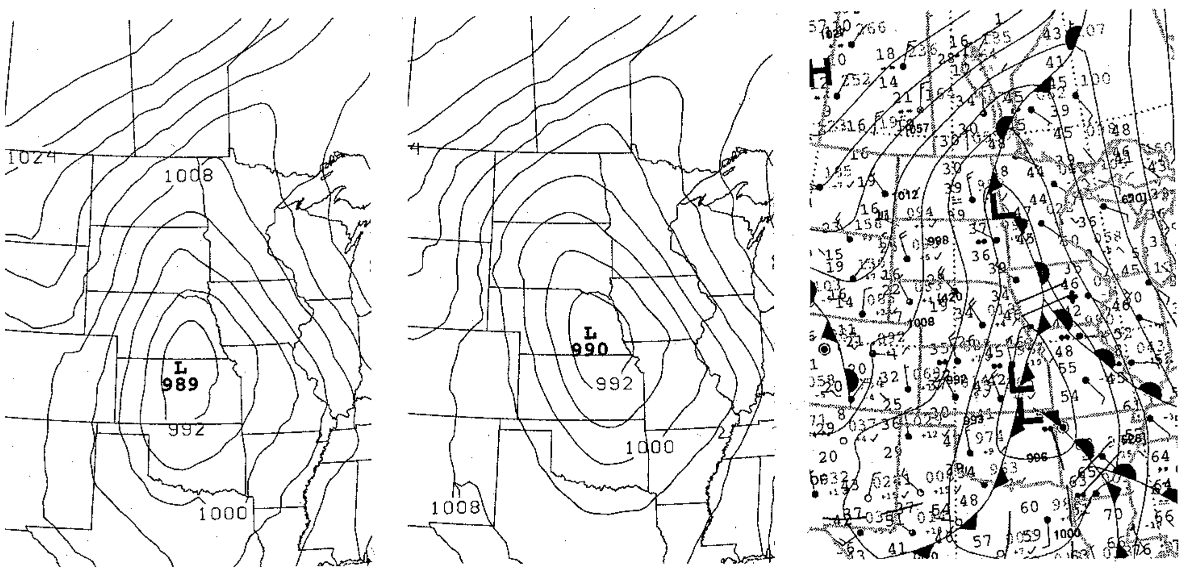

Fig. 1. The Eta Model 48 h forecasts valid 1200 UTC 6 November 2000, done using its operational eta code of the time (left panel), same but run using the sigma coordinate (middle panel), and the Hydrometeorological Prediction Center (HPC) verification analysis (right panel). The position error of the low of the Eta forecast is 215 km, and that of the Eta sigma coordinate forecast 315 km.

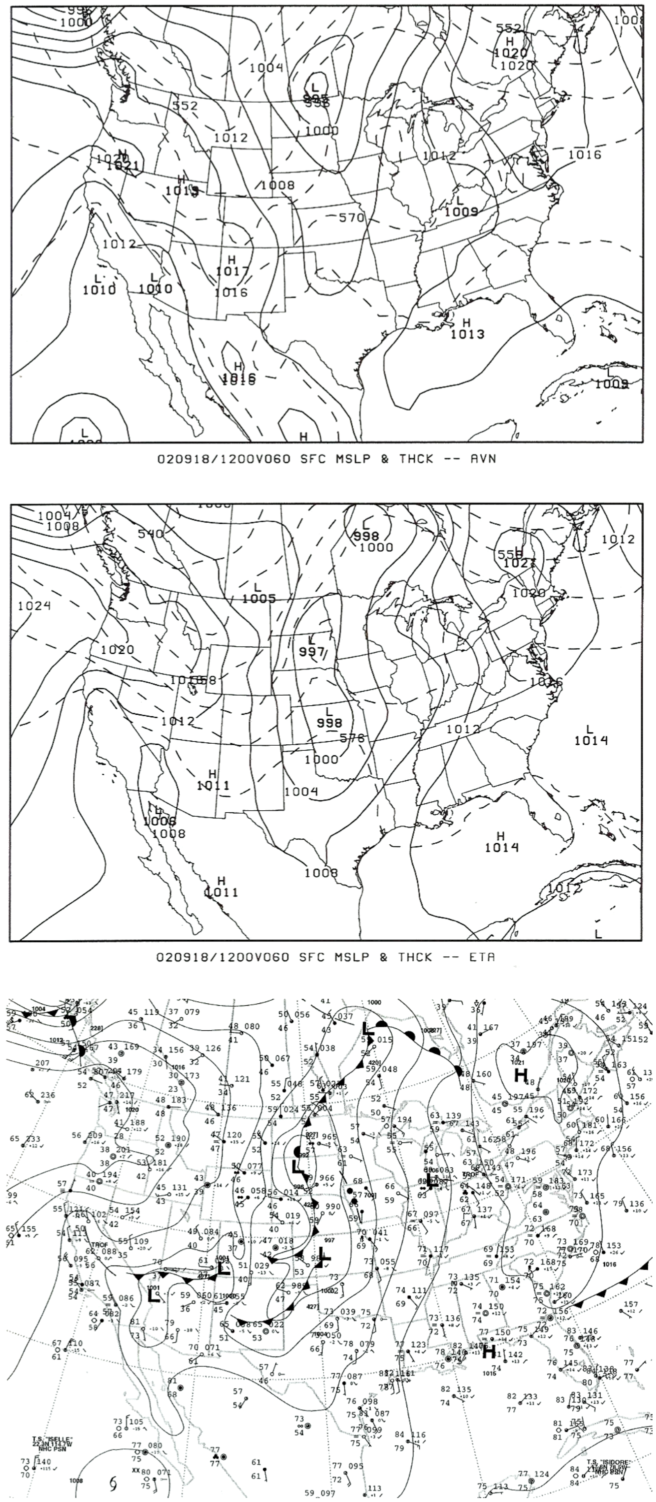

Fig. 2. The NCEP Avn model operational 60 h sea level pressure forecast valid 1200 UTC 18 September 2002, top; same but of the Eta, middle, and the Hydrometeorological Prediction Center (HPC) verification analysis, bottom. Note that the HPC analysis contains estimates of sea level pressure at each stamped center; they are 992 for the center over South Dakota, 997 for the one over Kansas, and 1000 hPa for the one over Ontario, respectively.

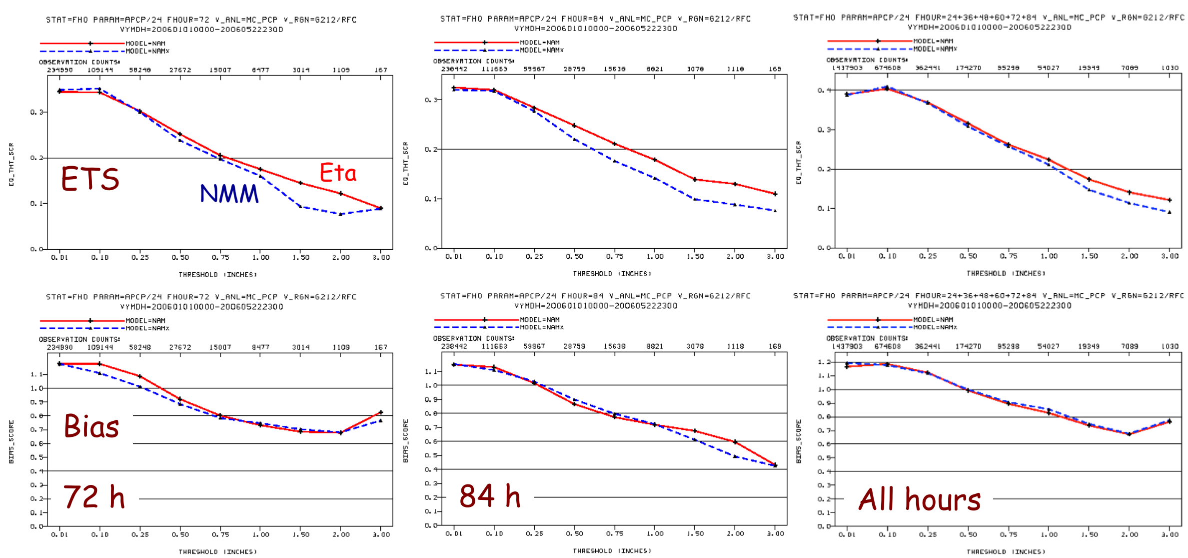

Fig. 3. 24-h precipitation Equitable Threat Scores (upper panels) and Bias Scores (lower panels) of the Eta model/EDAS (red) and NMM-WRF/GSI (blue), of the 1 January-22 May 2006 parallel, run at 12-km resolutions. 24-h precipitation thresholds are increasing from 0.01 to 3 in/24 hours along the abscissas of the plots. Verifications at 72 h (left), 84 h (middle), and combined 24, 36, 48, 60, 72 and 84 h (right). After DiMego (2006).

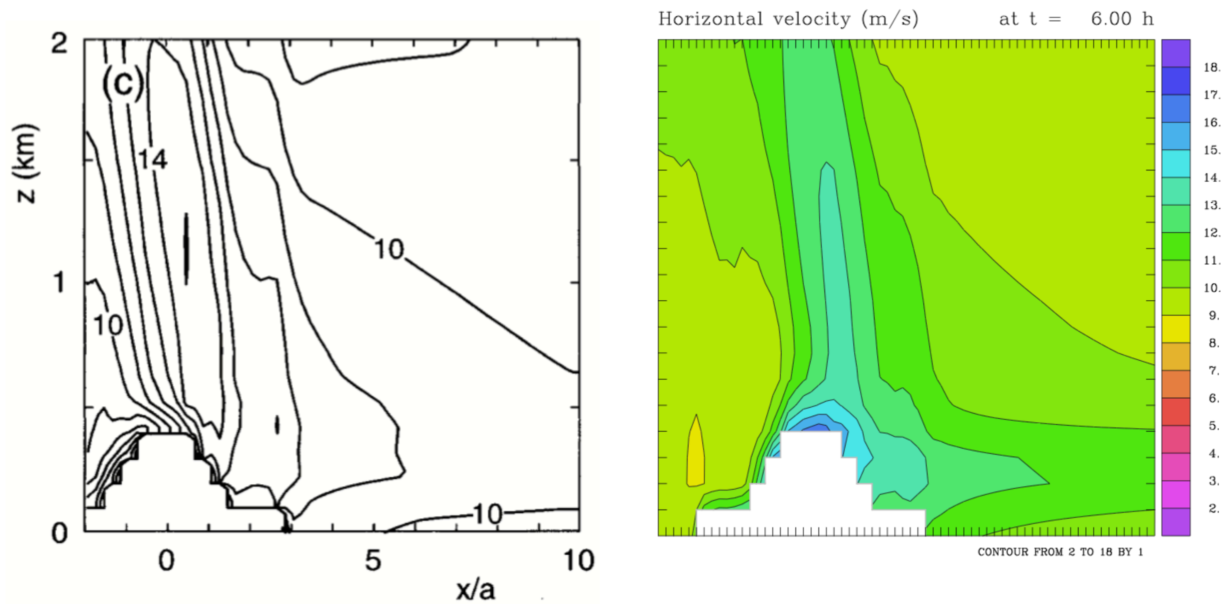

Fig. 4. Simulation of the Gallus-Klemp experiment with the Eta code allowing for velocities at slopes in the horizontal diffusion scheme, right hand plot. The plot (c) of Fig. 6 of Gallus and Klemp (2000), left hand plot.

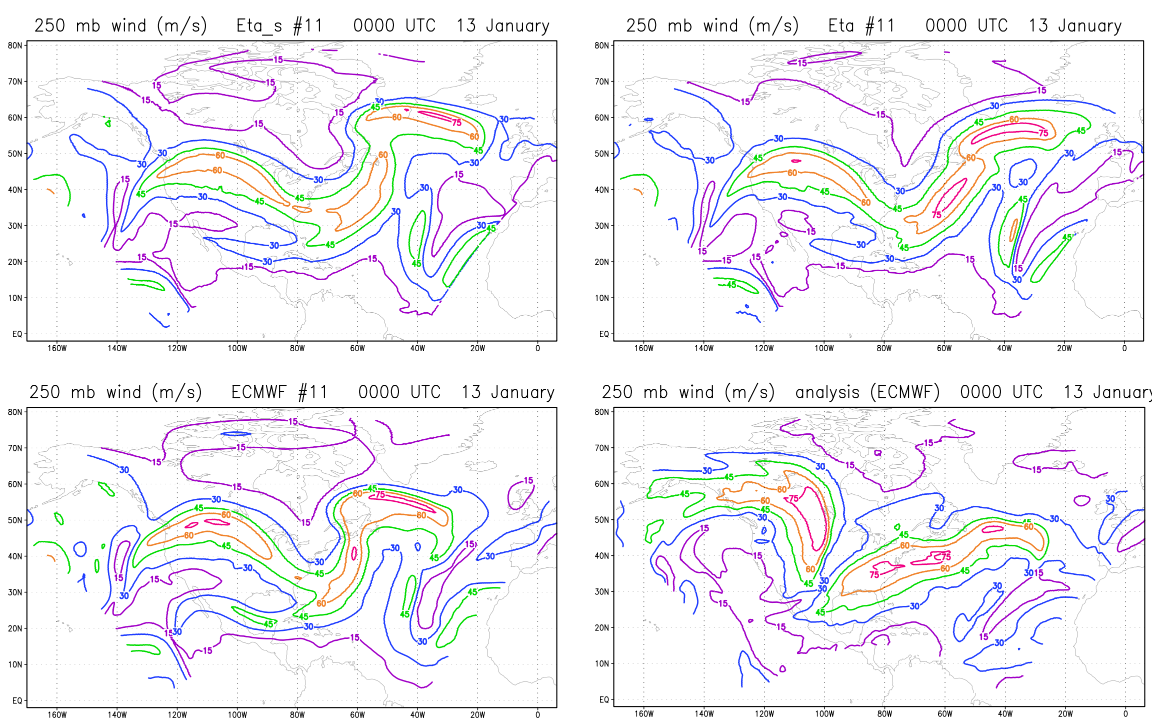

Fig. 5. Contours of the 250 hPa wind speeds of 12-day forecasts of the Veljovic et al. (2010) Eta member 11 run using sigma coordinate, top left; same but using the eta, top right; same but of the ECMWF ensemble member 11 used to drive these Eta forecasts, bottom left. Same except ECMWF analysis verifying at the same time, bottom right.

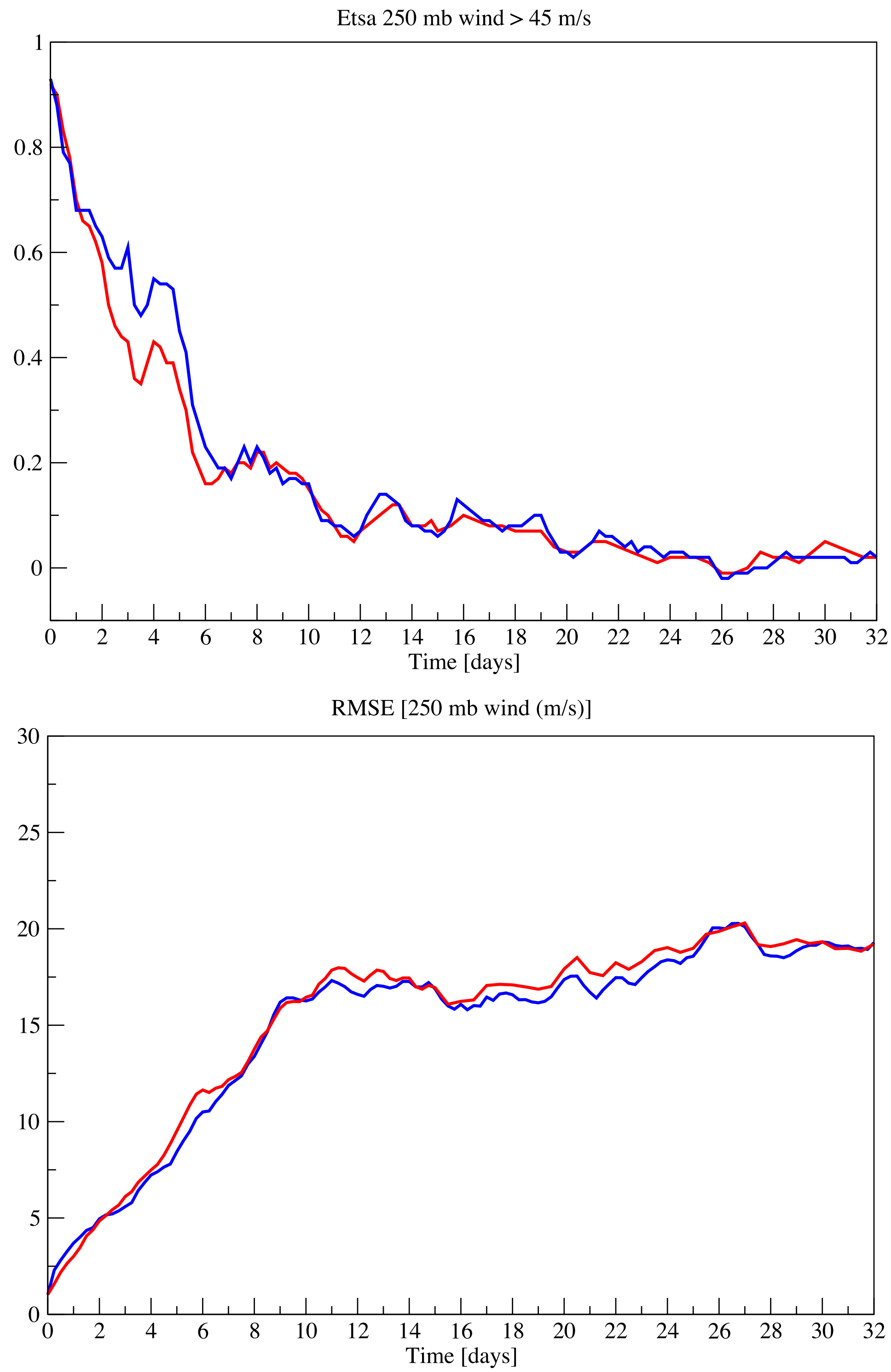

Fig. 6. Bias adjusted ETS scores of wind speeds greater than 45 m s^{-1}, upper panel, and RMS wind difference, lower panel, of the driver ECMWF ensemble members (red) and Eta members (blue), both at 250 hPa and with respect to ECMWF analyses. Initial time is 0000 UTC 4 October 2012.

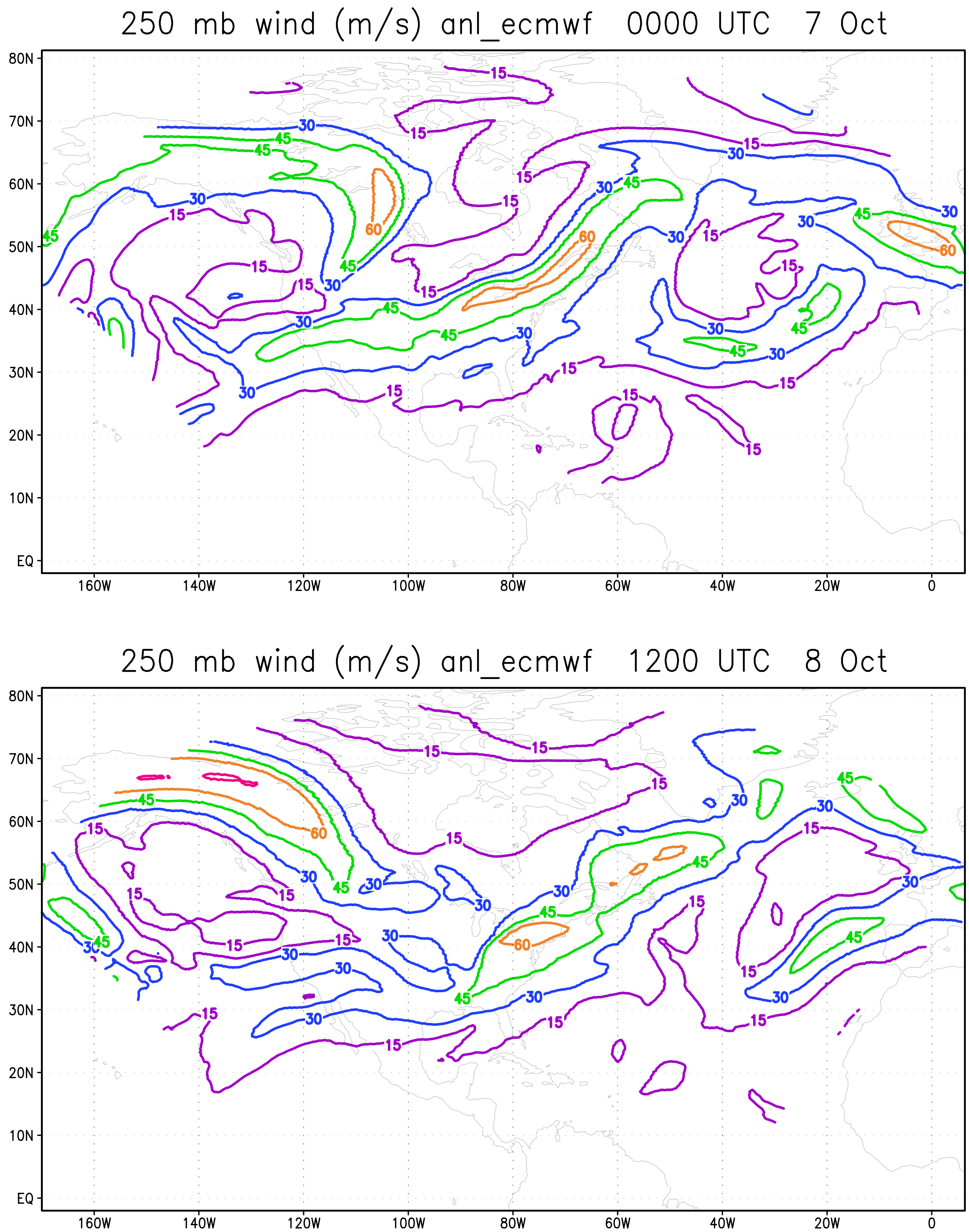

Fig. 7. Contours of the 250 hPa wind speeds, in m s^{-1}, of the ECMWF analysis valid at 0000 UTC 7 October 2012, upper panel, and of that valid at 1200 UTC 8 October 2012, lower panel. Note that these times correspond to day 3.0, and 4.5, respectively, of the plots of Fig. 6.

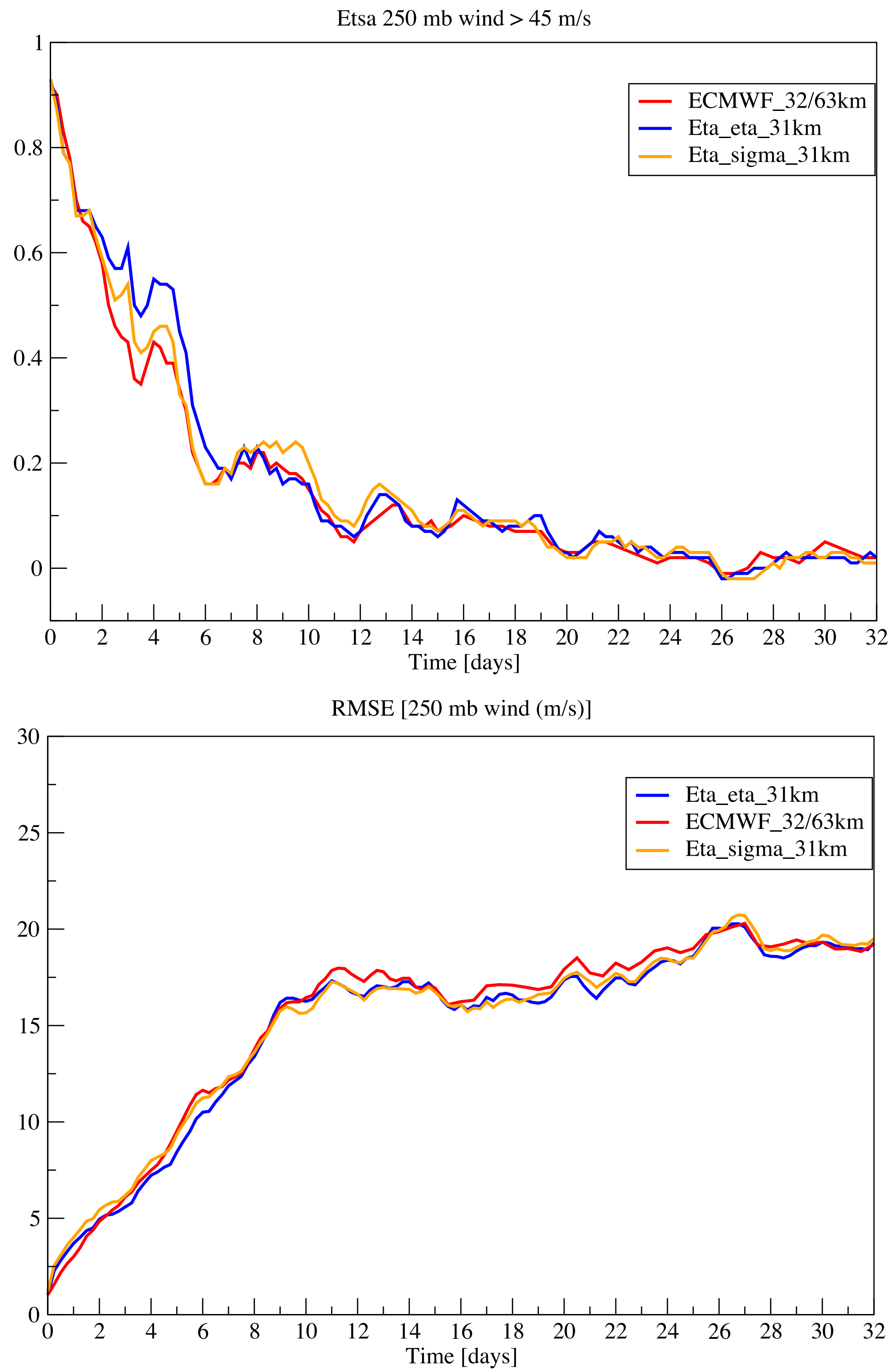

Fig. 8. Bias adjusted ETS scores of wind speeds greater than 45 m s^{-1}, upper panel, and RMS wind difference, lower panel, of the driver ECMWF ensemble members (red), Eta members (blue), and Eta members run using sigma coordinate (orange), all at 250 hPa and with respect to ECMWF analyses. Initial time is 0000 UTC 4 October 2012.

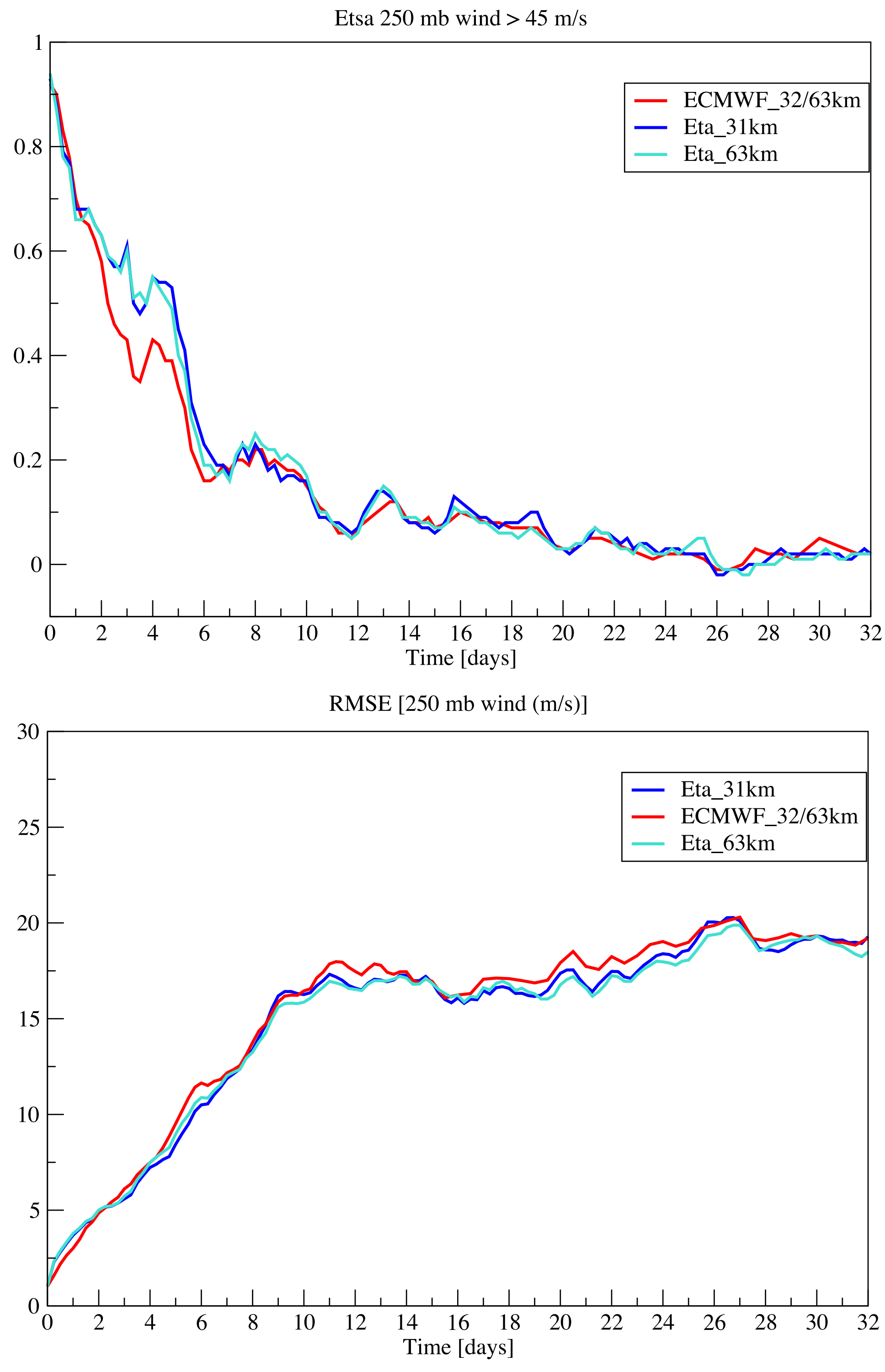

Fig. 9. Bias adjusted ETS scores of wind speeds greater than 45 m s^{-1}, upper panel, and RMS wind difference, lower panel, of the driver ECMWF ensemble members (red), Eta members run at 31 km resolution (blue), and Eta members run at 63 km resolution (turquoise), all at 250 hPa and with respect to ECMWF analyses. Initial time is 0000 UTC 4 October 2012.