Specification of External Forcing for Regional Model Integrations

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Submitted to Monthly Weather Review

Submitted on 2008/05/14

Revised on 2008/08/13

As of 2008/08/13

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ABSTRACT

The effect of vertical and time interpolations of external forcings on the accuracy of regional simulations is examined. Two different treatments of the forcings, one with conventional lateral boundary nudging and the other with spectral nudging are studied. The main result is that the accuracy of the regional simulation increases very slowly as the number of forcing field levels increase when no spectral nudging is used. Thus, for better simulation, it is desirable to have as many forcing levels as possible. By contrast, spectral nudging improves the regional model simulation when reasonably large numbers of forcing field levels, at least up to 9 levels, are given. The accuracy worsens drastically when the number of forcing levels is reduced to less than 9.

To improve the simulation, particularly when the forcing field is given at a coarse vertical resolution and at lower time frequency, an incremental interpolation method is introduced. The incremental interpolation in the vertical significantly improves the regional simulation at all numbers of forcing field levels. The improvement is largest at very low vertical resolution. Incremental interpolation in time also works excellently, allowing the use of daily output for reasonably accurate downscaling. By using a combination of spectral nudging and incremental interpolation, it is possible to make a reasonably accurate downscaling from the forcing given daily at 3-5 levels in the vertical with low overhead. This considerably reduces the amount of data currently believed to be required to downscale global model integrations.

1. Introduction

Integration of a regional numerical model requires time varying forcing fields at the lateral boundaries. These forcing fields are taken from the larger scale model forecasts or analysis, either from a global model or from a coarser resolution regional model that covers the target domain. The latter method is known as a multiple nesting. A regional model that uses some form of spectral nudging to reduce the systematic error of the model (Kida et al., 1991; von Storch et al 2000; Kanamaru and Kanamitsu 2006) requires forcing fields over the entire regional domain.

Since the horizontal resolution and the vertical levels of forcing fields are generally different from those of regional models, horizontal and vertical interpolations are necessary. Issues regarding potential errors due to the interpolation of the forcing fields have been mentioned in Warner et al., (1997), Denis et al., (2002) and others but they have not been studied intensively, probably because these errors were considered to have only a minor influence on the regional simulation. This may be true for a short-range regional forecast problem for which the initial condition is of greater importance, while the lateral boundary condition has less influence. However, the lateral boundary conditions may have a significant influence on the downscaling at climate time-scale, since they continuously influence the interior of the regional domain. The external forcings will be even more important for their use within the regional domain when the spectral nudging is applied.

We can surmise some apparent impacts of lateral boundary specifications on a regional simulation. The imbalance between wind and mass fields at the lateral boundary may be likely to excite artificial gravity waves, contaminating the integration within the domain. The bias in the regional model climatology and lateral boundary forcing might cause significant deterioration in the simulation (Misra and Kanamitsu, 2002). Again, these impacts will be much more significant when spectral nudging is applied.

Until now, there has been no comprehensive study that provides the adequate vertical and time resolutions of forcing fields required for accurate regional model integrations. In fact, the numbers of forcing levels and time frequencies have been somewhat arbitrarily chosen and very high resolutions in the vertical and in time, of the order of 25 hPa in the vertical and 6 hours in time, are believed to be required. Unfortunately, this high resolution forcing output restricts the number of cases of downscaling that can be performed. For example, the North American Regional Climate Change Assessment Program (NARCCAP; Mearns et al., 2005), aiming at downscaling global warming simulations over the continental U.S., Canada, and Mexico, limits the number of global warming simulation models to only four. The slow progress in the downscaling of ensemble seasonal forecast is also due to the practical difficulties in storing high resolution output from large ensemble members.

In this paper, we will examine the impact of the vertical resolution of the forcing field (Section 3). We will then introduce a new interpolation scheme that improves accuracy of a regional model simulation by the use of very coarse vertical resolution forcing fields with a small overhead (Section 4). In the last part of Section 4, we will present the importance of the time frequency of the forcing data and show that the new interpolation scheme applied in time can also improve the downscaling.

In evaluating the forcing specifications, we take into account the fact that the treatment of the lateral boundary is very different from model to model and the results are strongly dependent on the way the lateral boundary conditions are treated, namely, the width of the relaxation zone, the magnitude of relaxation and the way relaxation is applied, as well as many other factors. The use of spectral nudging (von Storch et al 2000; Kanamaru and Kanamitsu, 2007), which improves regional simulations, makes the specification of the forcing fields even more critical, since the large scale part of the forcing is used within the regional domain. Because of this, we decided to perform two experiments, one using the conventional lateral boundary zone nudging without any forcing within the domain and the other using spectral nudging, with the hope that the results of this paper might be widely applied to a variety of regional models.

2. Method

a. Global and regional models

The Scripps Experimental Climate Prediction Center (ECPC) global and regional spectral models (GSM and RSM) are used in this study. The ECPC GSM was based on the medium range forecast model used at the National Centers for Environmental Prediction (NCEP) for making operational analyses and predictions (Kanamitsu et al., 2002a). The physical processes in the GSM and RSM are identical for this study, which are similar to those in the NCEP / Department of Energy (DOE) Reanalysis 2 project (Kanamitsu et al., 2002b, hereafter R2) with some updates associated with the use of the Relaxed Arakawa-Schubert deep convection scheme (RAS; Moorthi and Suarez, 1992) and the Noah land surface scheme (Ek et al., 2003). The basic performance of the GSM has been well documented (*e.g.*, Caplan et al., 1997, Kanamitsu et al., 2002a) as an operational global weather forecast model, and has shown comparable performance in several global model intercomparison studies (*e.g.*, Kang et al., 2002). We chose T62 horizontal resolution (about 200 km) and 28 vertical sigma levels, the same resolution as that used in R2, for the global model integration. The sea surface temperature and ice distribution used in R2 were applied as lower boundary conditions.

The RSM has also been tested in many downscaling studies including the recent 57-year California Reanalysis Downscaling at 10 km scale (Kanamitsu and Kanamaru, 2007). A unique aspect of the model is that the spectral decomposition is applied to perturbation, which is defined as difference between the full field and the time-evolving background global analysis field.

In this study, the RSM was integrated with two different lateral boundary treatments: 1) applying a conventional nesting method, using sufficiently wide lateral boundary nudging zones, but leaving the interior of the domain free of any forcing (LBN) and 2) applying a spectral nudging scheme that forces the large scale within the domain to be that of the forcing fields (SN). For the nudging scheme, an improved form of the selective scale bias correction (SSBC; Kanamaru and Kanamitsu 2007, hereafter SSBC07) was used. The SSBC allows for the use of narrower lateral boundary nudging zones and weaker lateral boundary nudging relaxation. Based on a large number of sensitivity experiments, some of which are described in Yoshimura and Kanamitsu (2008), the SSBC has been improved from the original form proposed by Kanamaru and Kanamitsu (2007) by the following changes: 1) only the rotational part of wind is used with a slightly stronger nudging, 2) area averaged humidity is no longer corrected (area averaged temperature is still corrected), and 3) the boundary zones were narrowed from 23 % to the 5 % of the sides of the domain. Both temperature and humidity are very important to control dynamical circulation, but in an experiment in which wind is also forced, these two become more reliant on winds, causing imbalance between mass and wind fields and resulted in larger errors. From this experience, we decided to force only area averaged temperature and leave the humidity alone.

b. Design of the experiments

The control experiment (CTL) is an integration of the regional model using the lateral boundary conditions taken from the global model's output, whose sigma-coordinated vertical levels are placed identically to those of the regional model. The difference in topography between low resolution global and high resolution regional models requires vertical interpolation due to the difference in surface pressure (the spline interpolation is used for this procedure). But the differences of pressure at the same height in the two models are never too large (the maximum pressure difference is of the order of 1-2 hPa) and thus the difference introduced by this vertical interpolation is small.

For other experiments, we used 17 pressure level data created from the sigma coordinate CTL's data. The vertical interpolation procedure from the pressure to the sigma level is the same as that used in the NCEP operational post-processing procedure, as described in Eq.(1).

$$F_{P2S} \equiv \Im_{p\to s}(\Im_{s\to p}(F_a)) \qquad (1)$$

where F is a set of global prognostic fields in full sigma-level coordinate (*e.g.*, wind fields, temperature, and humidity), and suffices $_{P2S}$ denotes forcing field used for the experiments, and $_a$ denotes analysis data, which was used in the CTL simulation. $\Im_{p\to s}$ and $\Im_{s\to p}$ are interpolation operators from pressure-to-sigma and sigma-to-pressure coordinates, respectively. Note that Reanalysis data or model output is usually available in pressure-level coordinate, thus the data which we used in these experiments are already in the form of $\Im_{s\to p}(F_a)$.

We selected the following five combinations of pressure levels to generate the forcings.

17L: 17 levels (1000, 925, 850, 700, 600, 500, 400, 300, 250, 200, 150, 100, 70, 50, 30, 20, and 10 hPa),

9L: 9 levels (1000, 925, 850, 700, 600, 500, 400, 300, and 200 hPa),

7L: 7 levels (850, 700, 600, 500, 400, 300, and 200 hPa),

3L: 3 levels (850, 500, and 200 hPa), and

2L: 2 levels (850 and 200 hPa).

Hereafter, we will call the experiments forced by these interpolated forcings as P2S. For the LBN experiments, the 7L and 2L experiments were excluded. All the experiments are listed in Table 1, including those described further below.

We may also consider nudging only the levels the forcing is applied. However, this cannot be done easily in practice, since sigma level is a function of surface pressure, and therefore the standard pressure level forcing need to be applied to different model levels at different locations depending on the surface elevation. This regionally dependent forcing and spectral nudging, which is not local from its definition, makes it impossible to apply such procedure. In other words, locally dependent nudging and scale selective nudging does not work together.

The domain of all the experiments covers part of North and Central America including the U.S. and Mexico, (135-65W and 10-50N), with 50 km horizontal and 28-level vertical resolutions (identical to the forcing). The forcing is taken from R2. The integration period is January 1-11, 1985, which is somewhat arbitrarily chosen. Each set of experiments consists of 4 ensemble members that start at 00Z on the 1^{st}, 2^{nd}, 3^{rd}, and 4^{th}, respectively, and all end at 00Z January 11. These ensemble integrations are used to obtain the statistical significance of the difference between the experiments. The last 4-day averages (00Z 7^{th} to 00Z 11^{th} January) are used for all the investigations described below. After running 30 days of simulations and confirming that a conclusion is robust and independent on the simulation period, we set the simulation period as short as possible to reduce the computational cost.

In order to quantify how well the lateral boundaries were specified, we used the differences of near surface temperature, wind, and precipitation between the CTL and the experimental runs. These quantities were chosen for the following reasons: they are not directly nudged, they represent near surface small scale detail, and they are the quantities most frequently utilized in application studies. Note that there are two CTLs for the two different lateral boundary treatments, *i.e.*, LBN-CTL and SN-CTL, which are significantly different (more than the difference between CTL and 3L of LBN; figures not shown), and we used corresponding CTL for the computation of the differences. Because of this difference between the respective CTLs, there is no single reference state of near surface wind, temperature and precipitation to which the regional simulations can be compared in our experimental setting. Therefore direct comparisons of accuracy between the LBN and SN experiments are not possible and it is necessary to introduce some other measure. In Appendix A, we made an effort to directly compare LBN and SN, by using 500 hPa height as a reference variable.

3. Number of vertical levels of the forcing fields

a. Results from the conventional lateral boundary nudging integrations (LBN).

The dark bars in Figure 1 present a comparison of the root mean square difference (RMS) between CTL and the experiments with 3 different forcing level specifications (17L, 9L and 3L) for the conventional lateral boundary nudging (LBN). The left-most gray bars, the mean RMS among the ensemble members, indicate the variance of the simulations due to the difference of the initial conditions. This variability is considered to be the difference due to unpredictable or uncontrollable part of the control regional simulations. The figure shows that for the 2-meter temperature, the RMS increases steadily from 17L to 3L. For the 3L experiment, the RMS reaches 1.8K. For the 10-meter wind speed, the RMS seems to level off at 9L. Contrary to the temperature and winds, precipitation deteriorated to a large degree even for 17L, and 3L was much worse. In summary, when conventional lateral boundary nudging is used, it is desirable to use as many levels from the forcing field as possible.

b. Results from the spectral nudging (SN) integrations.

The dark bars in Figure 2 show the results from the same experiments as section 3a but using spectral nudging (SN). Firstly, compared to LBN (Fig. 1), the variability among the ensemble members is much smaller for SN, particularly for 2-meter temperature and precipitation. It is clear that SN produced similar RMS errors as LBN for the number of forcing field levels larger than or equal to 9. On the contrary, the RMS of SN for levels less than or equal to 7 is much larger than the RMS of LBN, except for precipitation. This indicates that the simulation with spectral nudging depends strongly on the accuracy of the forcing fields, which is less accurate if interpolated from a coarser vertical resolution forcing fields. This was expected since SN utilizes the forcing fields within the entire domain. By this reason, for LBN, the results are not so sensitive to the vertical levels of the forcing data since they were used only at and near the lateral boundaries. The huge discontinuity between the 9L and 7L was not simply a result of the lack of lowest-level (*i.e.*, 1000 and 925 hPa levels) forcing field, but rather a combination of the lack of forcing at both the lower and upper levels. The RMS of an additional experiment with 6 vertical pressure levels (at 1000, 925, 850, 700, 600, and 500 hPa) was found to be as large as that of 7L, indicating that the lack of lower levels is not a contributor to the degradation (figure not shown).

From these experiments, we came to the following conclusions for regional model integrations using spectral nudging. Spectral nudging gives similar accuracy of the regional simulation compared to conventional lateral boundary nudging, if a sufficient number of forcing field levels are available. If the vertical resolution of the forcing field is poor, the SN simulation deteriorates quickly. The vertical resolution of the forcing field is critical to the quality of the regional simulation when spectral nudging is used, and at least 9 forcing levels are required for reasonably good regional simulation. The specification of the levels in the vertical is not so critical, but evenly distributed levels in the vertical seem to be preferred.

As described in 2.b, our method of evaluation is not against the observation, but against the downscaling performed by the "best possible" forcing. We believe that if the downscaling by best possible forcing has less skill than the downscaling by coarser resolution forcing against observation, the problem is not in the specification of the forcing but in the model itself. We are not addressing the skill of the model in this paper.

4. Incremental interpolation

a. Description of the concept and procedure

In the previous experiments, vertical interpolation was performed using fields at given pressure levels. Since no information is available between the given pressure levels, the vertical scale less than the pressure level thickness cannot be resolved. The pressure level output most commonly utilized in a downscaling is produced from a forecast or a data assimilation system. These outputs are produced by interpolating the fields from model coordinate surfaces to specific standard pressure levels. Since the models usually have very high vertical resolution in the planetary boundary layer (and other altitudes, such as in the stratosphere and near the tropopause in some models), the vertical interpolation to coarser pressure levels result in the loss of information present in the high vertical resolution model field. In order to avoid this loss, many downscaling projects require forcing output in very high pressure level resolution, of the order of 25 hPa. This high vertical resolution increases the amount of the model output, burdening the global model simulation producers. In addition, even 25 hPa may not be sufficient for resolving fine vertical structure in the planetary boundary layer. Thus, it would be very convenient if a method for recovering the fine-scale vertical structure from given coarse vertical resolution fields could be established.

In this section, we propose a method to recover such fine vertical scale structure and examine how such a procedure can improve the regional simulation. The method we introduce here is a common procedure used widely in objective analysis, called incremental interpolation (*e.g.*, Bloom et al., 1996, Joergensen and Moehrlen, 2003). This method uses short range forecast with a global coarse resolution model (or a regional coarse resolution model covering an area larger than the area in consideration) as a guess, and vertically interpolates the difference between the external forcing field and the guess at the standard pressure levels to model levels. Since only the increment is interpolated, the fine structure in the guess field is preserved after the interpolation. Note that in the extreme case of no forcings, the fine scale detail in the initial guess field is preserved. To avoid model inconsistencies, the global model or the coarse resolution regional model used to produce the guess field should be as close as possible to the regional model used for downscaling in terms of model vertical resolution, level placement, numerics and physical processes.

There may be an argument against this requirement, *i.e.*, the model to be used to make the guess should be as close as possible to the model that generated the external forcing. Our argument is based on the consideration that the use of the model consistent with the downscaling model reduces undesirable large scale systematic error resulting from the model inconsistency. The inconsistency of model between external forcing and downscaling model always exist and cannot be eliminated but the use of the incremental interpolation may be a way to reduce this inconsistency. More results of the downscaling using external forcing and regional model which are completely independent are presented in section 4.c.

If we use incremental interpolation used in objective analysis to the vertical interpolation of the forcing, the forcing field F will be written as:

$$F = F_g + \Im_{p\to s}(\Im_{s\to p}(F_a) - \Im^*{}_{s\to p}(F_g)) \quad (2)$$

where F_g and F_a are initial guess field and analysis fields in full sigma-level coordinate, and $\Im_{p\to s}$ and $\Im_{s\to p}$ are interpolation operators from pressure-to-sigma and sigma-to-pressure coordinates, respectively. The terms inside the parenthesis on the right hand side of Eq.(2) is the increment on standard pressure levels, and application of vertical interpolation operator $\Im_{p\to s}$ to the increments implies "interpolation of increment". Note that the interpolation operators used in $\Im_{s\to p}(F_a)$ and in $\Im^*{}_{s\to p}(F_g)$ are generally not exactly the same, since vertical interpolation (frequently called post-processing) used in the models between analysis and guess models are different. As schematically shown in Figure 3, the incremental interpolation maintains the small scale vertical structure in the guess field, thus errors are much smaller than the simple interpolation, F_{P2S}.

For our application of the Eq.(2), we approximate the equation into the following form:

$$F_{INC} \equiv F_g + \Im_{p\to s}(\Im_{s\to p}(F_a)) - \Im_{p\to s}(\Im^*{}_{s\to p}(F_g)) \quad (3)$$

In this approximation, the nonlinear operator $\Im_{p\to s}$ is assumed to be linear. This form is much more convenient and easy to apply, since programs written to convert pressure to sigma level can be used without any modification. We may also interpret the Eq.(3) as correction of F_{P2S} (the second term on the RHS of Eq. 3 as defined in Eq.(1)) by adding $F_g - \Im_{p\to s}(\Im^*_{s\to p}(F_g))$, which is a loss of information by the vertical interpolation. In this interpretation, assumption of the linearity of $\Im_{p\to s}$ is not necessary.

A guess field is produced with a global model that runs from certain time earlier. Thus a cycle of the processes for making F_{INC} is:

1. Run the ECPC GSM from 6 hour and generate a guess field, F_g.
2. Interpolate F_g to pressure levels $\Im_{s\to p}(F_g)$ where pressure levels in the forcing data are available, and interpolate this output again to sigma levels to produce $\Im_{p\to s}(\Im_{s\to p}(F_g))$.
3. Calculate the difference (increment) between the interpolated guess ($\Im_{p\to s}(\Im_{s\to p}(F_g))$) and interpolated external forcing F_{P2S} at sigma levels.
4. Add the increment to the guess field at all sigma levels, F_g, to make F_{INC}.
5. Go back to the first step but for the next time level using the F_{INC} data as the initial condition.

The regional model integrations using the forcing data which are produced from the incremental interpolation method are hereafter referred to as "INC" (also see Table 1).

The cycle was done from some period before the regional downscaling period (about 10 days) to eliminate impact of the initial condition of the very first cycle. The overhead of the incremental interpolation regarding computational time and storage is relatively small compared to those required to do regional downscaling itself, since only a coarse (*e.g.*, T62 (~200 km) scale) global model integration is required. In case of the experiments in this paper (50km downscaling for N. America), additional overhead in time was about 10-15 % of a regional model integration. When finer resolution or larger domain is used for regional model, the relative cost decreases accordingly. Moreover the process is required only once for a common period of multiple downscaling simulations, such as those for different regions, ensemble experiments, etc. Necessary storage sizes can be the same for regional simulations with (INC) and without (P2S) the incremental interpolation and with the analysis field (CTL), since the data size of the global forcing data (F_{INC}, F_{P2S}, and F_a) are all the same.

b. Impact of the incremental interpolation: In the case using R2 as forcing field

Now let's go back to Figure 1. The white bars in the figure present the results of incremental interpolation for conventional nudging in the lateral boundary zones only (LBN). It shows a very clear improvement in reducing the RMS up to at least 9 pressure levels. A small improvement can be seen for 3L, but all of the improvements are highly statistically significant.

The white bars in Figure 2 present the same results for the cases with spectral nudging (SN). The incremental interpolation significantly improves regional simulation for nearly all ranges of pressure levels with the exception of precipitation in 17L, 9L, and 3L. The performance of the 7L results became very similar to that of 17L without the incremental interpolation (P2S-17L), and even 3L produced a reasonably good regional simulation compared to P2S-17L. Therefore, from a practical point of view, approximately 5 pressure levels will be sufficient to obtain reasonably accurate regional simulations. Comparisons of the geographical distribution of 2-meter temperature, 10-meter wind, and precipitation are shown in Figures 4, 5 and 6, respectively. We should note that the improvement is more apparent for 2-meter temperature and 10-meter winds. Reasonable improvement is also seen in precipitation.

c. Impact of the incremental interpolation: Independent forcings

The above results are somewhat biased toward the forecast model used, since the driving field, Reanalysis 2, utilized an older version of the forecast model used in this study. The differences in the model physics are fairly large, which include the convective parameterization of the simplified Arakawa-Schubert convection scheme (SAS; Pan and Wu 1995) vs. RAS (Moorthi and Suarez 1992), the long wave radiation of Schwartzkopf and Fels (1975) vs. the Chow schemes (Chow and Suarez, 1994), and the Oregon State University land model (OSU; Pan and Mahrt 1987) vs. the Noah land schemes (Ek et al., 2003). However, the model numerics and other components are similar. In order to examine the effect of the model that generates a guess field, we repeated the experiment using one of the CMIP3 outputs for current climate, the Japanese MIROC (Model for Interdisciplinary Research on Climate; Hasumi and Emori, 2004) 20th century T106 simulations, as external forcings at pressure levels, $\Im_{s\rightarrow p}(F_a)$. In this case, the model that produced the simulation was completely independent from the model used in downscaling. In these experiments, only the spectral nudging was used in order to simplify the discussion. We named the experiment "SNMiroc". We used the downscaling made from 23 pressure-level forcing as a control (SNMiroc-CTL) and performed two runs, 7L and 3L. See Table 1 for a summary of the experiments.

Figure 7 shows the RMS of the experiments against the control (SNMiroc-CTL). The incremental interpolation (INC) significantly improves the simulation compared to the simple interpolation (P2S), for both the 7L and 3L experiments. Thus the incremental interpolation that uses the guess created by the independent forecast model is still very significant. By comparing the RMS with those from the experiments discussed previously (Figure 2), the disagreement against CTL for 2m temperature in the P2S runs became much greater for the current experiment (about 1.5 to 2 times greater than the previous experiments). Note that this comparison may not necessarily be fair since the basic states of the two experiments are very different.

d. Incremental interpolation in time

In this subsection, the effect of the updating time interval of the external forcing field is examined. The same experiments described in sections 3 and 4.b were repeated, but the forcing fields were provided every 24 hours instead of every 6 hours. The experiments consist of various vertical resolutions in forcing fields; from the full 28 sigma levels to 17, 9, and 3 pressure levels (see Table 1). In order to simplify the study, we performed the downscaling with spectral nudging (SN) only. This set of experiments is referred to as "SN24h" hereafter. Before examining the incremental time interpolation, we briefly checked the effect of incremental vertical interpolation for 24 hourly external forcing. Comparing the white bars (INC) and gray bars (P2S) in Figure 8, it can be seen that the vertical incremental interpolation also worked well for the integrations using the 24-hourly forcing data, which was consistent with the previous results using the 6-hourly forcing data. The degree of the improvement was slightly smaller than the previous results.

Incremental interpolation in time (INC-T) is performed by linearly interpolating the increments at 24 hours into 6 hourly intervals and adding it to the forecast at corresponding forecast hours as shown in the equation below and schematically shown in Figure 9.

$$F_{INC-T,N} \equiv F_{g,N} + [\Im_{p\to s}(\Im_{s\to p}(F_{a,M})) - \Im_{p\to s}(\Im^{*}{}_{s\to p}(F_{g,M}))] \times N/M \quad (4)$$

where additional suffices N and M are forecast time in the target interval and the interval of the forcing data. Note that Eq.(4) and Eq.(3) become identical when N=M, meaning that the incremental interpolation in time is only meaningful to the data with fine vertical structure at full sigma levels including those processed by the vertical incremental interpolation.

A set of the INC-T experiments is named “SN24h6h” and results are shown in Figure 8. The RMS is only calculated at 00Z on each day. This figure shows that the incremental interpolation in time worked quite efficiently to reduce the errors in surface temperature and wind for all experiments, even for the runs using the full 28-levels. Even though the RMS did not dramatically drop in precipitation, it worked positively to make the averaged precipitation closer to the CTL simulations (figure not shown). Overall, these experiments suggest that we should use the incremental interpolation in time if only daily data are available.

5. Summary and Conclusions

In this study, we examined how the external forcing affects the accuracy of the regional downscaling and introduced an incremental interpolation method to improve the regional simulation, when the forcing field was given at relatively coarse resolution in the vertical and in time. The model system used in this study was the ECPC global to regional spectral model (G-RSM). The experiments were run over the continental U.S. with 50km resolution using NCEP/DOE Reanalysis 2 (R2) as a forcing, but the results would not vary significantly if other resolutions and forcing were used. Two regional model lateral boundary treatments were considered; conventional lateral boundary nudging within the specified lateral boundary zones and spectral nudging, which utilizes external forcing over the entire domain.

The control experiments were performed using the forcing at all of the regional model sigma levels, which are the same between R2 and the regional model used in this study. The experiments were made from various runs for which the R2 fields interpolated at various numbers of pressure levels were interpolated in the vertical to the regional model sigma levels. It was found that for the simple vertical interpolation, spectral nudging was very important in stabilizing and improving the regional model simulations, but a fairly large number of forcing field levels, at least up to 9 levels, were required to make reasonably accurate regional simulations. When conventional lateral boundary nudging was used, it was desirable to have as many forcing levels as possible; however, the accuracy of the downscaling was relatively insensitive to the number of forcing field levels.

In order to improve the vertical interpolation, incremental interpolation was introduced. The method utilizes global model short range forecast as a guess and vertically interpolates the difference between the model guess and the forcings at the pressure levels. This incremental interpolation significantly improved the regional simulation at all numbers of forcing field levels, but the improvement was most significant at very low numbers of levels. Even 3 levels in the forcing field were sufficient to produce as accurate a regional simulation as the one in which 17 forcing field levels were used without incremental interpolation. The improvement was apparent for 2-meter temperature and 10-meter winds, but was more moderate for precipitation. The incremental interpolation in time also worked excellently, allowing the use of daily output for reasonably accurate downscaling.

Additional incremental interpolation experiments for downscaling MIROC (one of the members that participated in CMIP3), demonstrated that incremental interpolation also works for the downscaling of coarse resolution simulations and analysis which are completely independent from the model used in the downscaling.

The shortcoming of incremental interpolation is that it requires a coarse resolution global (or regional) forecast model integration. However, since the integration of a coarse resolution global model is fairly inexpensive compared to the regional model, the overhead for incremental interpolation is probably of the order of 10-15%, but this is strongly dependent on the regional model domain size and resolution.

The relation between incremental interpolation and double nesting should also be noted here. From the point of view of the incremental interpolation, double nesting is identical to producing a guess field at the lateral boundaries, except that the guess is used as a lateral boundary value for the nested regional model integration without correction. The incremental interpolation method corrects the guess using pressure level values from the forcing field levels at the given lateral boundary location, which should better agree with the external forcing fields. In this sense, double nesting is a version of incremental interpolation without using pressure level forcing data.

Acknowledgments:

The first author thanks Postdoctoral Fellowships for Research Abroad by the Japan Society for the Promotion of Science. This work was funded by the California Energy Commission Public Interest Energy Research (PIER) program, which supports the California Climate Change Center (Award Number MGC-04-04) and NOAA (NA17RJ1231). The views expressed herein are those of the authors and do not necessarily reflect the views of NOAA. The authors sincerely thank Mr. G. Franco for his assistance in performing this research. We would also like to thank Dr. D. Cayan for continuous encouragement throughout this study. MIROC data were kindly given by JAMSTEC/CCSR research group, with particular help from Dr. M. Hara. The assistance of Ms. D. Boomer in refining the writing is appreciated.

APPENDIX A: Comparison of Conventional Lateral Boundary Nudging (LBN) and Spectral Nudging (SN)

We utilized RSM simulated 500 hPa geopotential height to directly compare

LBN and SN, by assuming the Reanalysis 500hPa height, which is used to force the RSM, as the truth. Note also that it is best suited for an examination of the large scale part of the simulation, since the small scale features tend to lose their amplitude with height and only the large scale features remain at this level. The forcing data used in this examination include the original NCEP/DOE Reanalysis 2 data in full 28 sigma-levels as a control (CTL) and those prepared from various combinations of pressure-level layers, namely 17L, 9L, and 3L. For the experiments using pressure-level data, simple vertical interpolation (P2S) and incremental interpolation (INC) were applied. The experiments are summarized in Table 1.

Figure A1 shows the root mean square differences (RMS) of 500 hPa height from Reanalysis 2. The first point worth mentioning is that SN (diagonally shaded bars in the figure) was always superior to LBN for the all the experiments performed. The RMS of LBN CTL is about 15 m, whereas that of SN is a little more than 10 m. The improvements by SN were most apparent in the P2S-9L and INC-3L experiments. In these experiments, the errors decreased to levels similar to those of the control experiments. Figure A1 also tells us that incremental interpolation is effective in reducing RMS for LBN in the 9L, but not the 3L experiments. By contrast, the incremental interpolation showed little improvement for 17L and 9L, in the SN experiments, but it showed a large improvement for the 3L experiment.

If we assume that the 500 height RMS of about 15 m (the value obtained in the CTL experiment with the LBN) is an acceptable level of error, then without the incremental interpolation 17 pressure levels are required to match this level of error for the simple vertical interpolation, while 9 levels would be sufficient when spectral nudging is applied. When incremental interpolation is used, 9 levels are needed for the simple lateral boundary nesting method (saving nearly 50% in external forcing storage), but 3 levels are sufficient for the spectral nudging method (a savings of 85%).

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Figure Captions

Figure 1. Experiments with the conventional lateral boundary nudging (LBN). Ensemble means of area averaged RMS between CTL (an experiment with full sigma level forcings) and experiments with different numbers of vertical levels used as forcings are shown for 2-meter air temperature (a), 10-meter wind speed (b) and precipitation (c). Dark gray and white bars denote the use of a simple vertical interpolation (P2S) and the incremental interpolation (INC) for the forcings. Light gray bars indicate the RMS between the CTL ensemble members. The error bars indicate standard deviations of the RMS of the ensemble members and one and two asterisks (*) denote the 95% and 99% significance levels of the difference from the same P2S experiments.

Figure 2. Same as Figure 1 but from the integration with spectral nudging (SN). In this set of experiments, the 7- and 2-level cases are added.

Figure 3: Schematic representation of the vertical incremental interpolation.

Figure 4: 4-member ensemble mean of 4-day averaged surface air temperature using spectral nudging (SN) is shown by contours, and the difference between the downscaling experiment and the control is shown by shades. A simple interpolation of the forcing data with a limited number of vertical levels was used to make the global base data for P2S experiments (a and c), whereas the incremental interpolation scheme was used for INC experiments (b and d). The numbers of vertical levels used are 9 levels (1000~200 hPa) for (a) and (b) and 3 levels (1000, 500, and 200 hPa) for (c) and (d).

Figure 5: Same as Figure 4, but for wind speed. The difference between the experiment and the control (shades) is calculated by $((U_{exp}-U_{ctl})^2+(V_{exp}-V_{ctl})^2)^{1/2}$.

Figure 6: Same as Figure 4, but for precipitation.

Figure 7. Similar to Figure 2, but for the experiments with independent forcing data using spectral nudging (SNMiroc). RMS is shown for 2-meter temperature, 10-meter wind speed, and precipitation between the regional simulations performed by 23 forcing levels (CTL) and 7 and 3 levels (7L and 3L).

Figure 8: Similar to Figure 2, but comparing the impact of daily forcing data (SN24h) and 6-hourly forcing data by the temporal incremental interpolation (SN24h6h) for different numbers of pressure levels selected in the forcings. All experiments used the spectral nudging (SN). CTL(6h) is the 6-hourly data with full sigma levels and is used as a reference for all other results. Dark gray bars correspond to the use of simple vertical interpolation (P2S), while white bars

denote the use of incremental interpolation in the vertical (INC) for the daily forcings. The black bar is the result of the temporal incremental interpolation in addition to the vertical incremental interpolation (INC-T). The asterisks show the 99 % significance for the difference between INC from P2S (black) and INC-T from INC or CTL (white).

Figure 9: Schematic representation of the incremental interpolation in time.

Figure A1: Ensemble mean of area averaged RMS in 500 hPa height between each experiment and the Reanalysis 2 forcing field. The sets of experiments with LBN (bars without diagonal lines) and SN (bars with diagonal lines) with several differently prepared forcing fields are shown: the control experiments using full sigma-level data (CTL; light gray); and those with forcing fields made by the simple interpolation (P2S; dark gray) and the incremental interpolation (INC; white) using 17 pressure levels (1000 ~ 10 hPa; 17L), 9 levels (1000 ~ 200 hPa; 9L), and 3 levels (1000, 500, and 200 hPa, 3L). Error bars indicate standard deviations of ensemble members.

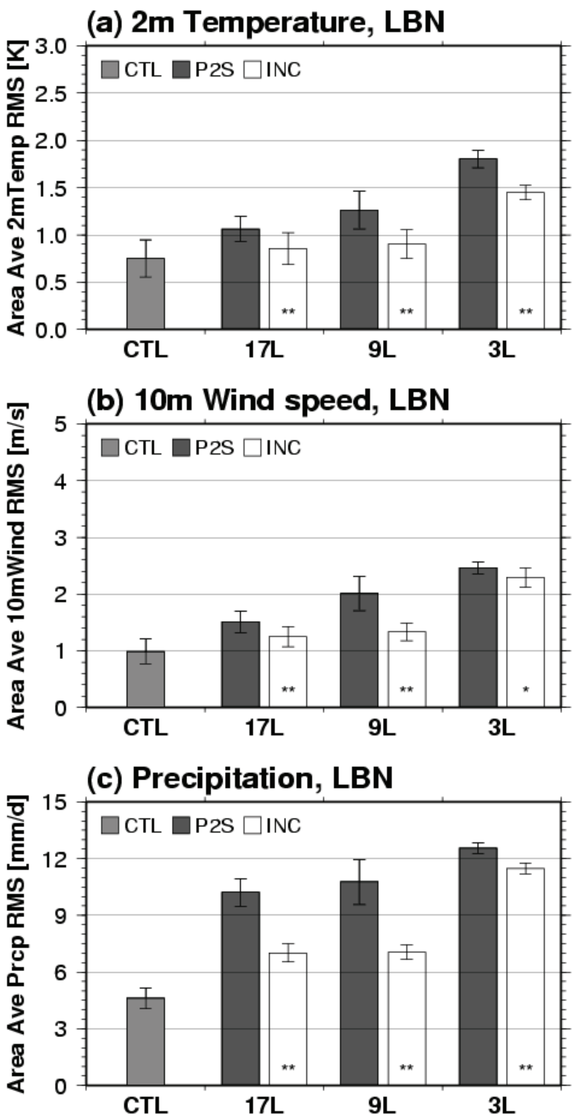
Table 1: List of the experiments performed in this study. The Xs show the regional model integrations performed with different lateral boundary treatments in the vertical column, and the different data used in the horizontal column.

	CTL	P2S					INC/INC-T				
		17L	9L	7L	3L	2L	17L	9L	7L	3L	2L
6-hourly update of forcing data											
LBN	X	X	X		X		X	X		X	
SN	X	X	X	X	X	X	X	X	X	X	X
SNMiroc	X^{*1}			X	X				X	X	
24-hourly update of forcing data											
SN24h	X	X	X		X		X	X		X	
24-hourly update of forcing data with incremental interpolation in time to 6-hourly											
SN24h6h	X^{*2}						X^{*3}	X^{*3}		X^{*3}	

*1: Data at 23 pressure levels are used as the control due to lack of full leveled sigma data.

*2: The incremental interpolation in time (INC-T) is processed to the 24-hourly forcing data in full sigma levels (SN24h-CTL data).

*3: The incremental interpolation in time (INC-T) is processed to those processed by the vertical incremental interpolation (SN24h-INC data).



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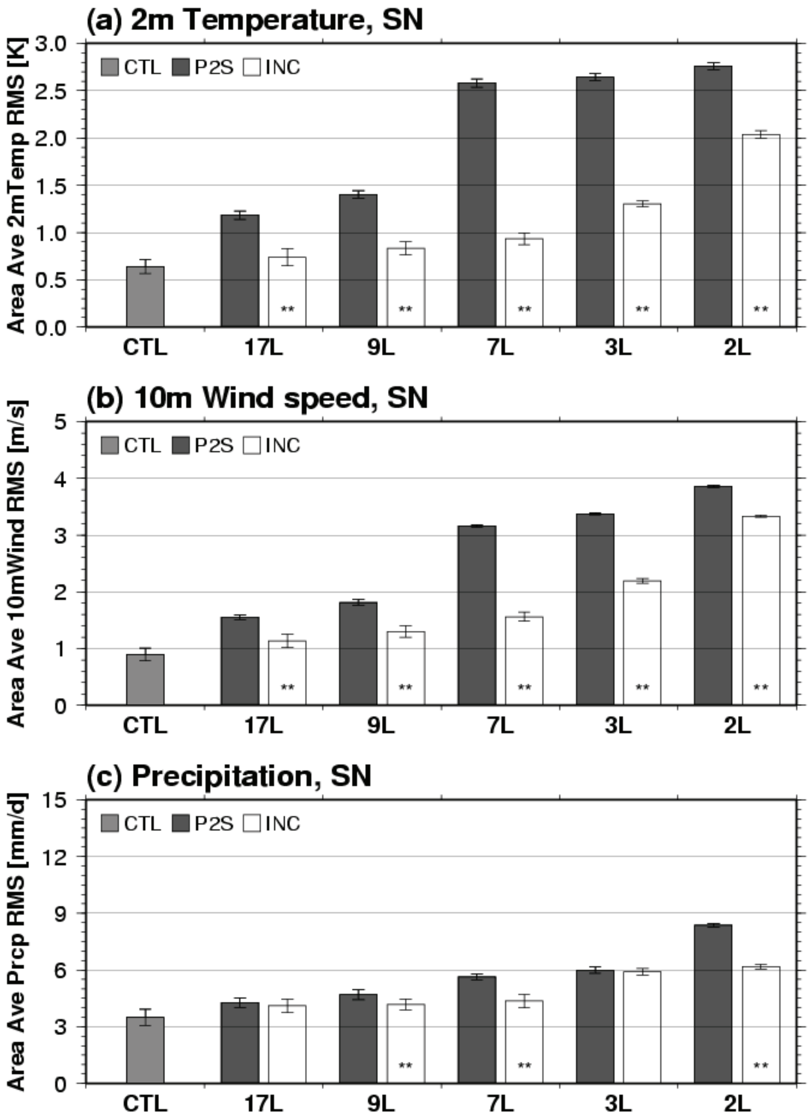

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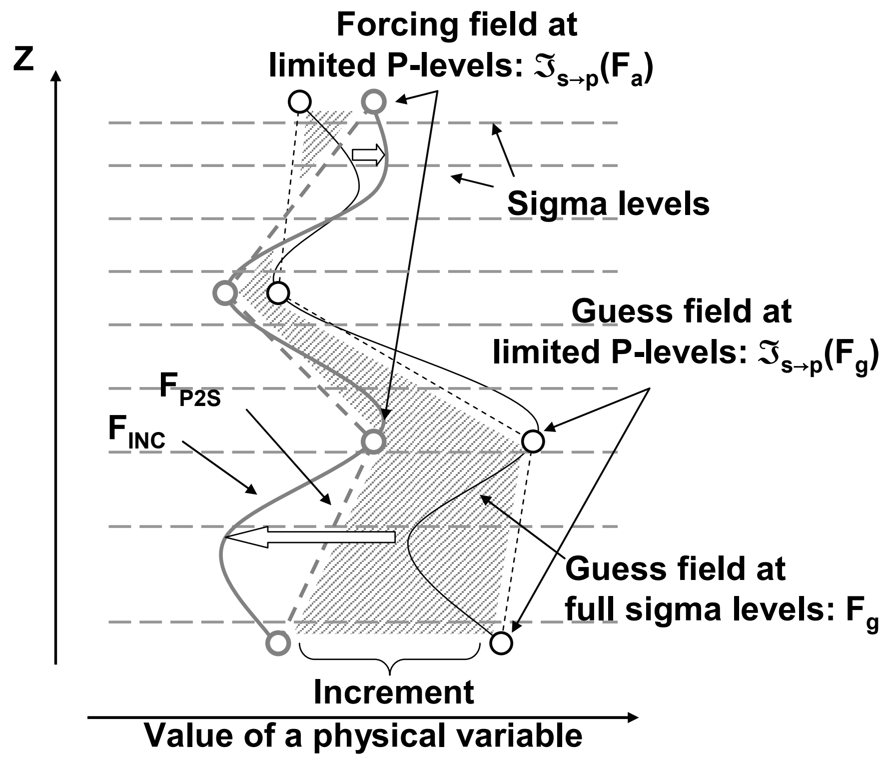
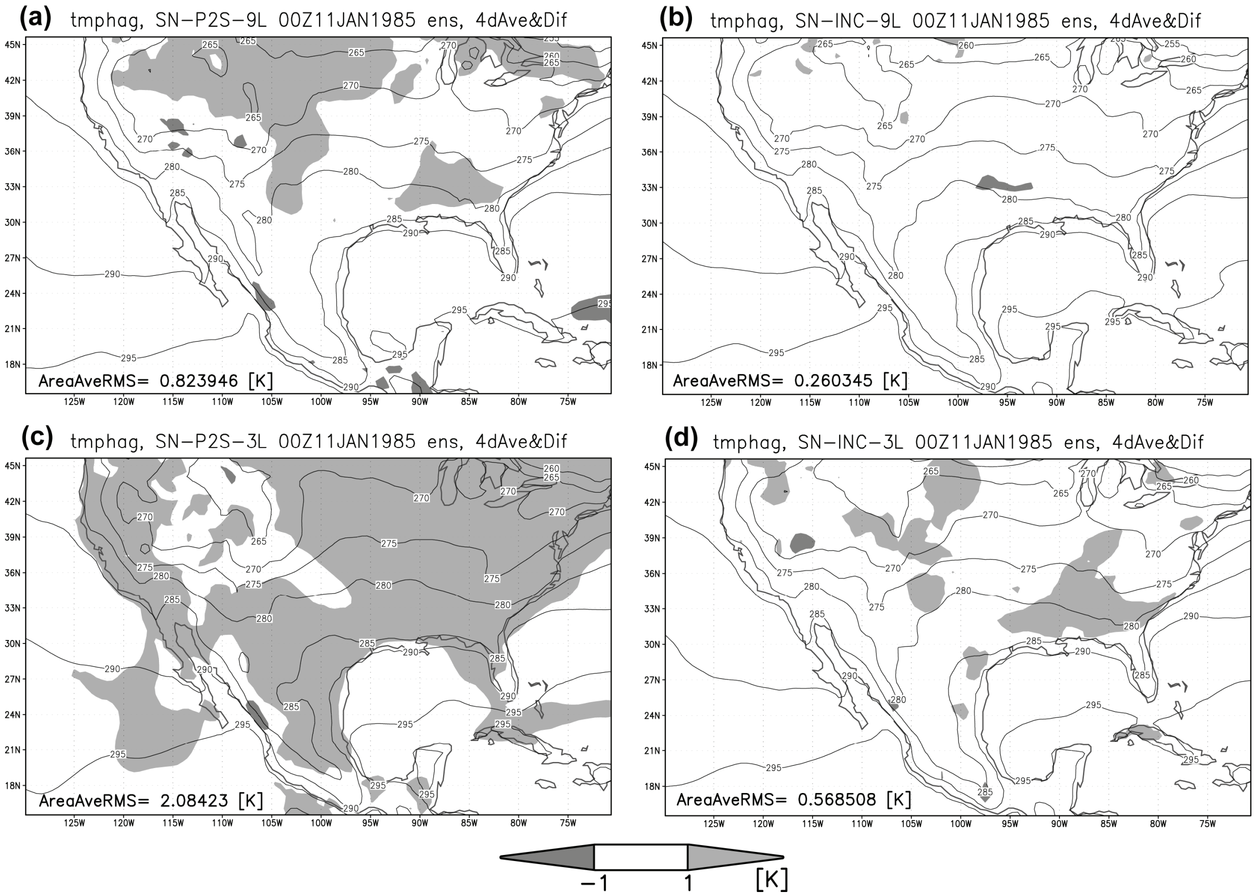


Figure 3: Schematic representation of the vertical incremental interpolation.



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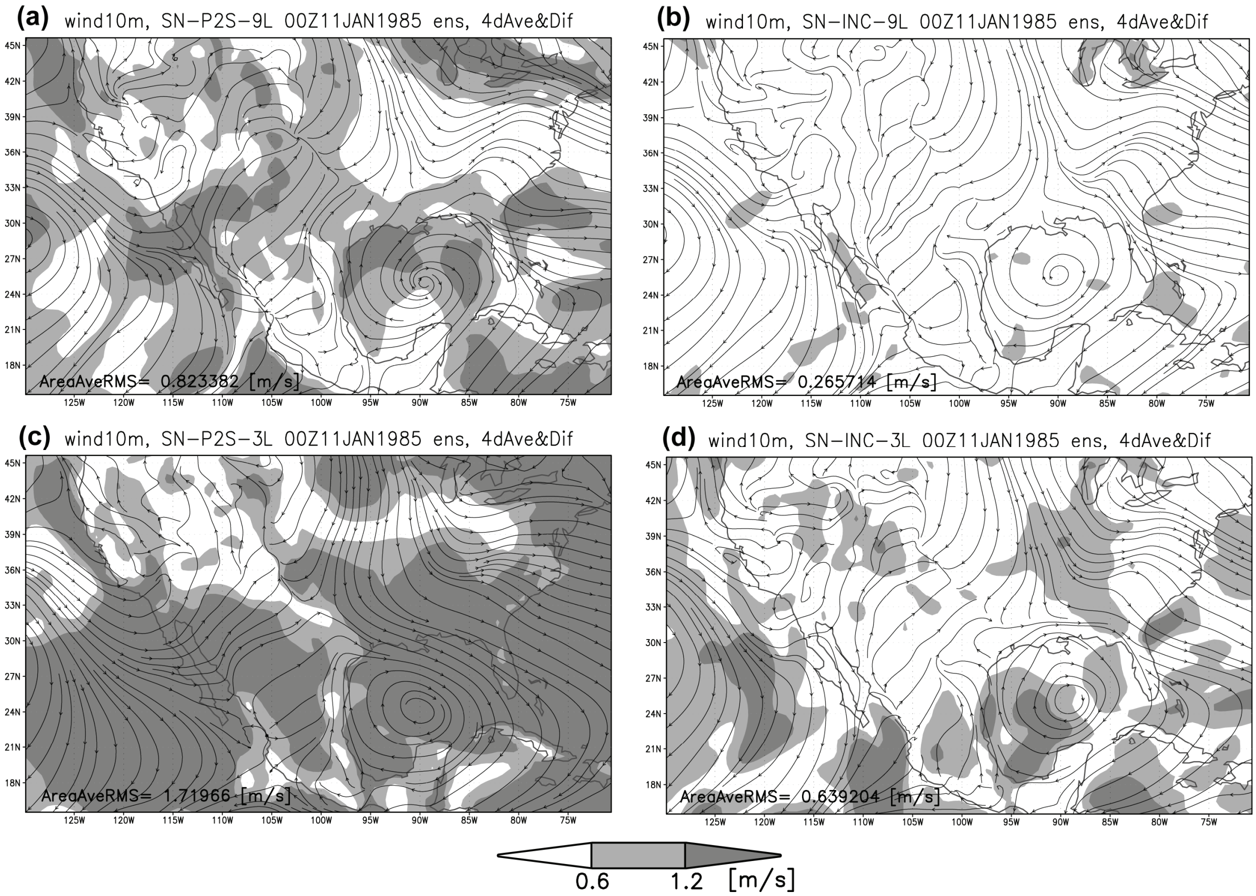

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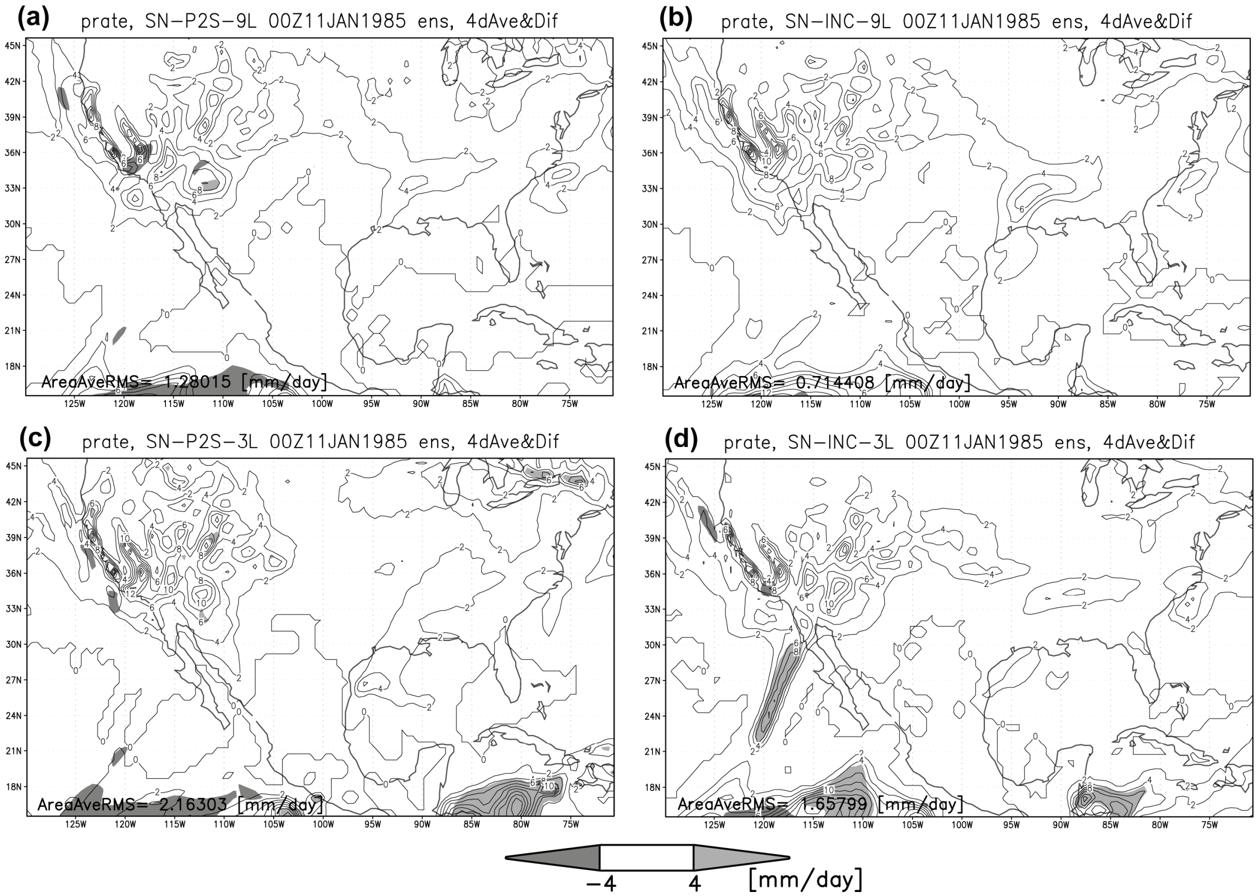

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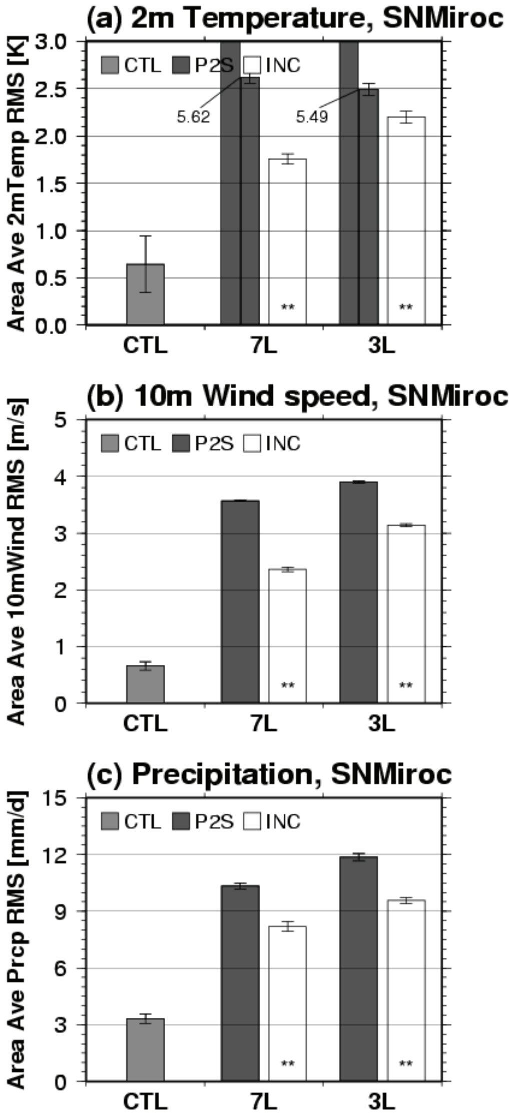

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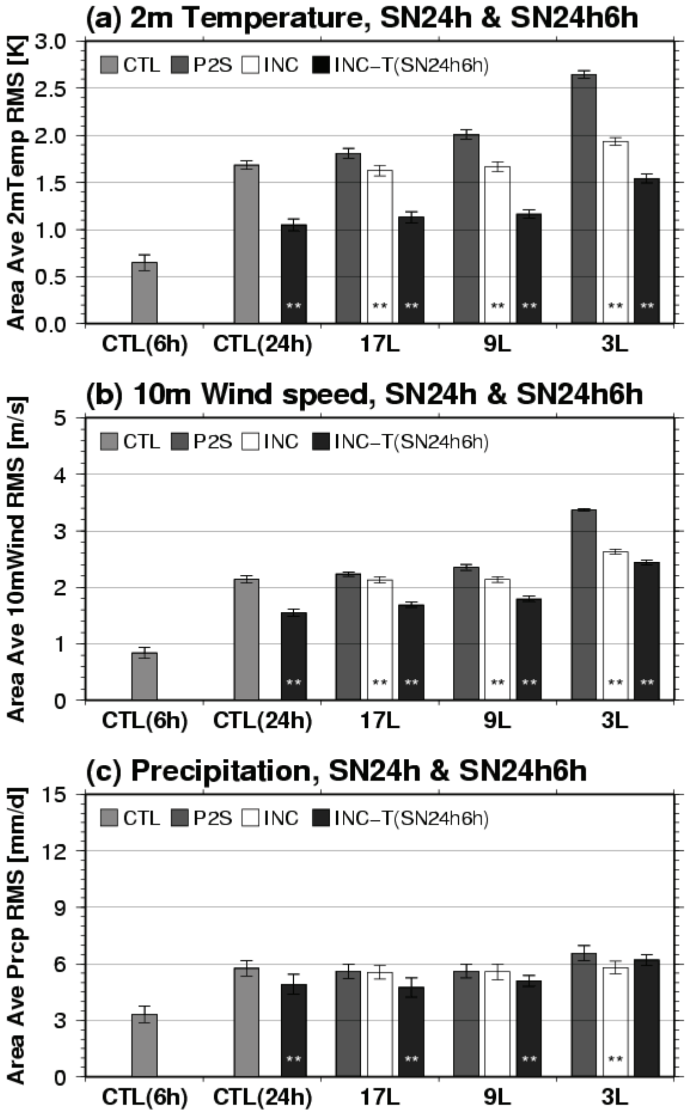

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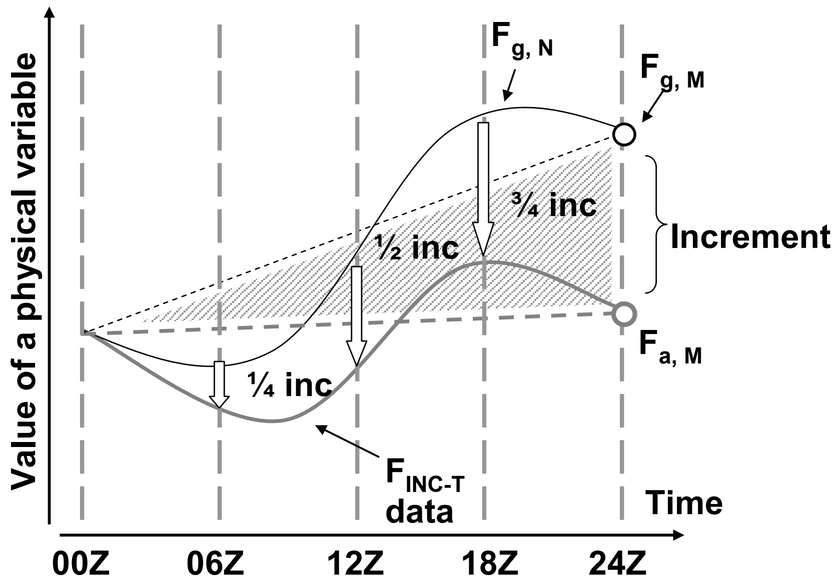

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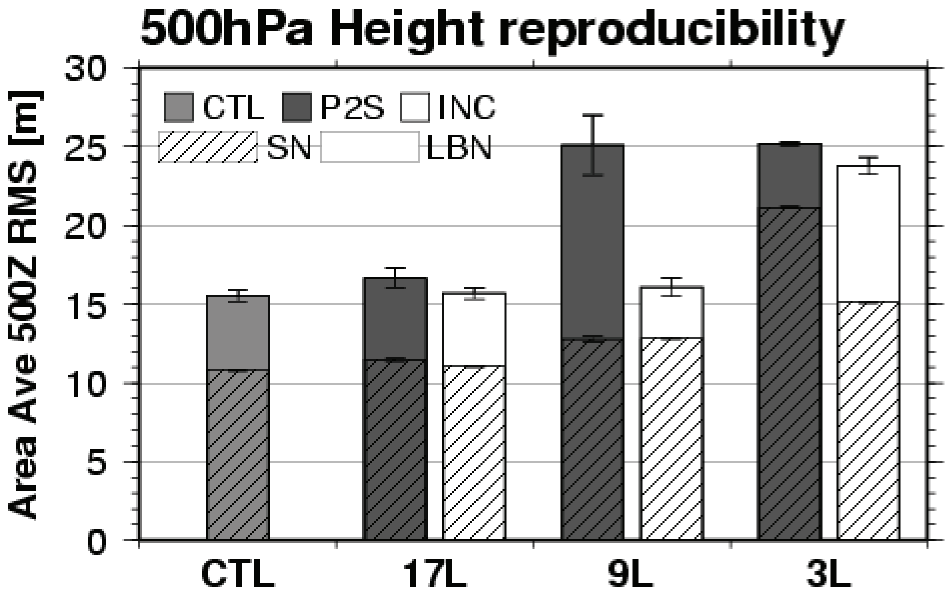

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