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Forecasts covering one month using a cut cell model

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Abstract

This paper investigates the impact and potential use of the cut cell vertical discretisation for forecasts of 5 days and climate simulations. A first indication of the usefulness of this new method is obtained by a set of five-day forecasts, covering January 1989 by 6 forecasts. The model area was chosen to include much of Asia, the Himalayas and Australia. The cut cell model LMZ provides a much more accurate representation of mountains on model forecasts than the terrain following coordinate used for comparison. Therefore we are in particular interested in potential forecast improvements in the target area downwind of the Himalaya, over South East China, Korea and Japan. The LMZ has been tested so far extensively for one-day forecasts on an European area. Following indications of a reduced temperature error for the short forecasts, this paper investigates the model error for five days in an area influenced by strong orography. The forecasts indicated a strong impact of the cut cell discretisation on forecast quality. The cut cell model is available only of an older (2003) Version of the model LM. It was compared using a control model differing by the use of the terrain following coordinate only. The cut cell model improved the precipitation forecasts of this old control model everywhere by a large margin. An improved version of the terrain following model LM has been developed since then under the name CLM. The CLM has been used and tested in all climates, while the LM was used for small areas in higher latitudes. The precipitation forecasts of cut cell model were compared also to the CLM. As the cut cell model LMZ did not incorporate the developments for CLM since 2003, the precipitation forecast of the CLM was not improved in all aspects. However, for the target area downstream of the Himalaya, the cut cell model improved the prediction of the monthly precipitation forecast even in comparison with the modern model version CLM considerably. The cut cell discretisation seems to improve in particular the localisation of precipitation, while the improvements leading from LM to CLM had a positive effect mainly on amplitude.

1 Introduction

The cut cell approach has recently been investigated in a number of two dimensional test models (see Steppeler et al., 2002; Dobler, 2005; Lock, 2008; Yamazaki and Satomura, 2008; Walko and Avissar, 2008; Yamazaki and Satomura, 2010). Compared to the more common terrain following coordinate, the cut cell approach offers a much more accurate vertical discretisation in the presence of orography and avoids a mathematical error occurring with the terrain following coordinate, when the change of mountain height between neighbouring grid points surpasses the smallest layer thickness. For a more detailed discussion of this point it is referred to Yamazaki and Satomura (2010) and Steppeler et al. (2006), referred to as Stal06. Using a three-dimensional cut cell model and real atmospheric data Stal06 were able to show that the cut cell discretisation had a positive impact on one-day atmospheric forecasts. Using a total of 50 cases with a resolution of 7 km it was shown that the vertical velocity was forecast differently and more realistically by the cut cells as compared to the model using terrain following coordinates. The precipitation forecast was substantially improved and the RMS of temperature of the one day forecast was reduced by several tenths of a degree as averaged over 50 one-day forecasts.

Because of the short forecast time of one day, Stal06 could only produce small improvements in the temperature and wind fields. The question arises, if for longer forecasts the cut cell discretisation has a stronger impact on forecasts. Finally, this question will have to be answered using a large ensemble of forecasts and an up to date physics scheme.

The intention of the present paper is to give a first indication of the impact of the cut cell discretisation for longer integrations. The model LMZ is used with lateral boundary values from observations. Here we use ERA-interim data. Such model setup is often used for model performance evaluation in climate impact studies. So we also will get a first indication of the usefulness of cut cells for such studies. The model area was chosen to see a strong orographic impact. It includes the Himalaya and a large area downwind, including South East China, Korea and Japan. In this target area we expect a strong impact of the cut cell discretisation.

A set of five day forecasts was produced covering January 1989 by six forecasts. The terrain following control model differs from LMZ only by the cut cell discretisation. In particular filtered orography is used for both models. Therefore a potential benefit of using the more realistic unfiltered orography with LMZ cannot be investigated here. In Stal06 filtered orography was used for the terrain following model version, which otherwise would not produce reasonable results. The LMZ in Stal06 was used with unfiltered orography.

2 The cut cell model

The model used is described in detail in Stal06. A few improvements were introduced with a view towards easy numerical experimentation. The time-step is increased to 90 % of the value used in the corresponding terrain following model version. For comparison this was 25 % in the model runs reported in Stal06. This was achieved by fine-tuning the tools already described in Stal06: implicit treatment of the vertical coordinate, combining small cells with neighbouring larger ones and artificially increasing the volume of small cells. The last model feature was called the thin wall approximation in Stal06. It was checked that these approximations had no significant impact on the model forecast, when compared to model runs with a smaller time step. In particular the thin wall approximation was only applied when necessary. For example small grid lengths in the vertical do not require the cell to be combined with a neighbouring one, when treating the vertical coordinate implicitly.

The model output is done using NetCDF file format, in order to facilitate the transfer of the model to different computers. Furthermore, features like restart files were introduced to allow use in the climate simulation mode. From the standpoint of the user the LMZ is identical to the LM model (Steppeler et al., 2003), and its climate simulation version CLM (Rockel and Geyer, 2008). In particular the input and output files are

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obtained by interpolating the z-levels to the same terrain following levels used in the terrain following version LM. In this paper the model comparison will be done using these terrain following output levels. The corresponding terrain following model (LM) will be referred to as the control model and differs only by the vertical coordinate from the cut cell model. In particular the physical parameterisations are the same for both models and are described in Steppeler et al. (2003). No tuning of the physics scheme was done, but rather the physics was taken over unchanged from the terrain following LM. For the one day forecasts reported in Stal06 the orography was filtered for the control model and unfiltered for the cut cell model. The cut cell model can run without orographic filtering, while the control model cannot. The results reported in this paper, however, were obtained with orographic filtering for both model versions, in order to have an exact control model.

The model runs reported in this paper are 5 day runs with starting dates 01, 06, 11, 16, 21, 26 January 1989. The model area can be seen from Fig. 1. The model setup uses 31 layers. The layers 20 and 25, used for verification, correspond to about 800 and 850 mb for points over the ocean. The horizontal resolution is 0.25°, roughly 25 km. There are 521 points is east-west direction and 321 in north-south. The physics and interpolation options are as in Stal06.

The control model and its cut cell version were developed from an old version of the LM, as described in more detail in Stal06. The results, in particular concerning precipitation, have improved since then (Rockel and Geyer, 2008). The reasons for this improvement include error corrections and a tuning of the model physics towards producing less precipitation. The model including these improvements is called CLM. The LMZ and its control model LM in comparison does not include these improvements and involves no tuning of the physics scheme at all. The older LM used for control purposes was in its time not used in the tropics and did not involve changes of the physics scheme coming from its hydrostatic predecessor.

The comparison of the cut cell model with its control version gives correct information on the potential impact of the cut cells on forecasts. The comparison of LMZ and CLM

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puts the LMZ at a disadvantage, as LMZ does not benefit from the improvements of the physics scheme since 2003, which are incorporated in CLM. Nonetheless we compare with CLM to make sure that the differences of the forecasts cannot be traced back to the problems of the control model with tropical rain.

3 Results

When discussing the results we will refer to the cut cell model runs as z-runs and to the results of the terrain following control model as noz. Figure 1 shows 5 day forecasts from 21 January of the wind-component u at 10 m height for z and noz. As an indication of the verification the 0-day forecast from 26 January is given (for noz). Both forecasts and the verification show the northern and southern trade wind systems with easterly surface winds. Weak winds prevail north and south of the two trade wind systems and in the convergence zone between them. Strong westerly winds are seen in the north-east corner of the forecast area, being associated with cyclonic activity. For the case shown in Fig. 1 the noz forecast has larger patches of westerly winds in the tropical convergence zone than the z-forecast and the verification.

These wind systems are highly variable in time (plots not shown). The trade wind zones can be a narrow band or rather wide, as shown in the example of Fig. 1. For the month of January 1989 the north-eastern corner of the model area shows continuous cyclonic activity, with a corresponding variability of the westerly wind.

The impact of the z-discretisation is strong. Some differences between the z- and noz-forecasts are typical. These are a stronger westerly wind patches embedded in the convergence zone for noz and for the z-runs stronger westerlies in the north east of the model area and less noisy fields.

The increased noise level of the forecasts is of a scale of 100–500 km. With a resolution of 25 km this consists of well resolved structures.

The difference of z and noz forecasts concerns all model levels. We are in particular interested in the area of cyclonic activity downstream of the Himalaya. Our target area

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is 30° to 40° N and 100° to 140° E. Figure 2 shows the 5-day forecasts for all 6 cases. The verification is available for the first 5 cases. The temperature for output level 20 is given, corresponding roughly to the 850 mb surface over the ocean. The forecasts of z, noz and the 0 day forecast for the target date for noz (verification) are shown. The differences of the forecasts are rather large.

Figure 3 shows the 5 day forecasts of the vertical velocities with starting date 21 January 1989. Again the 0 day forecast from 26 January is used for verification. For the preparation of this initial field it is referred to the well documented model LM (see Steppeler et al., 2003). Both forecasts and the verification show a band of rising motion in the tropical convergence zone, which in the east of the area is split into three branches. One of them is reaching far north into the vicinity of Japan. For the noz run the large-scale features are obscured by small-scale noise of rather high amplitude, which is present everywhere and is strongest over the high mountains and in the tropics, in particular downwind of Madagascar. These strong vertical velocities are responsible for heavy rain with noz. The forecasted vertical velocities for noz verify much worse than those of z as compared to the initial fields.

Some investigations were done concerning the noisy w field with noz and the associated heavy rain. These are summarised here without showing all corresponding diagrams. At the initial time z and noz have very similar w fields, which for the z forecast are evolving continuously and verify reasonably with the w from the analysed data. For noz large differences appear after the digital filter initialisation and are also seen in adiabatic runs. The digital filter initialisation creates large scale differences between noz and z in the vertical velocity field, which are not localised near mountains. They occur for example in a large area downwind of Madagascar.

For diabatic runs the strong vertical velocities with noz create heavy precipitation, in particular in the tropical belt. This again creates even higher vertical velocities. Apparently the creation of the noisy structures over the whole model area after 5 days is caused by amplification of rising motion using the energy source of the warm tropical ocean. In the course of the 5 day forecasts the high amplitude features of the *w*-field spread to the whole model area and cause increased rainfall rates everywhere.

The use of model initial fields for verification is problematical as the data assimilation derives fields also in areas with no observations. Therefore it is difficult to assess the accuracy of the data used for verification. In particular the vertical velocity field *w* is obtained as a model field at $t = 0$ (Steppeler et al., 2003), with no direct measurements of *w* being used. Therefore it is desirable to compare directly with observations. Most readily available are precipitation data. As precipitation depends strongly on the vertical velocity, precipitation verification can be seen as an indirect verification of *w*. Here, we use the daily gridded precipitation dataset for Asia from the APHRODITE (Asian Precipitation – Highly-Resolved Observational Data Integration Towards Evaluation) project with a grid resolution of 0.25° (Yatagai et al., 2009) as reference.

Figure 4 shows the accumulated precipitation for the z and noz forecasts for the whole month of January 1989. The observations are given in Fig. 5. The z-runs are much more accurate than noz, with the latter being double the observed values almost everywhere.

For a more detailed verification, Fig. 6 shows the z-forecast using another colour code. The CLM forecast is also shown. Unfortunately verification is available for the land surfaces only. This is a problem for the tropical islands, where all models show marked differences between land and surrounding oceans. CLM benefits from a tuning of the physics and error corrections, which are not yet available for the z-runs. This explains that the amplitudes of precipitation are at some places better for CLM than for z. Forecast differences in favour of CLM are a tendency of the z-runs to predict light rain in areas which are dry. This concerns parts of the Arabian peninsula, India and Australia. Also the rain produced south of the Caspian Sea with CLM is better. Many features of precipitation localisation are better with the z-runs. When a feature is predicted both by z and CLM, its position and shape is often better with z. The banded structure of the precipitation south of the Himalayas comes out better with z and it extends correctly further east. The observed local precipitation at 25° N and 85° E is

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correctly positioned by the z-run, though with an amplitude of 250, rather than the observed 450 mm. The z-run correctly creates precipitation over Sri Lanka and Thailand, which are dry with CLM. We leave it to the reader to ponder the forecast differences on the medium sized tropical islands. The largest differences are in the target area downwind of the Himalayas: South-east China, Korea and Japan. The z-runs give a better distribution of precipitation as compared to CLM. The precipitation is correctly concentrated in the South of China. Korea and Taiwan get precipitation and the rain over Japan is concentrated in the west of the country. These are differences involving a large area and they indicate that the mathematically more correct treatment of mountains with the z-runs has a considerable impact for prediction and climate simulation purposes. It is interesting that over dry areas in Arabia and India the vertical velocity is negative for z and noz. This may be seen as an indication that both model versions need an improvement of the physics scheme such as the changes leading from LM to CLM.

4 Conclusions

The cut cell discretisation removes mayor numerical errors near mountains. It was shown that the impact of this scheme for 5 day forecasts is considerable. The analysed vertical velocities verify reasonably with z and not very well with noz forecasts. After the digital filter initialisation the vertical velocities of the two model versions differ on a global scale, with noz having large differences to the analysis. As shown for shorter forecasts in Stal06, the vertical velocities and precipitation are more realistic for the cut cell model, when compared to the control model noz. The small improvements of temperature and wind forecasts reported in Stal06 become more substantial after five days. Over large areas the temperatures and winds are improved, when using the analysed fields as verification. As the control model had a problem for tropical forecasts, the up to date CLM was used for comparison as well. The CLM differs from the noz model by improvements such as error corrections and tuning of the physics scheme (see, e.g. Hollweg et al., 2008). These desirable improvements are not yet

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implemented in the z-model. In spite of this the z-model showed a better localisation of precipitation, even though in other aspects the CLM model gave better precipitation forecasts.

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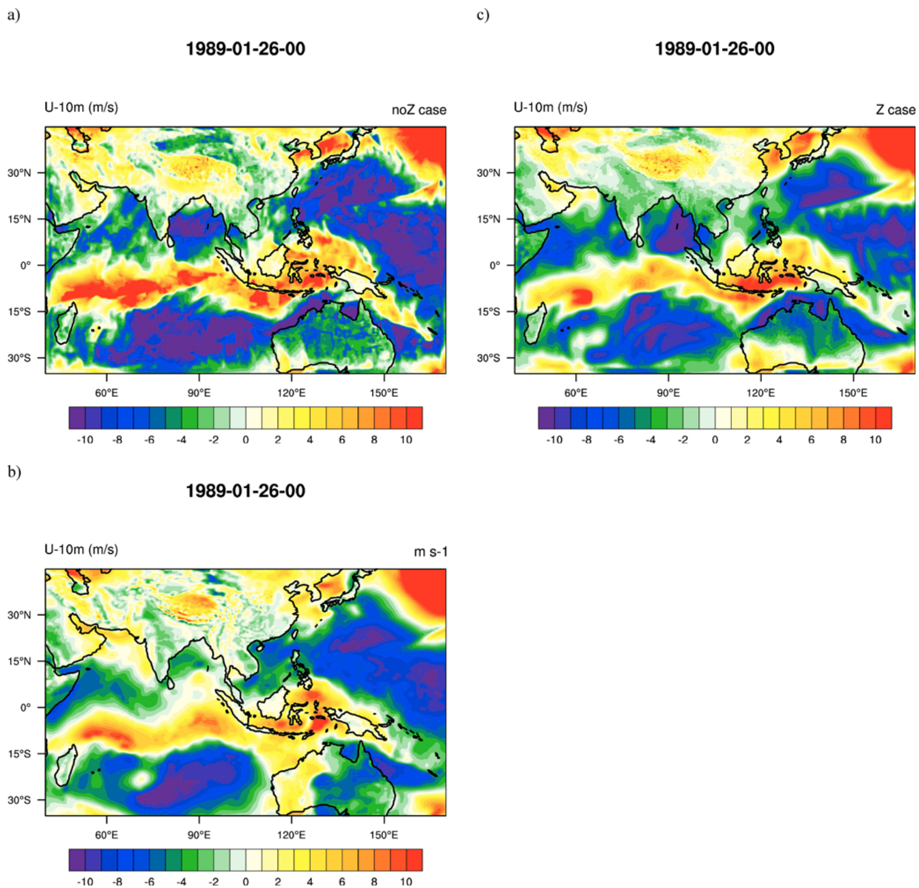

Fig. 1. (a) The 10 m wind in m s^{-1} as forecasted for 5 days from 21 January 1989 by the terrain following model noz; **(b)** as **(a)**, for the 0 day forecast from 26 January of noz ("verification"); **(c)** as **(a)**, for the cut cell model z.

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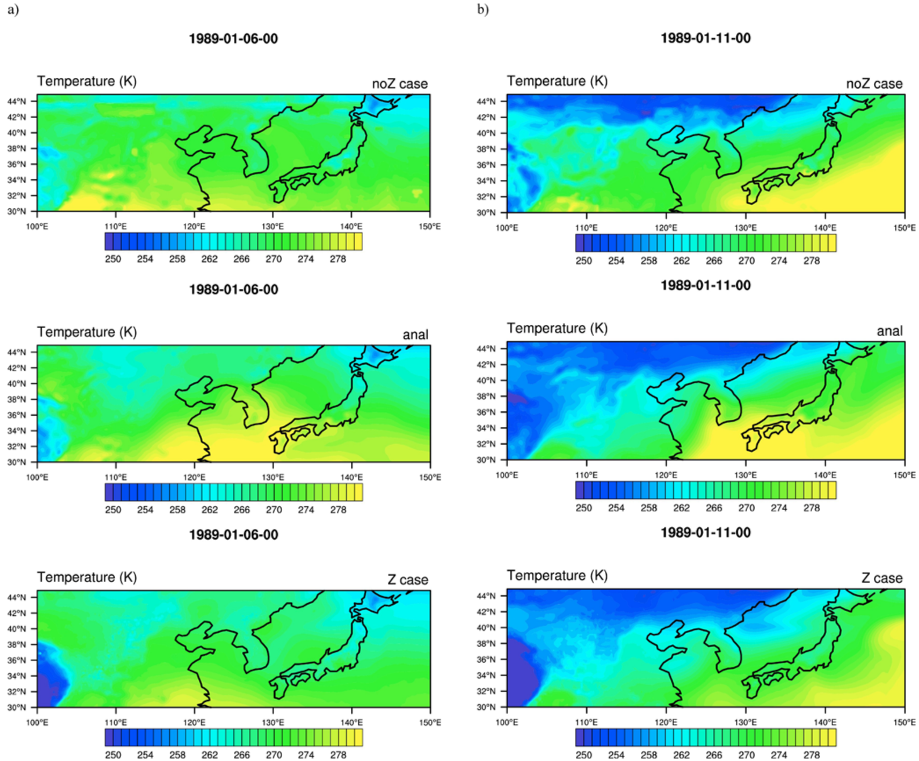

Fig. 2. (a) Temperature for the 5 day forecast from 1 January 1989 of level 20 for the terrain following model noz (top), the cut cell model z (bottom) and the 0 day forecast from 6 January 1989 ("verification", middle); **(b–f)** as **(a)**, for dates 6, 11, 16, 21, 26 January.

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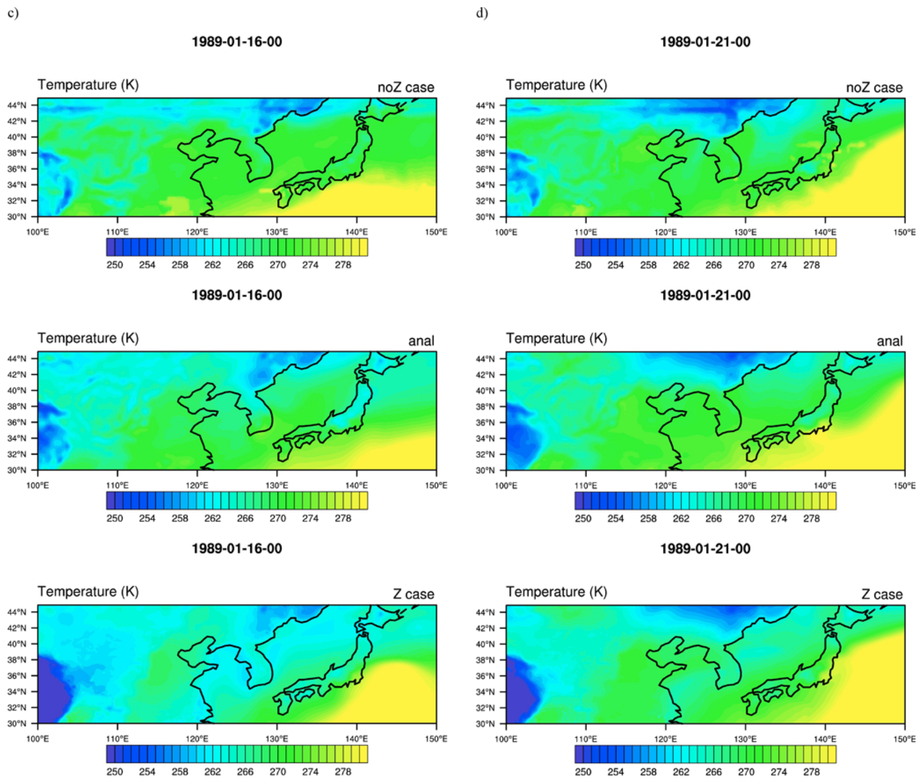

Fig. 2. Continued.

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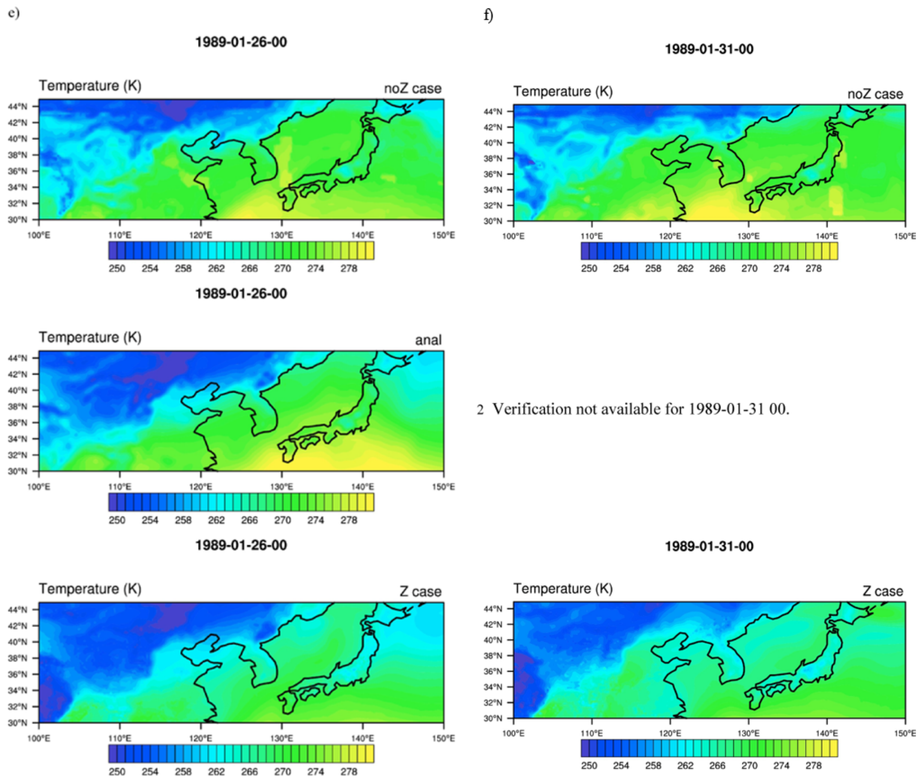

Fig. 2. Continued.

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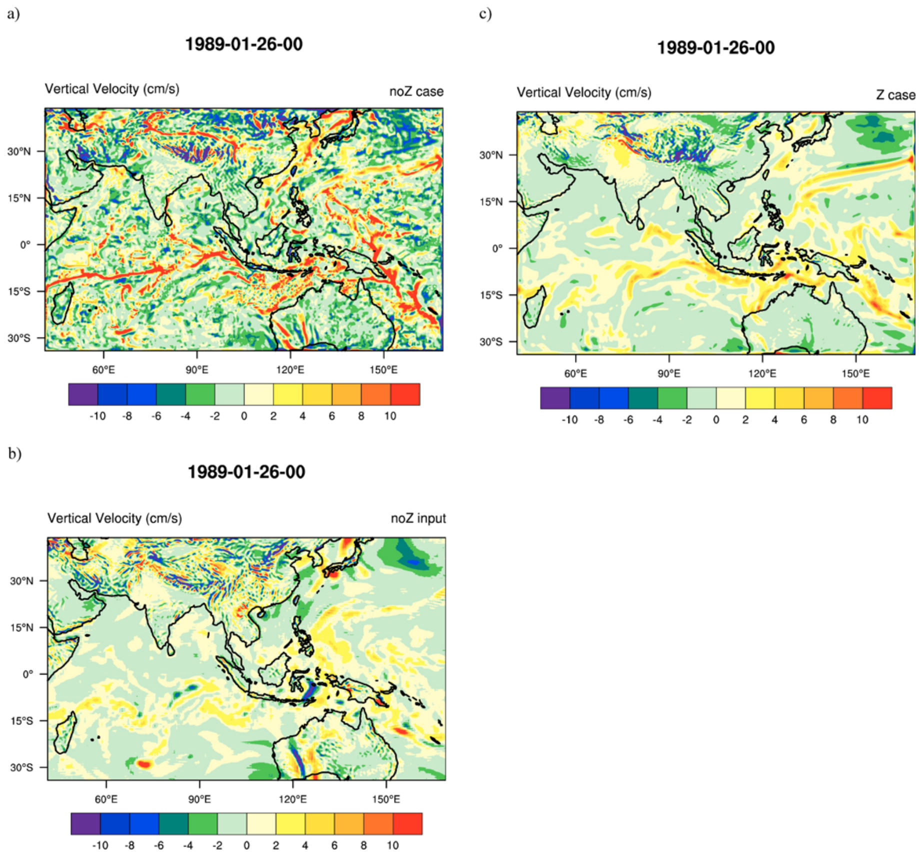

Fig. 3. **(a)** Vertical velocity *w* for level 20 of the five-day forecast from 21 January 1989 for the terrain following model noz; **(b)** as **(a)**, for the 0 day forecast from 26 January of noz ("verification"); **(c)** as **(a)**, for the cut cell model z.

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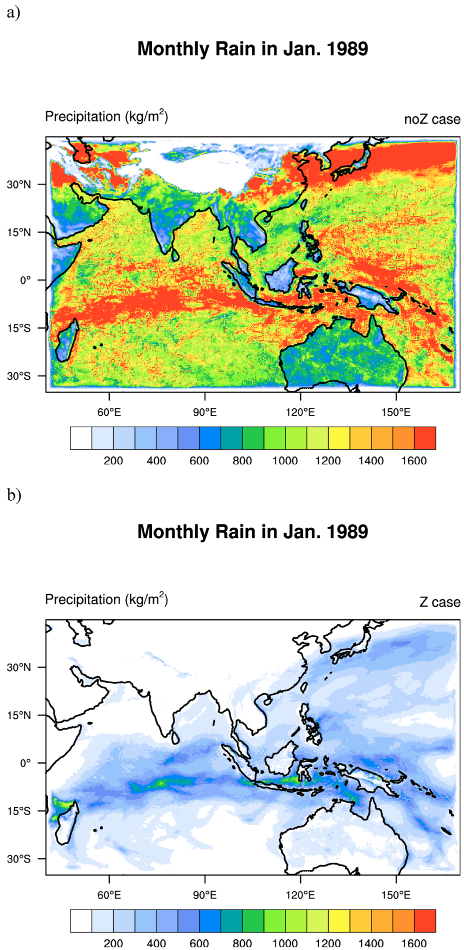

Fig. 4. (a) The forecasted accumulated precipitation for the whole January 1989 using the terrain following model noz; **(b)** as **(a)**, for the cut cell model z.

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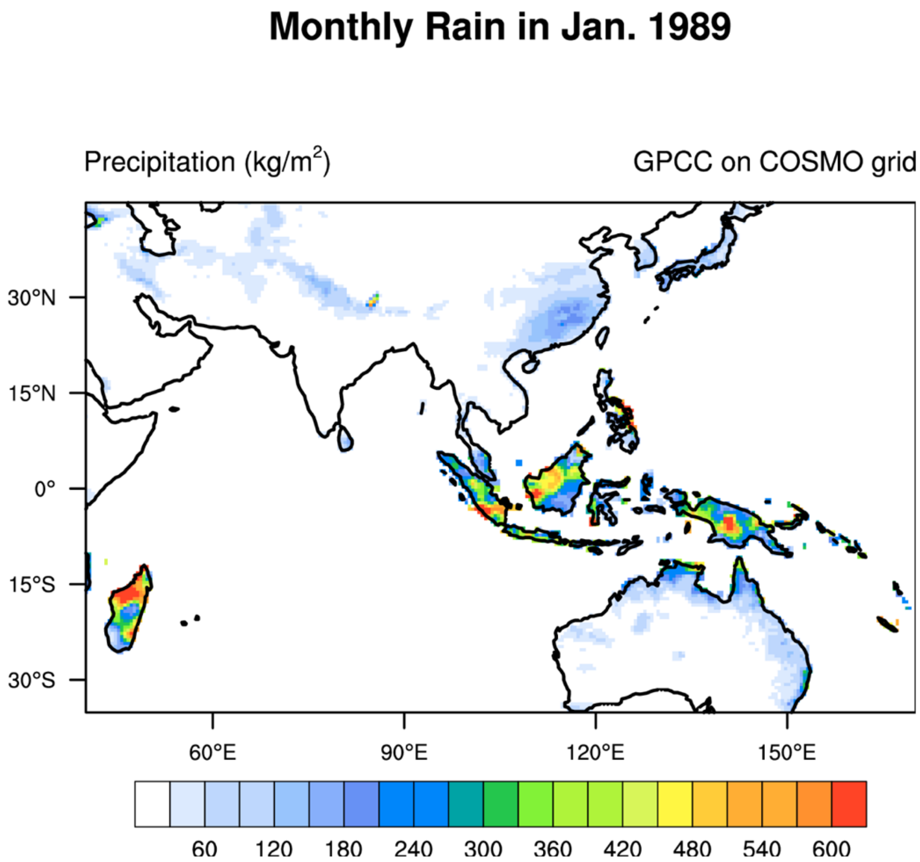

Fig. 5. The observed accumulated precipitation according to the APHRODITE dataset for January 1989.

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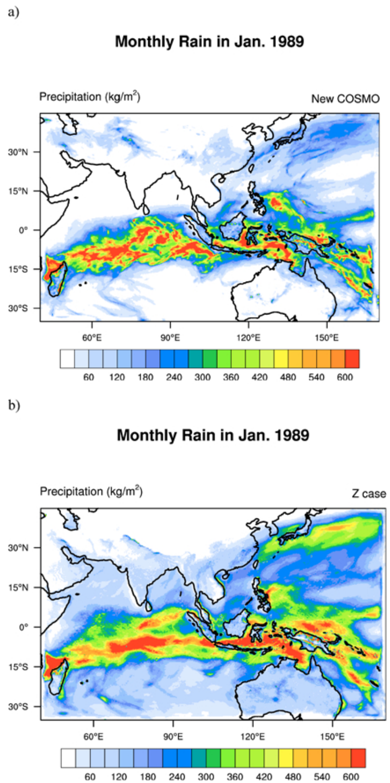

Fig. 6. (a) The forecasted precipitation accumulated for the whole January 1989 using the terrain following model CLM in its current version; **(b)** as **(a)**, using the cut cell model z with the 2003 physics scheme not tuned to the new discretization. (The same data are used as in Fig. 4, with a different colour scheme.) The colour schemes were chosen to correspond to that used in Fig. 5.

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