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COMPARATIVE STUDY OF DIFFERENT OROGRAPHIC REPRESENTATIONS WITH RESPECT TO THE INDIAN SUMMER MONSOON SIMULATION

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Abstract

In spectral General Circulation Models that are now widely used in operational weather forecasting and research, the time dependent atmospheric parameters and orography are represented in the form of double series. In such spectral transform methods, Gibbs oscillations appear due to sharp gradients in terrain height, moisture, and cloud fields. The present paper shows the usefulness of different digital filters in reducing the negative values of orography. The application of filters also reduces the heights of the mountain peaks. This affects the Indian region the most, because of the presence of the Himalayas and the Western Ghats.

In this paper, an attempt has been made to represent the orography by a new method, called the Filtered Modified Orography (FMO), in which a two dimensional Lanczos filter has been applied in the spectral domain globally with a subsequent local enhancement of the Himalayas and the Western Ghats. The dual advantages of reduction in negative orography values and enhancement of mountain peaks were achieved. A comparison with the envelope orography, where the mean orography is enhanced globally, shows that the new method is able to reduce some of the errors and disparities associated with the envelope technique while retaining some of the advantages of the barrier effect regionally. Results show reasonably good representation of global winds, geopotential and rainfall in FMO representation in T80 model of the National Centre for Medium Range Weather Forecasting.

Key words: Gibbs phenomenon, digital filters, envelope orography, general circulation models, Indian summer monsoon rainfall.

1. INTRODUCTION

Representation of orography in global spectral models poses serious difficulties due to the sharp spatial gradients of various orographic features. This is because of the Gibbs oscillations arising in the spectrally transformed orography owing to the inherent discontinuities. Errors due to the Gibbs phenomenon by the truncation of orography have been found to cause serious bias in the surface wind simulations of El Nino Southern Oscillation in the eastern equatorial Pacific (Miyakoda *et al*., 1993). Also, it is shown that the low-level meridional wind as simulated by a spectral **G**eneral **C**irculation **M**odel (GCM) undergoes larger amplitude errors corresponding to the steep Andes mountains (Navarra *et al*., 1994). Studies of Krishnamurti *et al*. (1984), Abraham *et al*. (1996), Grossman and Durran (1984), Hahn and Manabe (1975) also show that the intensity of Indian monsoon circulation, the formation and movement of cyclones and distribution of associated rainfall are affected by the type of orography prescribed in a GCM.

The two major problems related to orographic representation in spectral GCM are the following: (i) the reduction in the strength and frequency of the negative (oceanic) dips generated by the Gibbs phenomenon, and (ii) the retention of peaks of the major orographic features. The first problem is usually tackled by the use of digital filters applied to the input orography in the spectral domain. The use of several types of digital filters for representation of orography at T63 resolution of the spectral GCM of the **E**uropean **C**entre for **M**edium Range **W**eather **F**orecasts (ECMWF) had been studied earlier by Abraham *et al*. (1996) where the Lanczos filter was found to give the best results. Also in another study (Navarra *et al*., 1994) an isotropic filter based on Cesaro summation principle was found to be very effective in eliminating the negative dips. As far as the second issue of retention of heights of mountain peaks is concerned, the major approach has been the use of envelope orography. Envelope orography is constructed by adding the subgrid scale standard deviations of the terrain heights in a model grid box to the corresponding mean orographic heights. Studies reveal that the envelope orography produces a net improvement in the forecast accuracy beyond day 4. Also, a close relationship has been found between the location of the largest mean short-range forecast errors and the position of some mountain ranges in the Northern Hemisphere using ECMWF forecasts (Wallace *et al*., 1983). Case studies show that simulation of cyclogenesis in the lee of the Alps is generally improved by using some form of enhanced mountains, either by increasing the height of the orography used in the model (Bleck, 1977; Mesinger and Strickler, 1982; Dell'Osso, 1984; Radinovic, 1985) or by blocking the low level flow more explicitly (Egger, 1972). Overall improvements in the medium-range forecasts were reported from the use of enhanced orography in both extra tropics and monsoon tropical regions (Wallace *et al*., 1983; Krishnamurti *et al*., 1984). In spite of this, a number of detrimental effects of using envelope orography have also been identified, especially in the simulation of summer circulation. Degradation of short-range forecasts had been observed in general. In addition, increased local discrepancies between the actual and model represented mountain heights aggravate many practical problems in data assimilation and near-surface wind and temperature forecast products. Jarraud *et al.* (1988) found that the impact of envelope causes a local modification, which tends to propagate and amplify following the upper level flow.

It is well known that the height of the mountain barrier is better captured by the envelope orography than by the mean orography. However, spectral fitting of envelope orography has also a tendency to spread the width of the narrow mountain ranges. There is a risk of negative impact of spreading of the orography, particularly in the situations involving the flow parallel to a ridge. Hence, the appropriate choice of orographic representation as a mean or envelope with optimum multiplying factor may be different for different regions according to the complexity and layout of the local orography and the characteristics and variability of the local air flow patterns.

In this paper, an attempt has been made to realistically represent the global orography for the operational spectral GCM of the **N**ational **C**entre for **M**edium **R**ange **W**eather **F**orecasting (NCMRWF) located in New Delhi, India, with an explicit local modification of Indian orographic features. Sensitivity experiments have been carried out in the present work to test the above representation of orography and to study its impact on the seasonal simulation of Indian summer monsoon circulation and rainfall. This new method of orographic representation differs from earlier conventional methods in that the local enhancement of orography, which already is smoothed by digital filters to have the minimum ripples, is appropriately done in high mountainous regions by using the explicit physical replacements in those selected domains. Section 2 deals with different types of digital filters used along with the description of the envelope orography and the new representation of orography over India. The impacts of the new orographic representation on the Indian summer monsoon circulation and rainfall are described in Section 3. Section 4 contains the concluding remarks.

2. OROGRAPHIC REPRESENTATIONS AND ANALYSIS

Application of digital filters to orographic representation

The representation of orography in global models with sigma vertical co-ordinates requires either interpolation to the Gaussian grid points (interpolated orography) or area-averaging over the grid mesh (mean orography). For such representations, high -resolution global orography data of US Navy at intervals of 10 minutes are commonly used. In a spectral GCM, the mean or interpolated orography undergoes spectral transformation and hence the resulting orography being quasi-discontinuous tends to produce Gibbs oscillations. The bias is clearly seen in a series of oscillations with overshootings and undershootings near the vicinity of the discontinuity stretching over a distance from the transition zone. The increase in the resolution of GCM does not fully eliminate the ripples but only reduces the scale of oscillations.

One way of making Gibbs oscillation insignificant is to avoid very steep gradient in the input orography by smoothing of the original data before application of spectral transforms. Most effective method of smoothing is to multiply the spectral coefficients by certain window functions using non-recursive low-pass digital filters. This method is easy to handle and has better control over the Gibbs waves. In case of the spherical harmonics, the Gibbs waves are generated in both the east-west and north-south directions by Fourier and Legendre transforms, respectively. There are several one -dimensional filters that can be applied to Fourier transforms along the east-west direction. There are no similar filters yet known for the Legendre transforms. Hence, it is practically impossible to reach the resolution that eliminates the Gibbs bias completely, due to additional complexities of the two different transforms. One -dimensional filters are marginally effective in eliminating the oscillations in two directions and organize the oscillations in coherent bands oriented east-west (Navarra *et al*., 1994). The current study specifies one-dimensional (1D) filter as that which is defined in terms of zonal wave number *m*, and two-dimensional (2D) filter with the same weight function defined in terms of total wave number *n* (Sardeshmukh and Hoskins, 1984), since the latter implies a more isotropic smoothing.

The spherical harmonics expansion of any atmospheric variable *Z* defined on a sphere (Bourke *et al*., 1977) can be expressed for triangular truncation as

$$Z(\varphi,\lambda) = \sum_{m=-M}^{M} \sum_{n=|m|}^{M} W_n^m Z_n^m P_n^m(\cos\varphi)\exp(im\lambda) \ . \tag{1}$$

Here φ and λ represent latitude and longitude, respectively, P_n^m are the Legendre polynomials, Z_n^m are the spectral harmonic coefficients, *m* is the zonal wave number, and *n* is the degree of Legendre function or two-dimensional wave number for spherical harmonics. W_n^m is the window function. It is normally referred to as the rectangular filter when there is no filtering done. For triangular truncation

$$W_n^m = \begin{cases} 1 & \text{for } n \le m \\ 0 & \text{otherwise} \end{cases} \ . \tag{2}$$

Depending on the mathematical formulation of W_n^m in relation (1), a number of filters can be used. In this study, such digital filters as those of Lanczos, Gauss, Tukey, Hamming, Blackmann, as well as isotropic and Kaiser's (Sardeshmukh and Hoskins, 1984; Bourke, 1972; Lanczos, 1956; Jenkins and Watts, 1968; Hamming, 1989; Johnson, 1989; Stanley *et al*., 1984) have been applied to the mean orography used in NCMRWF operational model at resolution of T80.

Local modification of orography for the Indian domain

The application of filter in general considerably lowers the peaks of the Himalayas and globally smooths the entire topography. In order to overcome this problem, a filter had been developed by Navarra *et al*. (1994), which is applied in the physical space rather than in the spectral space and it gives the same result as the spectral space when applied globally. This technique had been applied selectively to the oceanic dips and negative values of orography. The new orographic representation, which is being discussed here, is similar to the above technique as it is applied in the physical space, but differs basically in two aspects. In the first place, Navarra *et al*. (1994) formulated a kernel for the conversion to the filtered orography. The present study does not employ the kernel but simply uses a direct replacement of the Gaussian grid point values in a latitude-longitude rectangular box corresponding to the higher orographic features and the subsequent application of the spectral transform. The emphasis is on the retrieval of the actual heights of peaks. Secondly, the local modification is done on the orography that is previously passed through two-dimensional Lanczos filter so that most of the oceanic ripples have already been eliminated. Thus, the resulting orography best reflects the combined benefits of smoother oceanic ripples and the retention of the local mountain peaks. This new representation of orography is named the **F**iltered **M**odified **O**rography (FMO).

The sequential steps for the construction of the FMO are as follows: (a) Compute mean T80 global orography over 256×128 Gaussian grid points; (b) Apply 2-D Lanczos filter to the mean orography in spectral space; (c) Convert to the grid space; (d) Replace AREA 1 and AREA 2 with grid values of envelope orography obtained using multiplying factor 0.7 (more details, see next section); (e) Do spectral transform to get the final orography as input to the model. As shown in Fig. 1, AREA 1 is a box comprising the Western Ghats and the whole of southern peninsula of India and the adjoining oceanic region of 70.7 to 84.3°E and 7.1 to 23.1°N. Similarly, AREA 2 is another box over the Himalayan region of 82.96° to 95.62°E and 30.11 to 35.71°N. Since, the envelope orography used to replace the filtered orography in the two boxes in Fig. 1 is obtained by multiplying 0.7 times the standard deviations, hereafter, such modified orography will be referred to as FMO0.7.

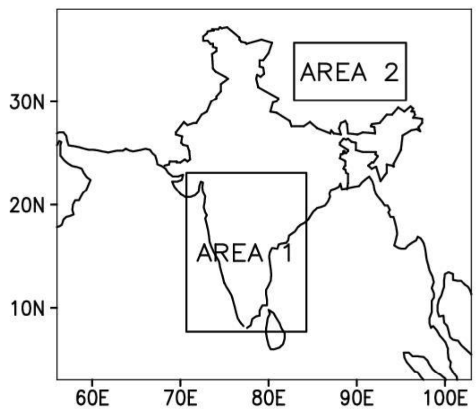

Fig. 1. Domains comprising the Western Ghats (Area 1) and the Himalayas (Area 2) used for Modified Filtered Orography over India.

Analysis of various orographic representations

The preferred criteria used for selection of the best filter in the present study are the following: (i) reduction in the number of grid points showing negative orography and also the magnitude of negative value, (ii) retention of the maximum heights close to those occurring in the interpolated orography for T80 resolution and (iii) less **r**oot **m**ean **s**quare **e**rror (RMSE) with respect to the terrain values in the interpolated orography. The present study is mainly concerned with the Indian monsoon, and hence the emphasis has been given to the model grid points over India and its neighbourhood, which is taken as 56-103°E, 3-39°N.

Figure 2 shows the number of grid points over India having negative values in the case of mean orography with few selected digital filters giving reasonably good results. The results of all 1D and 2D filters are not shown in this figure for the sake of clarity. It is seen that 2D filters are more effective than 1D filters in eliminating the negative orography. Among the 2D filters, it can be seen that Lanczos and Hamming windows show comparatively better performances. The Gaussian and isotropic filters completely eliminate the negative orography from the Indian domain. However, they have very high RMSE against the interpolated orography.

It is well known that envelope orography is essentially the enhancement of the grid-square mean orography by adding a multiple of the standard deviation of the sub-grid scale orography (Wallace *et al*., 1983; Jarraud *et al*., 1988). The multiplying factor is not well defined. Wallace *et al*. (1983) used a multiplying factor of 2, where Jarraud *et al*. (1988) used a factor of $\sqrt{2}$. In this study, we have experimented with

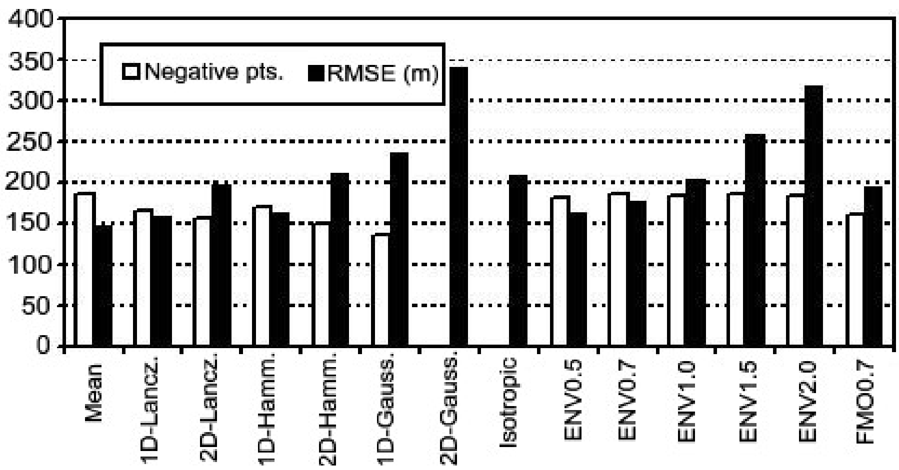

Fig. 2. Number of grid points having negative orography over Indian domain (56-103°E, 3-39°N) and the global root mean square error (RMSE) in meters (against interpolated orography) at T80 resolution for mean, one-dimensional and two-dimensional filters, envelope orography (with multiplying factors 0.5, 0.7,1.0, 1.5 and 2.0) and FMO0.7.

multiplying factors of 0.5, 0.7, 1.0, 1.5 and 2.0. Envelope orographies with such multiplying factors are denoted by ENV0.5, ENV0.7 etc. It may be noted that no filter is applied in the case of these five representations of envelope orography. Comparison shows that there is minimum number of grid points with negative orography and also with reasonably less RMSE in case of FMO0.7. Figure 3 shows the maximum and minimum values of orography obtained with different orographic representations corresponding to Fig. 2 in comparison with the interpolated orography. 2D filters slightly reduce the peak values. However, the negative dips are eliminated to a great extent. It shows that 2D Lanczos filter is able to reasonably retain the maximum height of the Himalayas as much as possible (5227.2 m) among the three best 2D filters mentioned above (with Tukey and Hamming giving values of 5169.8 m and 5175.6 m, respectively) while reducing the magnitude of the dips. Hence, 2D Lanczos filter is considered to yield the best results amongst all the filters used. It retains the peak height reasonably, reduces number of points with negative orography, gives reasonably less RMSE and also there is substantial reduction in the magnitude of negative dips. It has been examined in detail and it is found that 2D Lanczos filter smooths the entire terrain, though not so widely as the Gaussian filter.

As discussed earlier, the envelope technique is generally used to increase the barrier effect. Comparative study of five different types of envelope representations with multiplying factors ranging from 0.5 to 2.0 has been shown in Figs. 2 and 3. All these envelope representations have almost equal numbers of negative points, irrespective of the magnitude of the multiplying factor, and these points are greater than that in the case of FMO0.7. However, RMSE linearly increases with multiplying factor. Instead of envelope orography, that calls for a global enhancement of

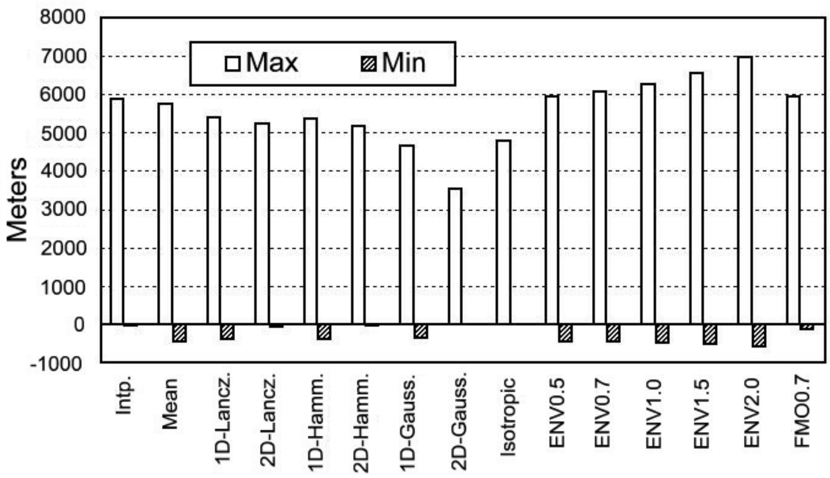

Fig. 3. Maximum and minimum orography (in meters) in the case of interpolated, mean, several one- and two-dimensional filters, envelope orography (with multiplying factors 0.5, 0.7, 1.0, 1.5 and 2.0) and FMO0.7.

orography, local enhancement has been achieved in FMO0.7 orography. From Figs. 2 and 3, it is seen that FMO0.7 has the minimum number of grid points with negative orography compared to ENV0.7, which has the same multiplying factor. Though RMSE for FMO0.7 is marginally higher than ENV0.7, it is able to reduce the RMSE in comparison with the 2D Lanczos-filtered orography. As seen in Fig. 3, the magnitude of negative orography is the lowest possible as in case of 2D filters. Also in case of FMO0.7, the magnitude of maximum orography is very close to that in interpolated orography.

The above discussion shows that FMO0.7 scores over other orographic representtations, especially over the Indian domain. It has also been found that the characteristics of the interpolated orography, which mostly reflect the true heights at the model grid points, are better captured in FMO0.7, as depicted in Fig. 4, specifically

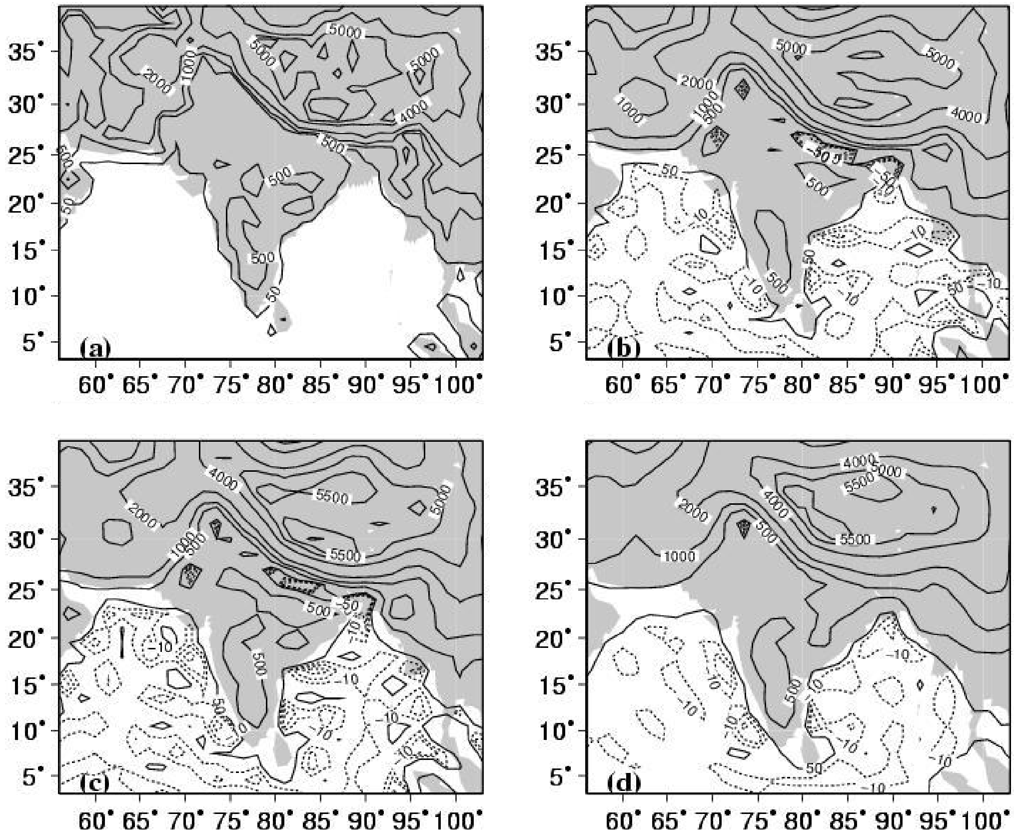

Fig. 4. The Indian orography (in meters): (a) interpolated at 256×128 global grids; (b) mean orography; (c) ENV0.7; and (d) FMO0.7. The solid contours are 50, 500, 1000, 2000, 4000, 5000, 5500 and 6000 m and dashed contours represent –10, –50 and –100 m.

for the Himalayas and Western Ghats. The interpolated orography (Fig. 4a) shows mainly three peaks around the points (89°E, 34°N), (86°E, 30°N) and (81°E, 34°N), which are better represented in FMO0.7 (Fig. 4d) by contour value of 5500 m, in terms of both location and strength compared to both mean (Fig. 4b) and ENV0.7 (Fig. 4c). It may be noted that in both cases, of FMO0.7 and ENV0.7, the envelope orography has been obtained by multiplying the standard deviation with 0.7 and then adding to the grid-square mean values. Negative dips over the oceanic region are significantly reduced, as evident from the dotted contours for FMO0.7. Figure 5 shows the histogram of number of grid points over the Indian domain covering 56-103°E, 3-39°N, as percentages falling under categories (each one being 500 m wide along the *x*-axis) ranging between –500 m and 6000 m. It is seen that the approximate percentage of grid points having heights above 5000 m is 4% for both interpolated and FMO0.7, whereas it is 3% and 7%, respectively, for mean and ENV0.7. The number of grid points over Indian domain having negative orography is the least (18%) for FMO0.7. Also, approximately 62% of the grid points over Indian region have heights equal to or below 500 m for both interpolated and mean orography. Similar percentages for ENV0.7 and FMO0.7 are 56% and 57%, respectively.

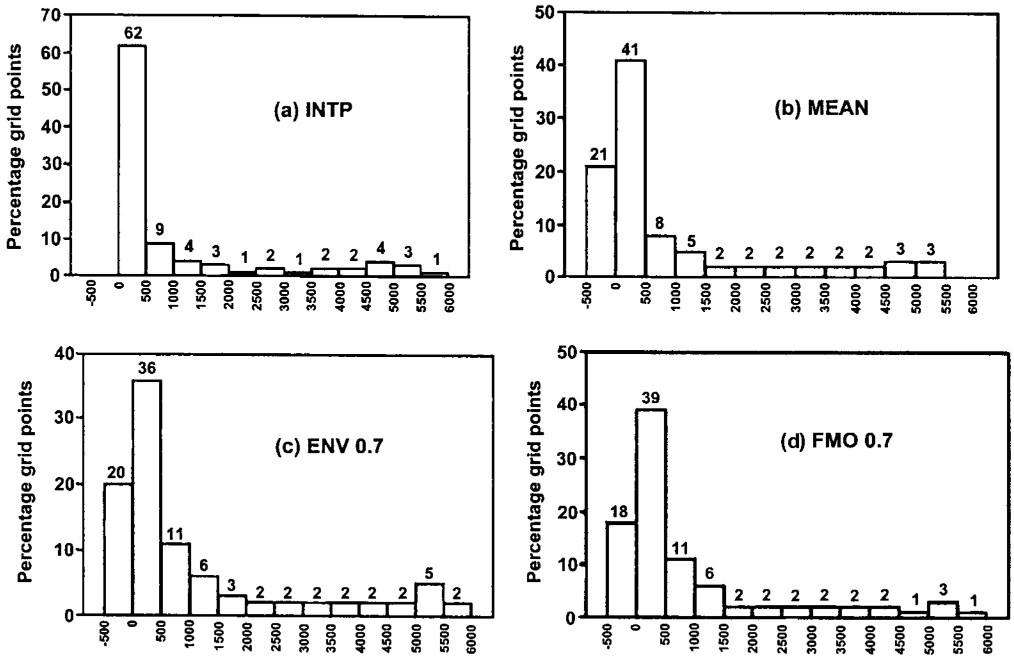

Fig. 5. Histograms showing the percentage of Indian grid points (over the domain 56-103°E, 3-39°N) falling under various categories of elevations at the interval of 500 m starting with –500 m: (a) interpolated orography at T80 resolution, (b) mean orography, (c) ENV0.7, (d) FMO0.7.

3. INDIAN MONSOON SIMULATION EXPERIMENTS

3.1. Model and methodology

The operational spectral GCM of NCMRWF at horizontal resolution T80 has been used for simulation of Indian summer monsoon circulation and associated rainfall. A brief description of the model can be obtained from Basu *et al.* (2002). NCMRWF operational analyses for 13-17 May 1999 have been used as the initial conditions for the model simulations in ensemble mode with five members. The model is integrated for the period covering the whole of summer monsoon season from June to September (JJAS) in climate mode, and few initial forecast days in May are left out to avoid the spin up. The **s**ea **s**urface **t**emperature (SST) is merged with climatology on day-to-day basis to avoid major drift. The experiments consist of three types of orographic representations such as (a) the mean orography (Mean), (b) **env**elope orography (ENV0.7) and (c) **F**iltered **M**odified **O**rography (FMO0.7).

3.2. Results and discussion

One advantage of using the filtered orography is the suppression of ripples in most of the forecast fields associated with the major mountain patterns. As seen from Fig. 4, the negative orography by strength as well as spread (indicated by the dashed contours) is the least for FMO0.7 and highest for ENV0.7 over the Indian Ocean region. Figures 6a and 7a show JJAS mean wind and geopotential heights at 850 hPa and 200 hPa levels, respectively, based on NCMRWF analyses. Figures 6b, c, d and 7b, c, d show the differences of JJAS mean simulated wind and geopotential fields in the case of Mean, ENV0.7 and FMO0.7 from the respective analyses. Examination of mean monsoon circulations simulated with Mean, ENV0.7 and FMO0.7 orographies indicates semi-permanent features such as monsoon trough, heat low, Tibetan high and tropical easterly jet reasonably well. It is found that the average position of monsoon trough is to the north of analysis and nearly over the sub-Himalayan belts as simulated in the case of all the three orographies with the Mean orography slightly closer to the analysis. Since the assimilation procedure employs mean orography, its influence gets reflected in the analysis also. On closer examination, it is found that the geopotential fields are well simulated at lower levels in both Mean and FMO0.7, compared to ENV0.7, although FMO0.7 lowers the geopotential heights slightly more than the Mean, especially over eastern Himalayan ranges (Fig. 6b,d). This is probably the effect of orographic enhancement and it provides ample rainfall over the eastern monsoon trough region. But, in contrast, ENV0.7 (Fig. 6c) raises the lower tropospheric heights unrealistically all over the Gangetic plains (by an order of 25-50 m). This result shows the advantages of using FMO0.7 compared to ENV0.7. At the upper level, however, the T80 model shows much reduction in height which has already been identified as one of the systematic errors of the model by Mohanty *et al*. (1995) in their earlier study. At 200 hPa level, the innermost contour for the analysis is

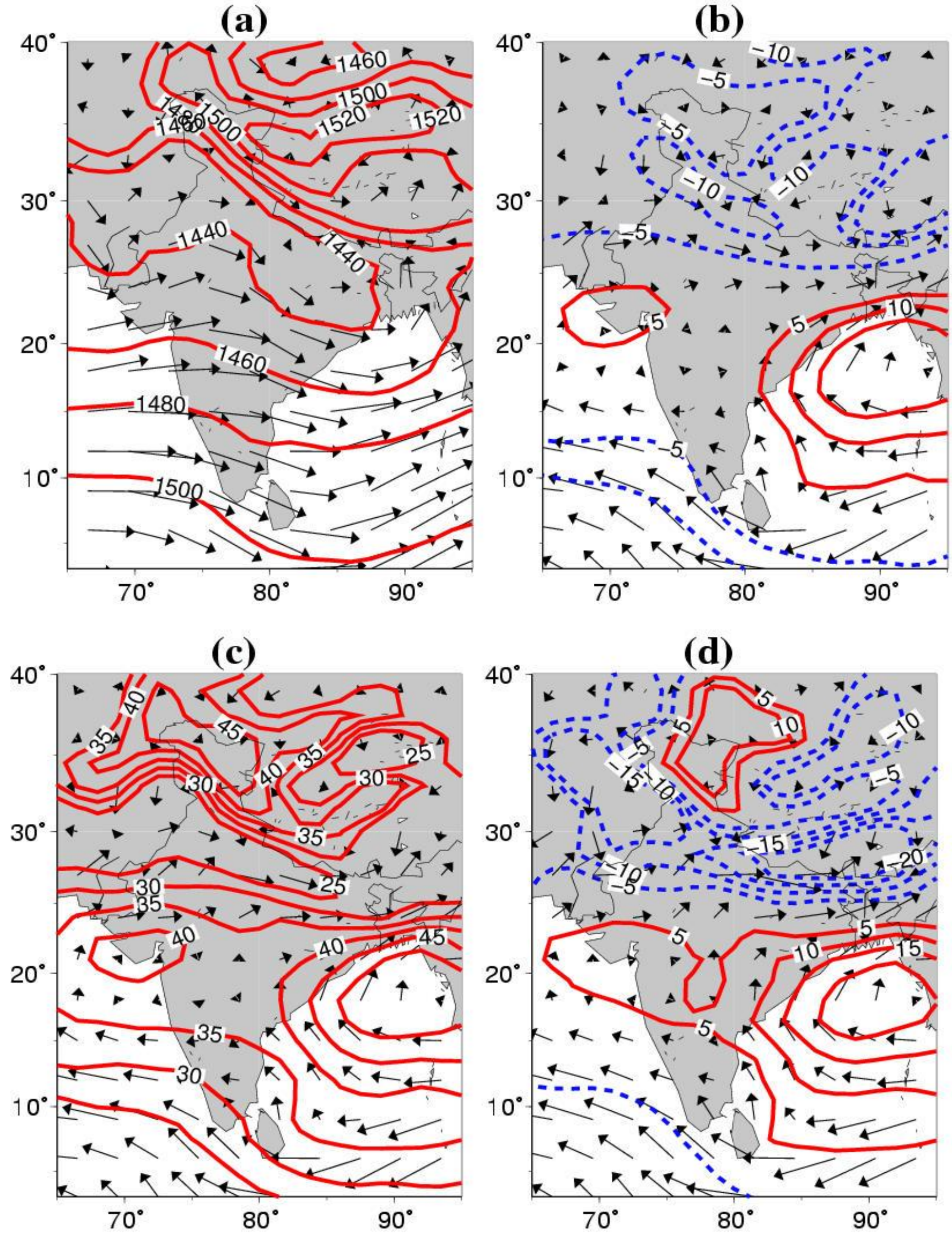

Fig. 6. Wind (in m/s) and geopotential heights (in meters) at 850 hPa level over India during JJAS 1999 for: (a) analysis, (b) mean – analysis, (c) ENV0.7 – analysis and (d) FMO0.7 – analysis. Initial conditions for the experiments are 00 UTC, 13-17 May 1999 for the 5-member ensemble run.

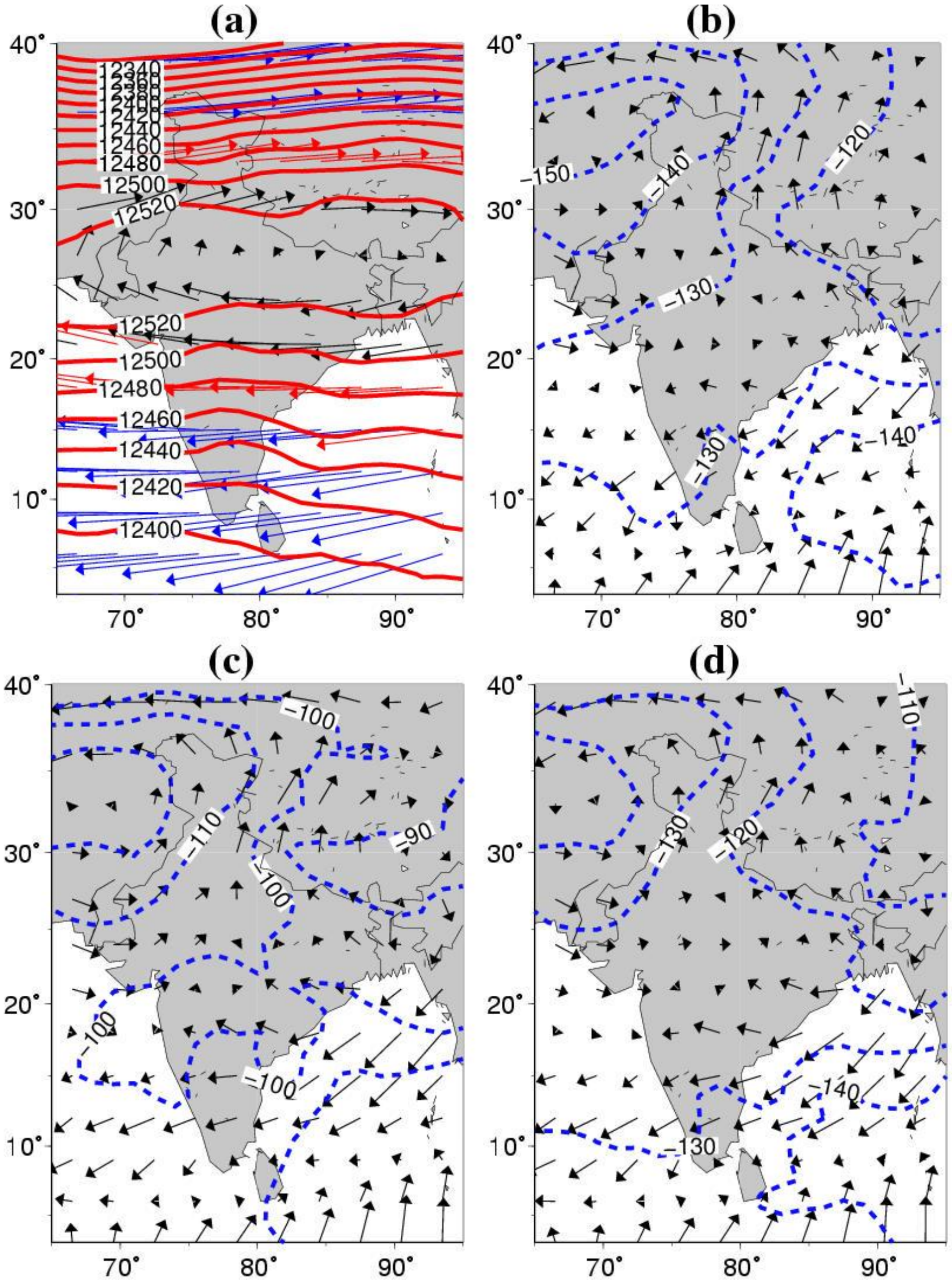

Fig. 7. Wind (in m/s) and geopotential heights (in meters) at 200 hPa level over India during JJAS 1999 for: (a) analysis, (b) mean – analysis, (c) ENV0.7 – analysis and (d) FMO0.7 – analysis. Initial conditions for the experiments are 00 UTC, 13-17 May 1999 for the 5-member ensemble run.

12,520 m (Fig. 7a) whereas both Mean (Fig. 7b) and FMO0.7 (Fig. 7d) highly underestimate the Tibetan high (by the order of –120 to –140 m). ENV0.7 shows slightly less reduction in the Tibetan high (of the order of –90 to –110 m) it being closer to analysis amongst all the three orographic representations. However, FMO0.7 simulates better than Mean at 200 hPa level. Moreover, FMO0.7 does not simulate the lower level height contours unrealistically high as in case of ENV0.7. Thus, it is seen that the envelope technique applied to the global orography gives rise to more discrepancies compared to FMO in simulating the geopotential field. FMO0.7 produces comparable skill relative to Mean and it is also able to produce more intense system as in the case of ENV0.7, while reducing the errors associated with the latter.

Figure 8a shows JJAS mean precipitation for 1999 from Level-3 **T**ropical **R**ainfall **M**easuring **M**ission (TRMM) analysis. Level-3 TRMM rainfall estimates are

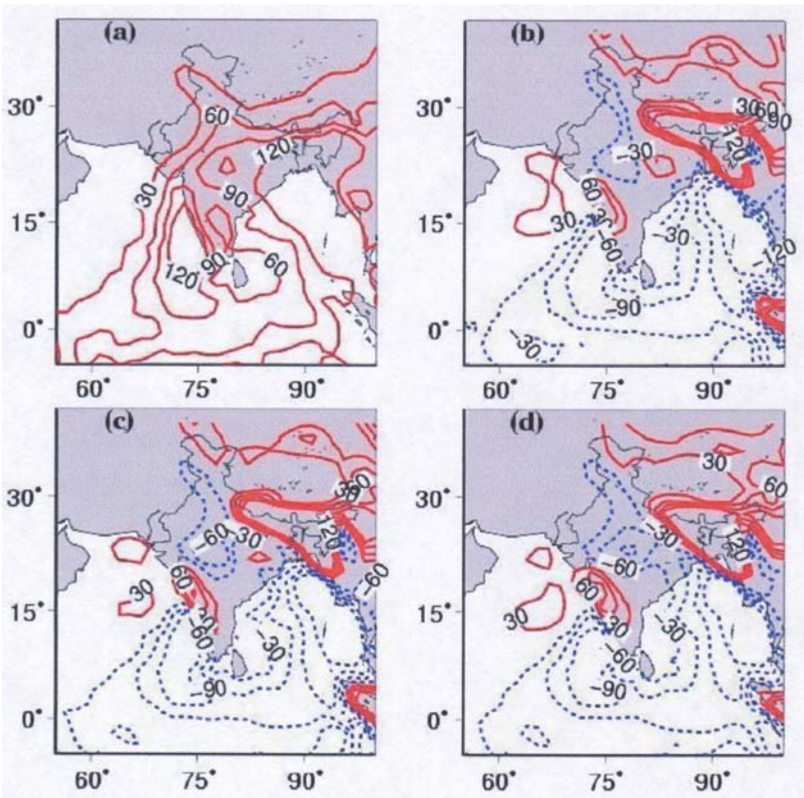

Fig. 8. JJAS precipitation (in cm) for 1999: (a) level 3 TRMM rainfall analysis, (b) mean – analysis, (c) ENV0.7 – analysis, and (d) FMO0.7 – analysis. The initial conditions for the control and experiments are 00 UTC, 13-17 May 1999 for the 5-member ensemble run.

produced by combining the monthly average unclipped **T**RMM **m**icrowave **i**mages (TMI) estimates, the monthly average SSM/I estimates, the pentad-average adjusted merged IR estimates and the monthly accumulated **C**limate **A**ssessment and **M**onitoring **S**ystem (CAMS) or **G**lobal **P**recipitation **C**limatology **C**entre (GPCC) rain-gauge analyses. As far as the distribution of JJAS mean rainfall is concerned, control and experimental runs give reasonably good match with the Level-3 TRMM rainfall analysis and most of the major precipitation patterns are brought out well except over the northwest Indian region (Fig. 8). FMO0.7 gives better distribution of rainfall than ENV0.7, whereas the latter brings up more intense patterns of rainfall over most parts of the subcontinent. The impact of the new orographic representation in FMO0.7 is more strongly felt over the eastern sub-Himalayan belt while it leads to more drying in the northwest India compared to Mean orography. Figure 9 shows the area-weighted rainfall computed from the observed individual meteorological sub-divisional rainfall values provided by **I**ndia **M**eteorological **D**epartment (IMD) in comparison with those simulated by the model with Mean, ENV0.7 and FMO0.7 for JJAS. From the figure it is seen that Mean orography overestimates JJAS rainfall and ENV0.7 underestimates the same. However, FMO0.7 simulates JJAS mean rainfall very close to the observed value.

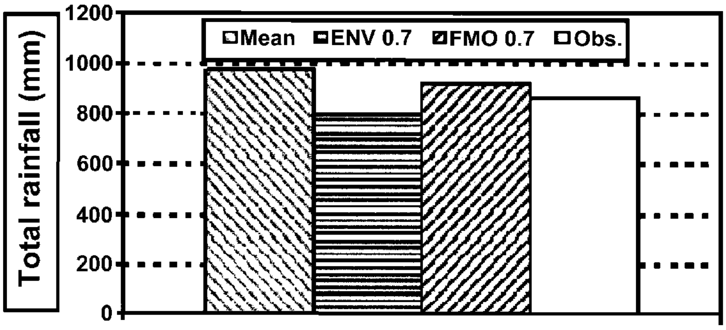

Fig. 9. All India JJAS mean rainfall (in mm) for Mean, ENV0.7, FMO0.7 and IMD observed rainfall.

4. SUMMARY AND CONCLUSIONS

GCMs are very sensitive to the prescribed orographic representations. The spectral GCMs are vulnerable to the orographic deformations due to the associated Gibbs bias of the spectral fitting, which in turn may have significant impact on climate simulations. It is possible to reduce the intensity of the anomalies in the transformed orography using digital filters, but the heights of mountains are not well reproduced. In this paper attempt has been made to regionally modify the orography in NCMRWF T80 model, so that the barrier ef fects of the Himalayas and the Western Ghats are realistically represented in the model.

It has been observed that the application of two-dimensional Lanczos filter over the whole globe and regional enhancement over the Himalayas and the Western Ghats in a new type of orographic representation FMO in spectral GCM of NCMRWF at horizontal resolution T80, helps in simulating Indian summer monsoon circulation features reasonably well. Global wind and geopotential fields are better simulated when FMO is prescribed in the GCM. FMO simulates JJAS rainfall as well as its regional distribution better than the envelope orography. Thus, this new orographic representation indicates enhanced barrier effect while minimising the errors and discrepancies produced by the envelope technique. The all-India JJAS mean rainfall simulated with FMO is very close to the actual observed rainfall in comparison with mean and envelope orography. However, the results of this study do not conclusively establish that FMO simulates the regional distribution of JJAS rainfall better than the mean orography.

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