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Poleward propagations of the ITCZ : Observations and theory

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सार – वेबस्टर मॉडल के संशोधित रूपान्तर द्वारा मौसमी द्रोणी में समुद्र और भूमि दोनों में टेढ़ा-मेढ़ा पथ बनाते हुए समुद्री क्षेत्रों द्वारा निर्गमित अभिध्रुव संचरण सहित ग्रीष्म मानसून में भारतीय देशान्तर पर ITCZ के अन्तराऋतुनिष्ठ विभिन्नताओं के प्रमुख लक्षणों को अनुकारित किया गया है। मॉडल में निहित संचरण विधि में अभिमध्यरेखीय क्षेत्र से सम्बन्धित अपसारी क्षेत्र के अभिध्रुव की तरफ अधिकतम संवहनी उष्मन से सम्मिलित होती है जिसका प्रयोग भूमि और समुद्र दोनों में किया जा सकता है। मॉडल में यह अन्तर संवहनी, अस्थिरता के मौसमी प्रवणता और आर्द्रता उपलब्धता से उत्पन्न होता है और इसलिए संवहनी उष्मन के तीव्रता घटक ही दोनों घटकों का गुणनफल है। यदि ऊर्ध्वाधर आरोहांक के संवहनी उष्मन के अनुपात, वास्तव में इन दोनों कारकों पर निर्भर है तो प्रेक्षित संचरण उसी विधि से उत्पन्न किया जा सकता है।

ABSTRACT. Many features of the intraseasonal variation of the ITCZ over the Indian longitudes in the summer monsoon including poleward propagations emanating from oceanic regions and traversing both ocean and land to culminate in the seasonal trough have been simulated by a modified version of the Webster model. The mechanism underlying the propagations in the model involves excess convective heating to the poleward side of the convergence zone relative to the equatorward zone and can operate on land or sea. This differential arises in the model from the seasonal gradient of the convective instability and moisture availability and hence the intensity factor of convective heating which is the product of the two factors. If the ratio of the convective heating to the vertical ascent in reality also depends on these two factors, the observed propagations could be generated by the same mechanism.

1. Introduction

The large-scale rainfall over the monsoonal regions, as over the rest of the tropics is associated with the ITCZ. The variation of the large scale rainfall is intimately related to the variation in the location and intensity of the ITCZ. Detailed analysis of the satellite imagery (in which the ITCZ appears as a zonal band of intense cloudiness) has revealed the rich structure of the supersynoptic variation of the ITCZ over the Indian longitudes during the summer monsoon (Sikka and Gadgil 1980). Within the seasonal envelope, the variation of the ITCZ is seen to be a succession of events involving genesis, an active spell (which may involve a propagation in space) and demise. There are two favourable locations of the ITCZ over these longitudes: one over the seasonal trough on the heated continent, and another over the warm waters of the equatorial Indian Ocean. Thus the latitudinal distribution of the occurrence of the ITCZ is bimodal with the zone of frequent occurrence over the continent and a secondary zone over the equatorial ocean. The most prominent feature of the intraseasonal variation is the poleward propagation of the ITCZ from the equatorial Indian Ocean onto the heated subcontinent throughout the summer monsoon season. These propagations involve ITCZ traversing over 20° in latitude, coherently over a region larger than 30° in longitudinal extent. Such a propagation during the onset phase leads to the establishment of the continental ITCZ and subsequent propagations at intervals of about 40 days lead to its revival from weak monsoon phases.

The poleward propagation of the cloudband, rainbelt and other features of the circulation during the onset phase has been well documented (Rao 1976) and is understood as the mode of the transition from the spring to the summer pattern. However, although the phenomenon of repeated occurrence of such propagations in the summer has been simulated by Webster and Chou (1980) it is yet to be completely understood. It must be noted that the ITCZ is seldom uniformly intense throughout its zonal extent, synoptic scale disturbances are generally embedded in it. The observed propagations of the ITCZ over the Indian longitudes are often associated with propagations of these embedded synoptic scale disturbances (Sikka and Gadgil 1980, henceforth referred to as SG). Given the property of cyclonic vortices to move poleward one may expect the ITCZ to exhibit poleward propagations in other parts of the tropics as well. However, McBride (1983) has shown that, while the ITCZ over Australian longitudes in the southern hemispheric summer exhibits considerable fluctuations in the location, there is no bias in the meridional propagations in favour of poleward ones and no poleward propagations of the type observed over the Indian longitudes in the summer monsoon. This suggests that the poleward propagations is not an ubiquitous feature of the intraseasonal variation of the ITCZ. On the other hand, if the propagation are attributed to surface hydrological feedbacks (Webster 1983, Goswami and Shukla 1984) which can operate only on land, there should be no propagations over the oceans. Observations are at variance with this prediction (SG). The hypothesis that the propagations are triggered by cold outbreaks from the southern hemisphere (Yasunari 1981) cannot be tested unless some testifiable predictions are generated.

In this paper the results of our recent empirical and theoretical studies are summarised, addressed towards gaining a deeper understanding of the phenomenon of poleward propagations. It is suggested that the observed propagations could arise from the same mechanism as the necessary conditions for the mechanism to operate are satisfied for the Indian longitudes during the summer monsoon. It is found that the observations for the variation of the ITCZ over monsoonal Africa in the southern hemispheric summer are consistent with the predictions generated by the model.

2. Observations

The variation of the ITCZ over the Indian longitudes has been studied by visual scanning of the visible and infrared imagery to identify the maximum cloudiness zone associated with the ITCZ (SG). This subjective approach has some advantages at the initial stages, firstly, because it is relatively easy to identify regions with deep convective clouds and secondly, because it utilizes fully the remarkable capacity of the eye to recognize coherent patterns even when the intensity is not uniform throughout. However, for an extensive analysis of the variations of the ITCZ over different parts of the tropics an analysis of digitized data would be preferable. For such an analysis, a method of objectively identifying coherent zones of intense cloudiness of the type associated with the ITCZ from digitized satellite data has to be developed.

We expect the data set on the 2.5-degree grid to be of adequate resolution for delineating the ITCZ on a day-to-day basis, since the accuracy with which the ITCZ can be located in a subjective scan of the NOAA satellite imagery (*viz.*, about 1-degree latitude in the location of the associated cloud band) has been found to be adequate for this purpose (SG). We, therefore, developed a method using the 2.5-degree data which we believe to be the simplest possible method, which incorporates the essential steps in the subjective pattern recognition from satellite imagery, so as to yield results which are comparable with those obtained earlier by visual scanning of satellite imagery (SG) for overlapping data.

2.1. *Identification of the ITCZ from digitized satellite data*

The delineation of the ITCZ involves firstly, the identification of the 2.5-degree squares which have a large fraction of deep convective clouds and then from amongst such squares, omitting those which are not organised over a large spatial scale. The 2.5-degree squares with a large fraction of deep convective clouds can be identified on the basis of the characteristic signatures of the deep convective clouds in terms of the ranges of the satellite derived parameters. The most important features that distinguish one cloud type from another are: (*i*) the level of the cloud top which determines the outgoing longwave radiation (henceforth OLR) or the brightness temperature and (*ii*) the vertical extent of the cloud which determines the albedo. Deep convective clouds of the type associated with tropical disturbances nd the ITCZ are at the low OLR, high albedo edge of the distribution while the stratocumulus and mid-level clouds are associated with distinctly higher OLR than those comprising convective thunderstorms and tropical disturbances. However, the cirrus clouds are also characterized by low values of OLR. Thus, while regions of high convection are always associated with low OLR, the converse is not true. Regions with high level cirrus overlying non-convective conditions are also characterized by low values of OLR. Morrissey (1986) has shown that this 'cirrus contamination' can lead to a poor correlation between OLR and precipitation/moisture budget (*i.e.*, precipitation—evaporation). We found that for the studies of the movements of the ITCZ on the intraseasonal scale, it is necessary to remove the cirrus contamination.

The basic data set consists of day-time OLR and albedo over a 2.5-degree grid derived from the measurements by NOAA polar orbitting satellites during 1974-86. The data utilized have already been corrected for changes in the equatorial crossing time and changes in instrumentation. The simplest way of identifying regions with low OLR and high albedo characteristic of deep convective clouds is by imposing a threshold. Richards and Arkin (1981) have shown that for estimation of the fractional area covered with deep convective clouds (from which the tropical precipitation is derived) from OLR data, the appropriate threshold is a brightness temperature of 240° K (*i.e.*, OLR of about 190 Wm^{-2}). However, all the studies of the distribution of the different cloud types in the OLR and albedo space and hence, of the appropriate thresholds for deep convective clouds are for the pixel scale. Whether the thresholds for the average values over 2.5-degree squares will be the same or less stringent depends on the detailed distribution of the pixels of the deep convective type in the OLR albedo space and the typical value of the fraction of the square covered with such pixels in a tropical disturbance or an ITCZ.

Chou *et al.*'s (1986) study of the distribution of the 10 × 10 km pixels in the OLR albedo space has revealed important features of pixels covered with deep convective clouds within the ITCZ over the West Pacific. The mean OLR of the pixels, identified by them as cloudy, is about 135 Wm^{-2}, and the fraction of such pixels in a 4-degree square within the ITCZ is over 70%. The average OLR for such 4-degree squares is less than 180 Wm^{-2}. Thus the thresholds appropriate for delineating the ITCZ may not be much more stringent than those suggested by the pixel scale studies. We have determined the appropriate thresholds by comparison of the results of the delineation of the ITCZ based on different sets of thresholds in the range suggested by studies on the pixel scale with those obtained by subjective visual scanning of the imagery.

The ITCZ is associated with organization of such deep clouds over large spatial scales. It has been suggested that the minimum longitudinal extent of the associated cloudband is 10 degrees (SG). To filter out from the set of grid points which have deep convective clouds (as determined from the threshold conditions) and those grid points which are not organised over a large scale, we adopted a very simple method. A grid point, at which the threshold conditions were satisfied, was retained as a

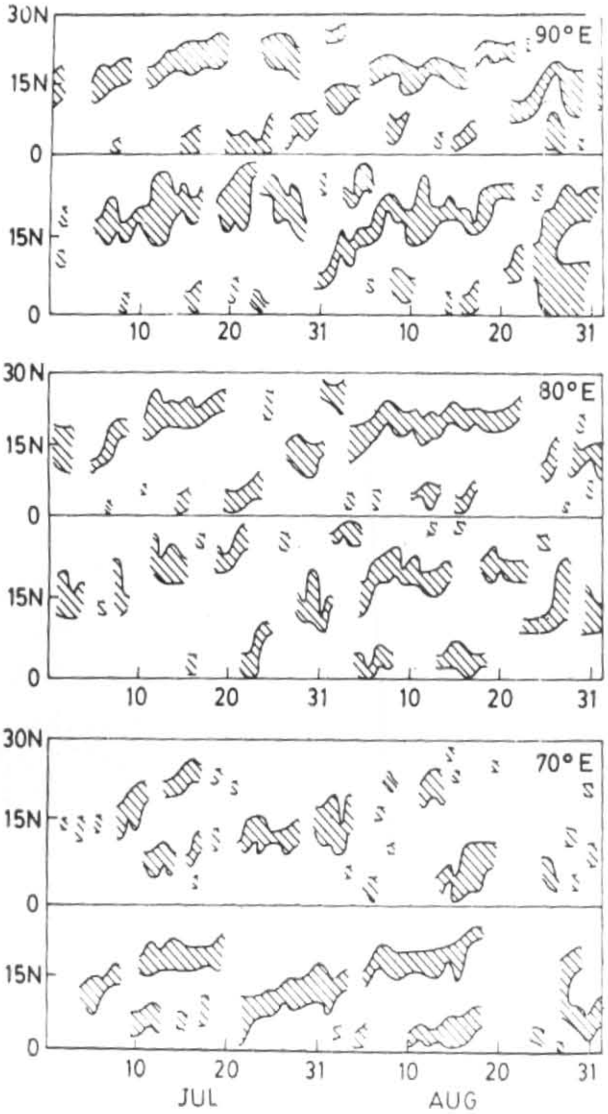

Fig. 1. A comparison of the variation of the ITCZ during July-August 1985 at 70°, 80°, 90° E of the results of subjective scans (above : *after* SG) and from 2.5-degree OLR-albedo data (below)

cloudy grid point only when, at least two of the eight grid points surrounding it, also satisfied the threshold conditions. This implies retention of only the grid points within organized large scale convection (over scales >500 km, *i.e.*, LCSA *after* Morrissey 1986). In general about 80-85% of the grid points, at which threshold conditions were satisfied, were retained after this filtering of the smaller scales. The other grid points are taken to be 'cloudfree'. Since the grid scale of the data is not small, this simple method was found to be adequate for filtering out isolated cloudy grid points.

Once the ITCZ is delineated, the variation of the ITCZ in the latitude-time domain at different longitudes is derived. For that purpose, the latitudinal extent of all the cloudbands at the longitude of interest has to be determined on a day to day basis. We take two cloudbands to be distinct if they are separated by at least three consecutive cloudfree grid points. This implies a minimum separation of 750 km between bands. In determining the latitudinal extent of the bands, gaps of one or two cloudfree grid points within a cloudy zone are ignored. Occasionally parts of the cloudy zone may not be as intense as the rest and so the threshold criteria may not be satisfied at all the longitudes within what the eye sees a coherent cloudband. To take care of such cases when the band is less intense over the longitude of interest, the occurrence of the band at the two neighbouring longitudes was also tested. The variation at the central longitude was obtained by spatial smearing over the three neighbouring longitudes.

The results for the summer of 1975 using a variety of thresholds were compared with those obtained earlier (SG). It was found that an OLR threshold of 185 Wm^{-2} (*i.e.*, brightness temperature of about 240° K implying 2.5-degree average cloudtop height of about 300 mb) and for the albedo a threshold of 0.5 give results which are closest to those obtained by visual scan of satellite imagery (Fig. 1). The results for thresholds for OLR in the range 170-200 Wm^{-2} are not too different. For more stringent OLR thresholds the number of days of ITCZ occurrence is drastically reduced, while for larger OLR thresholds the cloudband become unrealistically wide on a few days leading to an apparent merger of the oceanic and the continental bands over the Indian longitudes. The results are also not very sensitive to the exact value of the albedo threshold chosen.

Murakami (1983) has suggested a method for delineating regions of intense convection based on an analysis of OLR data with a resolution of about 5 km. The method involves derivation of the mean and standard deviations of equivalent blackbody temperature T_{BB} on 1-degree square mesh. The squares with the standard deviation larger than 5 K are taken to be convective and the intensity index of convection is defined in terms of the mean values of the cloudtop temperature for clouds higher than 400 mb. The zones characterized by high index of convection during July 1979 by Murakami's criterion are found to be markedly similar to the region characterized by a high frequency of occurrence of the deep clouds delineated by the far simpler bispectral threshold method used here.

2.2. *Intraseasonal variation of the ITCZ over different regions*

The frequency of occurrence of deep convective clouds over a given region in any month (as derived from the number of days on which the threshold conditions on OLR and albedo are satisfied by the 2.5-degree grid points within it) varies from 0 over the purely non-convective regions to 10-15 days over regions near the centres of the major convective zones. The major zones of convection in the northern hemispheric summer are : (*i*) the Asian monsoon-W. Pacific zone (70°-150° E), (*ii*) the E. Pacific zone (120°-80° W) and (*iii*) a relatively weaker zone extending from E. Atlantic to the African continent (20° W-20° E). During the southern hemispheric summer, the major convective zones are (*iv*) one streching from the equatorial Indian Ocean across the maritime continent (70°-170° E), and western and southwestern Pacific, (*v*) over the southern equatorial

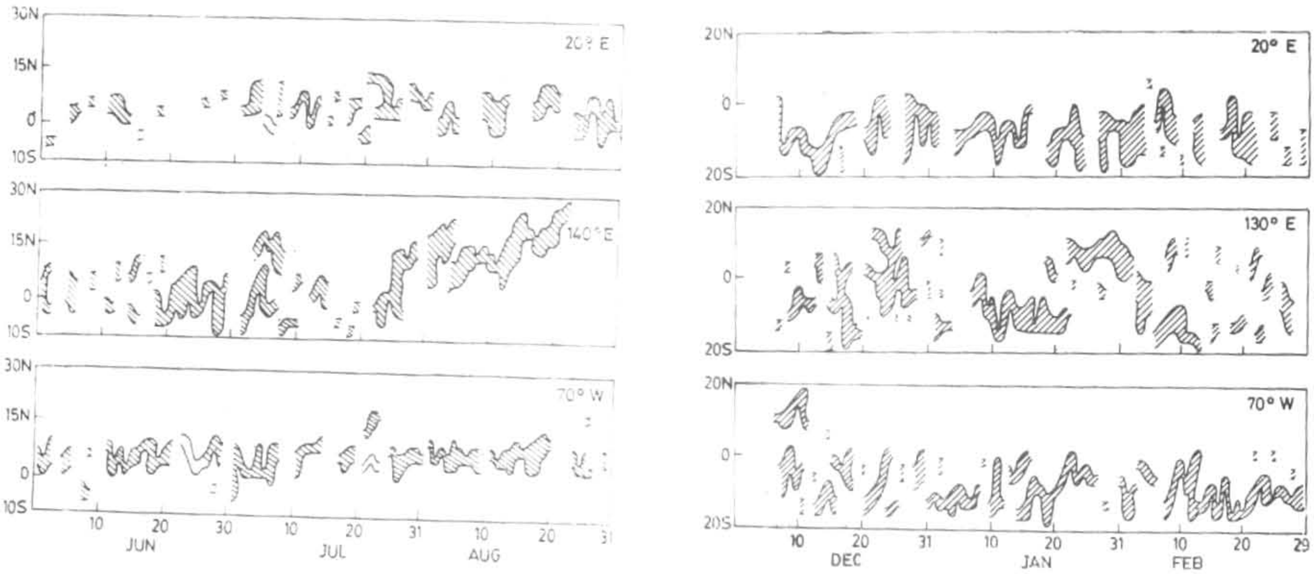

Fig. 2. Variation of the ITCZ at different longitudes during (a) northern summer and (b) northern winter

parts of the African continent (20°-35° E) and (*vi*) another over the South American continent (80°-50° W). It is found that the latitudinal extent of the distribution is largest for the Asian monsoon-W. Pacific zone during the northern hemispheric summer, in comparison with the other zones. During July-August the distribution of occurrence is bimodal over most of that region with the primary zone over 15°-25°N and a secondary zone over the equatorial ocean. The latitudinal extent of the convective zones over the other regions characterized by a continental ITCZ (*i.e.*, *v* and *vi*) is considerably smaller [although somewhat larger than the zones (*ii*) and (*iii*)] and the distribution is unimodal.

The variation of the ITCZ of the continental zones (*v*, *vi*) during the southern hemispheric winter of 1975-76 are shown in Fig. 2. While there are considerable fluctuations in the location of the ITCZ over these continents, poleward propagations of the type observed over the Asian longitudes in the summer monsoon are not observed. Over the zones (*ii*, *iii*) also no poleward propagations are observed (Fig. 2). Over the Asian winter monsoon region (*iv*), only one poleward propagation is seen at 120° E. However, it appears to be restricted to a relatively small longitudinal belt and furthermore does not occur every year. Thus, we may conclude that coherent sustained propagations of the type observed over the Asian summer monsoon region are not observed elsewhere.

3. Theory

The poleward propagations of the ITCZ have been simulated in an axisymmetric climate model developed by Webster and Lau (1977) and Webster and Chou (1980) which will henceforth be referred to as the Webster model. In this model with a continental cap north of 18° N, and ocean over the rest of the earth, the intraseasonal variation comprises a succession of ITCZ events involving genesis at the land-ocean boundary and subsequent poleward propagation. There is a marked similarity between the observed variation of the axis of the ITCZ and that of the axis of the convergence zone in the model, suggesting that an insight into the mechanisms underlying the observed variation can be gained by an in-depth study of the model.

There are some differences, however, between simulations and reality. The variation in the model is less complex than observed with more orderly periodic propagations at intervals smaller than the observed. The revival of the continental ITCZ occurs only through such poleward propagations. Also, while the observed propagations occur from the equatorial ocean onto the land surface, for the parameters/oceanic conditions of the model runs reported (Webster and Chou 1980), the ITCZ is always generated only at the land-ocean boundary and the propagations occur only over the land surface. Webster (1983) has suggested that these propagations arise due to north-south differential in total heating generated by surface hydrological feedbacks. Goswami and Shukla (1984) also found that the meridional propagations in their model occur only for the continental case and that too only when surface evaporation is taken into account. Obviously, the observed propagations across the oceans and the continent cannot be understood in terms of this mechanism since it can operate only on land.

We find that the simulations become more realistic when the model is modified and the propagations are no longer restricted to land.

3.1. *Modifications of the Webster model*

The temporal variation of the model atmosphere is in response to the variation of the conditions at the lower boundary, which in turn are forced by the variation in the insolation. The response time of the land surface depends on its thermal inertia. Since this time-scale is much smaller than the response time of the ocean, as a first approximation the thermal inertia of land is taken to be zero in most climate models including Webster's.

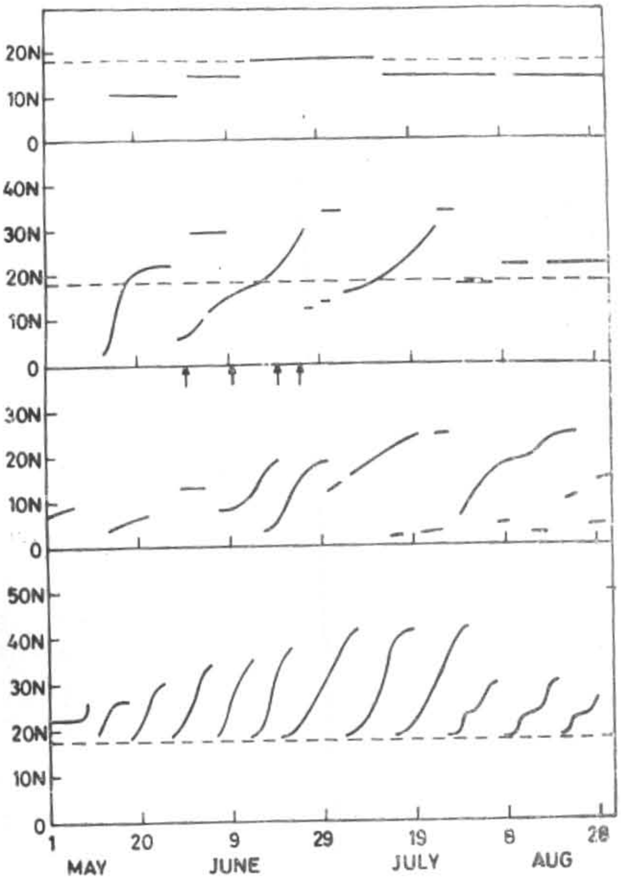

Fig. 3. The variation of the axis of the ascent in :

(a) Webster's model

(b) a smoothed version of the observed variation at 90 E from Fig. 1

(c) in the modified version of Webster's model and

(d) in the modified version of Webster's model when the intensity factor I in the convective heating parameterization is a constant.

While this assumption has no serious consequences for the evolution of the monthly or seasonal fields, we expect the impact on the intraseasonal variation to be significant. We have, therefore, modified the Webster model to incorporate thermal inertia of the ground.

As suggested by Hansen *et al.* (1983), the thermal capacity of the soil is taken to be that commensurate with an equivalent depth of the annual thermal wave, *i.e.*, a depth of 4 m in order to account for the seasonal heat storage in the soil. In addition, the field moisture holding capacity of the soil has been enhanced from the value of 10 cm (assumed in Webster and Chou 1980) to a value of 30 cm which is more representative of Indian subcontinent (Hansen *et al.* 1983). Both these changes had an impact on the time-scales of intraseasonal variation, the first factor having by far the largest impact. Since the sea surface temperature predicted by the coupled ocean-atmosphere model of Webster is somewhat lower than the climatological values for the oceans over the Indian longitudes in the summer, the model was decoupled and run with specified seasonally varying sea surface temperature based on the climatological data (in the region of 80°-100° E).

The results of the modified model are shown in Fig. 3. The pattern of variation is more realistic. Once established, the continental ITCZ revives by genesis in the primary zone near the seasonal trough or by propagation from the secondary zone. There is a significant improvement in the period between consecutive poleward propagations of ITCZ. The genesis of the events now occurs over the oceanic regions and the propagations occur over both the ocean and land.

3.2. *Mechanism of propagation*

The ITCZ in the Webster model propagates northward from the point of genesis because there is an excess of heating to the north of the ITCZ relative to the region directly beneath and to its south. This excess of heating in the north leads to an intensification of the ascent in the region to the north of the axis of the ascent, and a subsequent northward shift of the axis. We seek an explanation for the propagations in the model in terms of a more general mechanism than surface hydrological feedbacks which can operate on land or sea. We find that the key element of the mechanism, *viz.*, the north-south differential in the total heating arises from the nature of the meridional variation of the convective heating, which is the dominant component of the heating function. Even when the vertical velocity profile is asymmetric with stronger ascent to the south of the axis of maximum ascent, there is more convective heating to the north of the axis than to the south. It is clear that such an excess of convective heating, and hence total heating, in the north can lead to an intensification of the ascent in the region to the north of the axis of the ascent, and a subsequent northward shift of the axis. Thus the poleward propagations can arise in this manner due to the meridional lag between convective heating and the vertical velocity.

The lag in the model between the convective heating and vertical velocity profiles can be understood by considering the parameterization of cumulus convection in the Webster model. The convective instability factor as well as the moisture availability factor depend upon the surface temperature. In the summer, the monthly/seasonal values of each of these factors and hence of I attain a maximum at the latitude of the maximum surface temperature, *i.e.*, at the seasonal trough induced by the solar insolation. Subseasonal variations in the intensity factor I, arise from various factors such as the changes in surface temperature due to hydrological feedbacks, the stabilization of the vertical enthalpy profile due to the mid-tropospheric heating associated with convection etc. Despite these subseasonal changes, the maximum over the seasonal trough persists in the daily profiles of I throughout the summer. A secondary maximum in I appears over the zone of genesis. Between the secondary zone and the seasonal trough there is a positive meridional gradient of I. The presence of such a gradient in the intensity factor induces a lag between the vertical velocity profile and convective heating profile.

To test the hypothesis proposed here, *viz.*, that the poleward propagations arise due to the meridional lag between convective heating and the vertical velocity profiles generated by the meridional gradient of the intensity factor, I, both the original and modified versions of the model were run after specifying the intensity factor to be a constant over the entire domain. The result in each case was dramatic—the propagation totally disappeared (Fig. 3). In contradistinction with the standard case, there was no lag in space or time between the convective heating and vertical velocity profiles in this case and the ITCZ did not propagate. From this we may conclude that the northward propagations depend primarily on the latitudinal variations of the intensity factor I in the parameterization of convective heating in the model, which arises from the seasonal gradient in the insolation. As demonstrated, the proposed mechanism can operate on land or sea. Since the meridional gradient of the sensible heat flux is also positive over the region characterized by propagations, it enhances to some extent the north-south asymmetry in the heating and, thus, reinforces the propagations generated by the variation in the intensity factor. Modulations of the surface temperature by hydrological feedbacks and variations in the stablity of the atmosphere also have some impact on the detailed structure of the propagations.

The observed mean summer fields of the conditional instability and the specific humidity at the top of the boundary layer exhibit an increase with latitude in the summer hemisphere over the region equatorward of the latitude of the seasonal trough. The necessary condition of a positive meridional gradient of the intensity factor, I, is likely to be satisfied by the tropical atmosphere for the region over which these propagations are observed. Hence, if the convective parameterization used in the model can be shown to be realistic, then the mechanism responsible for the observed propagations could in fact be the one proposed here.

We note that such propagations will occur whenever the latitudinal variation of the intensity factor is bimodal with genesis occurring over the secondary maximum, provided the gradient of the intensity factor is positive in the region between the zone of genesis and the primary maximum located over the seasonal heat trough. In the modified Webster model with ocean equatorward of the continent, the secondary maximum is associated with the maximum sea surface temperature. If the continent stretches across the equator with ocean poleward of the boundary (*e.g.*, continent from 18° S up to 90° N) in the season in which the sun is over the hemisphere with the ocean (in the southern hemispheric summer in our example), there is no secondary maximum in the equatorial regions and the ITCZ occurs over the seasonal heat trough throughout the season. This simulates well the observed variation of the ITCZ over the African region in the southern hemispheric summer (Fig. 2).

4. Concluding remarks

Many features of the intraseasonal variation of the ITCZ over the Indian longitudes in the summer monsoon including poleward propagations emanating from oceanic regions and traversing both ocean and land to culminate in the seasonal trough have been simulated by a modified version of the Webster model. The mechanism underlying the propagations in the model involves excess convective heating to the poleward side of the convergence zone relative to the equatorward zone and can operate on land or sea. This differential arises in the model from the seasonal gradient of the convective instability and moisture availability and hence the intensity factor, I, of convective heating which is the product of the two factors. If the ratio of the convective heating to the vertical ascent in reality also depends on these two factors, the observed propagations could be generated by the same mechanism.

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