MODELING OF FORECAST SENSITIVITY ON THE MARCH OF MONSOON
ISOCHRONES FROM KERALA TO NEW DELHI, THE FIRST 25 DAYS

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Submitted to the Journal of Atmospheric Science

June 2011

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Abstract

This study addresses observational and modeling sensitivity on the march of the onset isochrones of the Indian summer monsoon. The first 25 days of the passage of the isochrones of monsoon onset is of great scientific interest. Surface and satellite-based datasets are used for high resolution modeling of the impact the motion of the onset isochrones from Kerala to New Delhi. These include the asymmetries across the isochrone such as soil moisture and its temporal variability, moistening of the dry soil to the immediate north of the isochrone by non-convective anvil rains, formation of newly forming cloud elements to the immediate north of the isochrone. The region, immediate north of the isochrone, is shown to carry a spread of buoyancy elements. As these new elements grow, they are continually being steered by the divergent circulations of the parent isochrone to the north and eventually to the northwest. CLOUDSAT was extremely useful for identifying the asymmetric cloud structures across the isochrone. In the modeling sensitivity studies, we used a mesoscale WRF model to examine days 1 to 25 of forecasts of the onset isochrone. We first modeled prediction experiments during normal, dry, and wet Indian monsoon seasons using default values of model parameters. This study was extended to determine the effects of changes in soil moisture and non-convective rain parameterizations, these are parameters suggested by the satellite observations. These sensitivity experiments show that the motion of the isochrones from Kerala to New Delhi are very sensitive to the parameterization of soil moisture and non-convective anvil rains immediately north of the isochrone.
1. Introduction

The annual cycle of the Asian summer monsoon carries the passage of onset isochrones of precipitation. This is a major feature of the monsoon life cycle. Chang (2004) illustrated the march of the principal monsoonal heat source from Indonesia to the eastern foothills of the Himalayas between January and July and a reverse trek during the remaining months of the year. This is the belt of the heaviest monsoon rains that exhibit an annual seesaw in its traverse pattern. This axis should be labeled as a principle axis of the monsoon. A feature that follows this rain belt is the upper tropospheric outflow that can be seen as a distinct upper anticyclone such as the Tibetan high. During these months, the flows exhibit a response to the heating, following the symmetric and antisymmetric heating/circulation scenario of Gill (1980). A clockwise large-scale gyre over the southern hemisphere Indian Ocean makes its way well into the northern hemisphere by July (Fig 1). This gyre of clockwise circulation meets the southwest coast of India, the Kerala State, normally during early June. Thus the progress of the broadscale differential heating also dictates the onset of the monsoon rains over Kerala. The subsequent progress of the onset isochrones is sensitive to the overall structure of heat sources and sinks. The response of the northward progress of the monsoon to the heating along this principal axis of the monsoon was addressed by Krishnamurti and Ramanathan (1982). They noted that flow features such as those during the onset and active monsoon spells were sensitive to the location of the heat source of the monsoon. In that sense, the heating along the principal axis is also important for the isochrone positions. During the months between May and July, these isochrones, plotted at five-day intervals (Rao 1976), show a passage from the Indian Ocean south of India to the foothills of the Himalayas. The standard deviations of the dates of onset over different parts of India have been summarized by Rao (1976). These isochrones are elongated from the southwest to the northeast and the onset rains shows a meridional and
eventual westward motion. Chang (2005) presented a climatology of the onset isochrones for the entire Asian monsoon that looks at the east Asian monsoon and the Indian monsoon in a collective manner (Fig 2). The Myanmar monsoon onset precedes the Indian monsoon onset by about a month. Lwin (2002) noted that the onset of the Myanmar and Indian monsoon are related to the passage of two successive waves of the ISO (Intraseasonal Oscillation), that strengthen the Myanmar monsoon westerlies during early May. The Kerala onset in India happens during early June from the passage of a second wave of the ISO. Prediction of the passage of the onset isochrones is the same as the prediction of the first rains of the monsoon after a dry season. This does not necessarily convey anything specific about the total rainfall for a season over all of India. From an examination of model output and surface and space-based observations, we noted a scenario that seems to provide an explanation for the meridional motion of the onset isochrones. A typical isochrone during the early part of June is shown in Fig. 3. This illustration is based on the climatological positions of the onset isochrone as defined by the India Meteorological Department (IMD). This line is typically found over the southwest coast of India, over the Kerala State, and it extends northwestward over the Bay of Bengal coast and passes through the central Bay of Bengal and northward over Bangladesh and the northeast Indian states. The India Meteorological Department routinely provides valuable annual summaries of the summer monsoon onset (Srivastava and Yadav 2009; Khole et al. 2010, 2011). IMD has adopted the following new objective criteria for declaring monsoon onset over Kerala based on rainfall, wind field, and OLR data. The criteria are as follows:

Onset over Kerala is declared on the second day if after 10 May, 60% of the available stations report rainfall of 2.5 mm or more for two consecutive days. The depth of westerlies should also be maintained up to 600 hPa, in the box equator to Lat 10°N and Lon 55°E to 80°E. The zonal wind speed at 925 hPa over the area bounded by 5°N -10°N, 70°E to 80°E should be at
least of the order of 15-20 knots. Another important criteria is that the INSAT- derived OLR
value should be below 200 W m\(^{-2}\) in the box confined by Lat. 5-10\(^{\circ}\)N and Lon 7\(^{\circ}\)-75\(^{\circ}\)E. After the
onset over Kerala, the onset isochrones for the later dates are drawn connecting the places which
report rainfall of 2.5 mm or more for two consecutive days. The land mass to the north and west
of this line, not having experienced much rain during the spring season, is close to semi-arid.
The soil moisture is very low over these land areas with typical values around 0.15 fraction of
saturation (volumetric m\(^{3}\) of water in a m\(^{3}\) of soil). A couple of days after the passage of the
onset isochrone those values jump up to 0.35 of saturation (volumetric m\(^{3}\) of water in a m\(^{3}\) of
soil). The soil moisture increase generally starts to occur a day or two before the arrival of the
onset isochrone. This has to do with a cloud asymmetry across the isochrone. While the clouds
over and behind the isochrone carry a larger proportion of deep convective clouds as compared
to stratiform clouds, the cloud anvils ahead of the isochrone carry a larger proportion of
stratiform rain. The anvils are advected in front of the isochrone by the prevailing divergent
circulations. The fresh, lighter rains from the anvils enhance the soil moisture ahead of the
iscochrones and the warm daytime temperatures facilitate a rapid increase of buoyancy in the
region. The enhanced buoyancy results in the growth of newer convective elements ahead of the
iscochrone. These elements are advected northward and/ or north-westward by the prevailing
divergent circulation that was produced by the heavy rain of the parent isochrone. As the older
clouds undergo their life cycle and die, the newer elements grow and the new isochrone and the
entire system shows the familiar isochrone motion from south to north and east to west in the
northern latitudes. On certain years, a stagnation of the onset isochrones can be noted possibly
related to unusual behavior of the large scale, as reflected by the rotational winds. At times the
winds around the Tibetan high can have a stronger northerly component that can contribute to
stationary of the isochrone. This entire scenario is schematically illustrated in Fig 4. In this
paper the observational aspects using conventional datasets and vertical cross sections from
CLOUDSAT, sensitivity using a mesoscale high resolution WRF model, and validation of this scenario are addressed. The goal of this study is to illustrate the major role of soil moisture, stratiform cloud and divergent circulations for the motion of the onset isochrones from Kerala, 10°N to New Delhi near 25°N.

2. CLOUDSAT imagery across the onset isochrones

CLOUDSAT is a NASA satellite that was launched in 2006. The main instrument is a millimeter wavelength radar. Ground-based radars generally carry a wavelength of one centimeter. The mm wavelength radar of CLOUDSAT enables it to detect much smaller particles of liquid water and ice that define clouds. This cloud radar provides vertical plan views of hydrometeors (the cloud profiling radar). Two other satellites, Aqua (provides water vapor profiling), and CALIPSO (Cloud Infrared Pathfinder Radar Observations) are important for joint studies with CLOUDSAT. Collocated datasets from CLOUDSAT, AQUA, and CALIPSO have enabled NASA to develop algorithms to define cloud structure and type. These datasets are routinely provided by NASA at their website. Figure 5(a-c) illustrates typical vertical cross sections from CLOUDSAT showing cloud asymmetry across onset isochrones. In these illustrations, a map of India with infrared cloud imagery and the traverse of the satellite are shown on the right. The satellite traverse includes both ascending and descending nodes. To the left, the vertical plan view of the clouds are depicted. A vertical green dotted line provides the location of the onset isochrone (as defined by IMD) for three sample dates. In these cross sections, we clearly see a plethora of deep convective elements behind the onset isochrone. The picture ahead of the isochrone generally shows high cloud anvils, cirrus, a few towering cumulus, and several cumulonimbus clouds. A NASA classification of cloud types is shown just below each vertical cross section. This region is moistened by the anvil rains, (non-convective rains) and the warm surface temperatures ahead of the isochrones, and the evaporating rain
carries a large buoyancy. New cloud elements form and grow in this region ahead of the isochrone. We have examined the asymmetry of clouds across the isochrone for different periods of the monsoon during the last three years and noted very similar structures. This asymmetry is an important characteristic of the newly forming clouds that grow and define a new parent isochrone. The motion of the isochrone seems to be dictated by the divergent circulations described in section 7.

3. Model experiments

a. The WRF/ARW model

The WRF/ARW model is a collaborative effort among the NCAR Mesoscale and Microscale Meteorology Division (MMM) and NCEP’s Environmental Modeling Center (EMC). The WRF model is a fully compressible, nonhydrostatic model (with a runtime hydrostatic option). Its vertical coordinate is a terrain-following hydrostatic pressure coordinate. The grid staggering is the Arakawa C-grid. The model uses the Runge-Kutta 2nd and 3rd order time integration schemes, and 2nd to 6th order advection schemes in both the horizontal and vertical. It uses a time-split small step for acoustic and gravity-wave modes. The dynamics conserves scalar variables. We used the following physics options for this model: Radiation schemes Longwave: rapid radiative transfer model (rrtm) (Mlawer et al. 1997) Shortwave: Dudhia scheme (Dudhia 1989; Grell 1993), Surface physics: Monin-Obukhov (Janjic) scheme (Monin and Obukhov 1954), Land surface model: 5 layer thermal diffusion (Skamarock et al. 2005) Planetary boundary layer scheme: Mellor-Yamada-Janjic (MYJ) TKE PBL (Janjic 1994) Convection scheme: Kain-Fritsch (new Eta) scheme (Kain and Fritsch 1993), Explicit moisture scheme: WRF Six-class graupel scheme (WSM6) (Hong and Lim 2006; Hong et al. 2004). The model is run with a single domain at 25 km horizontal resolution and 27 vertical levels.
NCEP's GDAS carries a 6 hourly gridded data archive. The GDAS is derived from the NCEP's operational model runs called the final analysis FNL. This includes late conventional and satellite datasets (Petersen and Stackpole, 1989). This assimilation is run 4 times a day, i.e., at 00, 06, 12, and 18 UTC. Model output is for the analysis time and a 6-hour forecast.

Precipitation and surface fluxes are only available at the forecast hours. Details of the GDAS are described by Kanamitsu (1989), Derber et al. (1991), and Parrish and Derber (1992). NCEP post-processing of GDAS converts the data from the spectral coefficient form to 1 degree latitude-longitude (360 by 181) grids and from sigma levels to mandatory pressure levels. The data are written to the NIC (NOAA Information Center) FTP server (nic.fb4.noaa.gov) in GRIB (GRIdded Binary) format. These datasets are used in our study.

b. The soil moisture parameterization in the WRF/ARW model

In most numerical models, the soil moisture algorithm interfaces with the moisture equation of the constant flux layer, thus exchanging precipitation and evaporation relevant to the ground and the atmosphere. The soil moisture algorithm is in fact a time dependent equation for the forecast of soil moisture over four soil layers that carry thicknesses of 10, 30, 60, and 100 cm. The soil model predicts surface skin temperature, total soil moisture, liquid soil moisture in each layer, soil temperature for each layer, and the canopy water content (this can be dew or frost intercepted precipitation). These require initial states that are provided by the WPS of the ARW/WRF based on past experimentation. The soil moisture equation is of the form,

$$\frac{d c_s}{dz} = \frac{\partial}{\partial z} \left( D \frac{\partial c_s}{\partial z} \right) + \frac{\partial K}{\partial z} + F_s \quad (1)$$

where $D$, $K$ functions for soil texture and soil moisture and $F_s$ represents sources (rainfall) and sinks (evaporation).
The soil temperature prediction equation takes a form:

\[
C(\theta) \frac{\partial T}{\partial z} = \frac{\partial}{\partial z} \left( K_r(\theta) \frac{\partial T}{\partial z} \right)
\]  

(2)

where \( C, K_t \) are functions for soil texture and soil moisture. Soil temperature information is used to compute ground heat flux.

The surface water budget is estimated from the relation:

\[
dS = P - R - E
\]

where \( dS \) is the change in soil moisture content, \( P \) is precipitation, \( R \) is runoff, and \( E \) is evaporation.

The evaporation is a function of soil moisture and vegetation type, rooting depth, and the green vegetation cover. This formulation utilizes Noah algorithms of the NCAR models, which also include the parameterizations for surface evaporation, vegetation transpiration, and canopy resistance. These details can be found in Chen et al. (1996, 2001).

In this paper, we began with experiments using the default model from WRF/ARW. For the sensitivity studies on soil moisture, we altered the soil moisture in various experiments as described below.

**b. Non-convective rain in weather and climate**

The definition of non-convective rain used by radar meteorologists and numerical modelers appears to be somewhat distant from each other. Most numerical modelers invoke non-convective rain if the location in question carries a dynamic ascent of absolutely stable and near-
saturated air. Disposition of supersaturation provides a measure of non-convective precipitation at that location. Krishnamurti et al. (2006) describe two other, more rigorous methods for the estimation of non-convective precipitation that are variants of this same principle i.e., the disposition of supersaturation.

The language of the radar meteorologist invokes features such as those shown in Table 1 (Stano et al. 2002). To expect for these two methods to match closely, even after averaging at meso or larger-scale grid sizes, would be difficult to achieve. In most of these radar-based estimates of convective and non-convective rains, parts of the deep convective systems carry anvils and provide stable non-convective rains. These are systems where the two coexist in proximity. In large-scale models, mostly in the context of large sheets of stratus and altostratus that span for thousands of miles, in extratropical weather systems, the modeling definition works reasonably well for estimates of non-convective rain. However, in the monsoon isochrone context, we are dealing with a plethora of deep convection behind, and stratiform anvils ahead of the isochrones. If such coexisting, convective/stratiform cloud systems are important for the motion of the isochrones then a better definition of stratiform rain may be needed for future modeling. Those can be brought about in cloud resolving, very high resolution models, where the microphysical processes are explicitly tagged. In the current WRF/ARW model that is presented here, the non-convective rain at 25 km resolution comes from the disposition of supersaturation. Those results are presented in section 5c. In order to see further details on the asymmetry of cloud types across the isochrones, a few experiments were also carried out at a 3 km resolution where explicit clouds, instead of parameterized clouds were used. Those structures are described in section 6.
4. Results from Modeling

a. A control experiment during a near normal rainfall year

We selected the monsoon season of the year 2000 for the control experiment since the model-based rainfall totals for the first 25 days, all India averaged, were close to the observed totals for the same period. In Fig. 6 we show, by a dark line, the observed march of the isochrones for the summer monsoon season of the year 2000. This is based on an official IMD product. The predicted field of the onset isochrones from the mesoscale WRF/ARW model is shown as a red line in Fig. 6. Here the accumulated precipitation is also shown in each panel, where the panels cover the dates June 1-25 at intervals of roughly 5 days. The forecast has many deficiencies; the initial position of the isochrone, observed versus modeled, and shows almost a three degree latitude displacement over the Bay of Bengal. Forecasts generally improved during the first 5 days, and the day 5 forecast showed the least errors and thereafter the model isopleth motion was consistently slower compared to the observed positions. Such errors have to be expected because the current predictability for tropical rainfall prediction is only of the order of a few days. Through sensitivity studies, shown in the next section, the goal is to find out factors that can either slow down or speed up the motion of the isochrones. This, and two other examples presented below, are shown to illustrate the nature of the current prediction using a WRF/ARW model that utilized some default values for various parameters. Overall this is not a very poor forecast for day 25, considering that a northwestward march of the isochrone is implied by this forecast with overall errors that are less than 4 degree latitude.

b. Modeling isochrone motion during a dry monsoon year

The observed isochrones for the 2002 season, based on the IMD datasets, are shown in Fig. 7 by a dark line. This was a below normal monsoon rainfall year. The march of the
isochrones during the first 25 days reflected a slower than normal meridional motion. The accumulated predicted rains preceding the forecast day, in color shading, are shown at intervals of 5 days, and the predicted isochrones are shown by a red line (Fig 7). The model, in general, carries a somewhat slower northward and eventual northwestward motion for the isochrone, and as a result, the control run of the model predicted a somewhat drier monsoon compared to the dry season of 2002. Overall, again this was a very reasonable forecast for the positioning of the isochrone through day 25 of the forecast, since the position errors were less than 5 degrees in latitude.

c. Modeling isochrone motion during a wet monsoon year

This was the 2003 summer monsoon season, the seasonal totals of rain over all of India were above normal, but the onset of monsoon over Kerala, on the southwest coast of India, was delayed by a week. The observed and predicted isochrones for this experiment are shown in Fig. 8. Also shown are accumulated rainfall totals proceeding the day for which the forecast is labeled. This was again a fairly reasonable forecast for the march of the isochrone during the first 25 days of forecast. As in all previous experiments, the motion of the predicted isochrone was roughly 3 to 4 degrees latitude slower than the observed positions. Clearly, model improvement is needed to somewhat speed up the motion of the isochrone. This is addressed in the next section.

5. Sensitivity studies

Observations and modeling suggest that two parameters, the parameterizations of non-convective rain and the representation of soil moisture have a strong impact on the meridional motion of the monsoon onset isochrones. These are illustrated in this section.
a. Variations of soil moisture and precipitation across the isochrones

Figure 9 shows the time variations of the predicted soil moisture (shown along ordinate, labeled at right) and of the predicted precipitation (shown along ordinate, labeled along left) at two single grid points during the passage of the isochrone. The abscissa shows the latitude normal to the isochrone with respect to a specific location of the passage of the isochrone. The dataset is simply obtained from model outputs during a forecast for the June 2000 onset. The location of the isochrone is marked by an arrow. Both the precipitation and the soil moisture shows a drop in values north of the isochrone. This region to the north of the isochrone does not have a very sharp drop in precipitation due to the presence of newly growing cloud elements and the anvil rain. This is also reflected in the slower drop of values of the soil moisture as one proceeds north of the isochrones. Precipitation and soil moisture ahead of the isochrone contributes to an increased buoyancy over this region immediately ahead of the isochrone where newer clouds can grow. Typical distribution of buoyancy are illustrated in section 6.

b. Enhancing soil moisture by 15 percent over the entire land area of the domain

In section 3b, the current soil moisture scheme was described and was always used as a default scheme. The results from that scheme were presented in Fig 8. After some trial and error, it was noted that a uniform 15% increase in the overall soil moisture compared to what WRF/ARF provides would reduce the error in the rate of meridional propagation of the isochrones. At each time step after the rainfall (from the model) is computed, the grid-soil moisture was modified by 15%, depending on whether a particular grid point has rainfall. In experiment 1, the soil moisture is increased uniformly 15% at all grid points, and in experiment 2, the soil moisture is increased by 15% at 5 grid locations north of the raining grid. Only the soil moisture at the top layer is modified. As always, ocean points carry a tag of 0.9 and above and those were left alone. Those results for the 2003 season are presented in Fig 10. Here a
much closer agreement between the model-predicted positions of the isochrones and the observed positions as noted by IMD for all map times are noted. The errors in the positioning of the isochrone for most panels are of the order of 2 degrees latitude. This is a very promising result. Such an overall enhancement of soil moisture is, however, not necessary, since the motion of the isochrone is most likely affected by what goes on in its immediate vicinity. Our contention, based on observations, was that the region to the immediate north of the isochrone was most important in this regard. Here the enhanced soil moisture contributes to enhanced evaporation over a previously very dry and hot region. That evaporation contributes to formation of new clouds and an enhanced buoyancy over this region to the north of the isochrone, thus permitting further growth and a slow formation of a new position for the isochrone. The isochrone itself moves north and eventually northwestward because of the orientation of the divergent wind that steers these newly forming elements. The next experiment shows results from an enhancement of soil moisture to immediately north of the isochrone.

c. Enhancing soil moisture to the immediate north of the isochrone

Since what must influence the northward motion of the isochrone is the soil moisture to the immediate north of the isochrone, a simple experiment was designed. Here we increased the soil moisture perpendicular to the leading edge of the isochrone over 5 successive grid points by 15% compared to the default values of WRF/ARW discussed in section 4. The 15% value came from some experimentation that basically yielded almost the same results as shown in the previous section where the soil moisture was enhanced by 15% over the entire land area of the computational domain. These new results are presented in Fig 11. This confirms the idea that the isochrone motion is largely sensitive to the soil moisture to the immediate forward side of the isochrone. This is the region where anvil and newly forming towering cumuli carry somerain and contribute to an enhancement of the soil moisture.
d. Sensitivity experiment for the enhancement of non-convective rain

Through experimentation, a large sensitivity was noted for the speed of motion of the isochrones of monsoon onset to the parameterization of non-convective rain discussed in section 3c. The disposition of supersaturation asks for a model relative humidity of 100 percent. Since this is a stringent requirement, because there may be some subgrid-scale regions of subsaturation, that threshold value has been reduced in most operational modeling. After some experimentation, it was noted that a value of around 85% was better suited for anvil rains. The anvil rains occur from pressure levels below 400 hPa. Here the criteria for the ascent of absolutely stable and saturated air are met for invoking non-convective rain. It was further noted that even that threshold did not adequately cover the needed enhancement of soil moisture. This leads to an experimentation where the non-convective rain ahead of the leading edge of the isochrone was enhanced successively by 10, 15, and 35%. This enhancement was necessary to account for subgrid-scale regions of possible saturation. The best results (Fig. 11b), came from enhancing subgrid-scale rains by 15% where the observed and the predicted isochrones carried an error in positioning by 2 degrees latitude or less during the 25 day forecast.

6. The Buoyancy field ahead of the leading edge of the isochrone

The Buoyancy is defined as follows:

\[
B = g \left( \frac{T_v'}{T_v} - r'_l \right)
\]  

(3)

where \( r_l \) is the liquid water mixing ratio, and \( T_v' \) and \( T_v \) respectively denote virtual temperature values inside a cloud (where \( r_l > 0.1 \) g/kg) and outside a cloud (where \( r_l < 0.1 \) g/kg). \( T \) is the virtual temperature and \( T_v \) is defined as
where $T$ denotes air temperature, $r_v$ is the mixing ratio of water vapor, and $\varepsilon$ is the ratio of molecular weights of water vapor and dry air ($\varepsilon = 0.622$).

To illustrate the details of the isochrones evolution, we have repeated several of the experiments, presented here, at a 3 km resolution. That is particularly useful for seeing the region ahead of the leading edge of the isochrone. Figure 12 illustrates a typical field of the buoyancy from the model output field. This makes use of the predicted liquid water mixing ratio. This shows several interesting features including a spread of buoyancy ahead of the leading edge of the isochrones. This is the region where the buoyancy helps the growth of a new line of clouds thus establishing a new isochrones in place of the older isochrones. We also see a distribution of positive buoyancy behind the isochrones where the monsoon becomes active subsequently. Also seen in the illustration were some pre-monsoon onset thunderstorm regions that showed a line of positive buoyancy.

**a. Radar reflectivity cross section across the predicted isochrones**

Figure 13 shows a vertical cross section, computed inversely, from the model-predicted hydrometeors. This is a standard output product that is included for all high resolution forecasts of the WRF/ARW. This model forecast was made at a horizontal resolution of 3km. In this figure, the ordinate is a height coordinate and the abscissa denotes longitudes across the isochrone for June 15, 2003. Here we are portraying an isochrone that was located over northeastern India and the forward side of the isochrones is to its west. This was the forecast for day 14, the left half of the diagram denotes the forward side of the isochrone and the right side carries the back side of the isochrone. Of interest here are the radar reflectivities to the forward
side that carry some upper clouds and weaker deep convective elements. Those are important features, that were noted in the CLOUDSAT imagery of the radar reflectivity, as were shown in fig. 5c.

7. Local divergent circulations and the onset isochrones passage

Given the mesoscale model forecasts on the passage of onset isochrones, the post-processing of local divergent circulations gives an important perspective for the passage of these isochrones. The divergent circulations roughly emanate from regions of the largest vertical upward motions and heavy rains. This divergent circulation steers the newly forming precipitating elements that lie ahead of the isochrones in a direction which is roughly perpendicular to the line of heavy rains. The mapping of those features from the model output is illustrated in this section. The divergent circulations are computed from the following equations:

\[
\psi_x = -\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right) \tag{4}
\]

Given the horizontal velocity components \(u\) and \(v\), one can compute the velocity potential \(\psi_x\) by solving the above Poisson equation (Krishnamurti and Bounoua 1996). The divergent wind is given by the relation:

\[
u = -\frac{\partial \psi_y}{\partial x} \tag{5}
\]

\[
u = -\frac{\partial \psi_x}{\partial y} \tag{6}
\]

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Those divergent wind components were computed, at the 200 hPa level, to show the steering for the newly formed precipitating cloud elements ahead of the parent clouds of the isochrone. In Fig. 14a, the divergent winds from the FNL analysis are illustrated on top of the velocity potential $\kappa$ of the 200 hPa surface. These results pertain to June 15, 2003. The weak rains ahead of the isochrone lie in a region that carries strong divergent wind steering directed away from the isochrone. The isochrone is strongly dictated by the steering of newly growing deep convection ahead of the parent isochrone. The rotational part of the wind, Fig. 14b, is nearly always parallel to the isochrone, and that stronger wind does not steer the isochrone. The divergent wind is perpendicular to the isochrone in its vicinity, and is better able to steer the newly growing precipitating cloud elements. As these new elements grow and the older elements of the isochrone die, a new position of the isochrone is established. Figure 14c shows the predicted 200 hPa level velocity potential and the divergent wind streamlines. This applies for day 15 of the forecast valid on June 15, 2003. These are the results from the mesoscale model forecast from the WRF/ARW. The salient observed features of the divergent wind can be seen here. The model forecast carries a divergent flow that provides the northward steering for the newly forming cloud line that replaces the preceding isochrone.

8. Summary

This study addresses the meridional march of the summer monsoon onset isochrones. Here we examine the first 25 days of the meridional march that roughly covers a passage from Kerala at 7°N to New Delhi at 27°N. The title of the paper alludes to the first 25 forecast days. The number of days of progress of the monsoon from Kerala to New Delhi can vary, however, on the average it is around 25 days (that is based on the climatological positions of the onset isochrone as shown in Fig. 3). We show that this speed of northward motion is sensitive to the
parameterization of the non-convective rain and to the modeling of the soil moisture. We make use of a mesoscale model with a horizontal resolution of 25 km and 27 vertical levels that utilizes the initial states and lateral boundary conditions from the GFS/FNL NOAA model. All experiments cover the period June 1 through June 25 for different years. The model internally carries algorithms for the non-convective rains and the specification of soil moisture as discussed in this paper. A scenario for the meridional movement of the summer monsoon isochrones over India was developed based on satellite (CLOUDSAT) and reanalysis datasets. That scenario suggested the following ingredients for the motion of the isochrones. There exists an interesting cloud, precipitation and soil moisture asymmetry across the isochrones. The forward side, in the immediate vicinity of the isochrone, experience light rains (partly anvil rains), increase of soil moisture, increase of buoyancy, and growth of newly developing clouds. This line of newly forming and growing clouds are steered to the north and eventually to the northwest by a divergent circulation that has its strongest upward motion along the parent isochrone. The rotational part of the wind has less of a role in the steering of the isochrone, since that flow generally appears to be parallel to the isochrone. The newly growing clouds slowly replace and become the parent isochrone. This process repeats itself during the isochrones passage from Kerala to New Delhi. Scientifically this problem is important since the motion of the isochrones vary from year to year. Further study is warranted on possible strong variations of the rotational wind that can keep an isochrone stationary by having strong rotational winds oppose its meridional motion. The first runs, covering the seasons of the years 2000, 2002, and 2003, were designated as control experiments since they utilized the default values in the parameterization of the non-convective rain and the soil moisture. These experiments clearly showed that forecasts based on the WRF/ARW model carried slower speed for the meridional motion of the isochrones. This was followed up with a large number of model sensitivity experiments where the intensity of non-convective rains and soil moisture were
increased by various percentages compared to the default values of WRF/ARW. Through these sensitivity experiments it was clearly noted that a much improved motion of the model's summer monsoon onset isochrones from Kerala to New Delhi was achievable, compared to the observed estimates of the India Meteorological Department. We have discussed those modifications for the parameterization of soil moisture and non-convective rains in this study. Future modeling will require addressing this problem for operational weather forecasts. The mechanism portrayed here could well apply for the meridional motion of the ISO waves, where the higher frequency motions could be affected by the divergent wind steering and the influences of soil moisture and stratiform clouds as shown here, and the low frequency motions would form the envelope of such events. The mechanism portrayed here could also be used for the analysis and interpretation of the dry and wet spells of the monsoon. In future studies, it would also be important to examine specific years where unusual stagnation in the progress of monsoon isochrones have been noted. There had been years when stagnation was observed on more than one occasion in a given year and those are worth examining.

Acknowledgement: We wish to acknowledge the NASA grant NNH09ZDA001N-PRECIP. DN gratefully acknowledge support from NSF CAREER ATM - 0847472.
References


Table 1. Criteria for determining convective and stratiform rain as seen by TRMM radar

<table>
<thead>
<tr>
<th>Condition</th>
<th>Convective rain</th>
<th>Stratiform rain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Presence of light bands</td>
<td>✗</td>
<td>✓</td>
</tr>
<tr>
<td>Absence of bright bands</td>
<td>✓</td>
<td>✗</td>
</tr>
<tr>
<td>Reflection 20–40 dbz</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Reflection &gt;40 dbz</td>
<td>✓</td>
<td>✗</td>
</tr>
<tr>
<td>Presence of strong gradients of radar reflectivity</td>
<td>✓</td>
<td>✗</td>
</tr>
<tr>
<td>Absence of reflectivity gradients and reflection &gt;20 dbz</td>
<td>✗</td>
<td>✓</td>
</tr>
</tbody>
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