Mesoscale modeling for the rapid movement of monsoonal isochrones

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Abstract
The progresses of fast moving 2013 monsoonal isochrones were simulated with WRF model at 25 km and compared with slower moving isochrones of 2014. A large number of sensitivity experiments were performed by enhancing of soil moisture, stratiform rain up to 25%, their combination and reducing soil temperature by 12%, over 5 grid points to the north of the isochrones over a relatively dry soil layer. The modified soil parameters and stratiform rain ahead of isochrones enhances the population of the buoyant elements, divergent flows of the local Hadley circulation normal to the isochrones; resulting in a fast movement of the isochrones.

Keywords: monsoonal isochrones; dry soil layer; buoyant elements

1. Introduction
Northward extension of ITCZ reaches the southern tip of India (around May–June at 7°N) and augmentation of the first rainfall over Indian landmass is known as the arrival of Indian summer monsoon (Rao, 1976). Evolution of Indian summer monsoon includes onset, active-break phases, and thus a progress of rainfall from southernmost tip (Trivandrum, Kerala) to the northwestern end of India (Jaisalmer, Rajasthan). The movement of rain bands from southeast to northwest direction is locally termed as the onset of monsoonal isochrones or simply isochrones (Chang et al., 2004). Once the monsoon onset is officially declared, Indian meteorologists watch its day-to-day northward progress over Indian subcontinent. Movement of monsoonal isochrones (northern limit of monsoon) over Indian region is governed by symmetric and antisymmetric heating/circulation (Gill, 1980), heat source and sink (Krishnamurti and Ramanathan, 1982), pressure gradient across landmasses (Ananthakrishnan et al., 1968), reversal of temperature gradient over land and sea (Yanai et al., 1992), meridional passage of the ISO wave (Wang, 2005), stratiform rain (Krishnan et al., 2011; Samir and Sikka, 2013), and land surface processes (Yeh et al., 1984). From all abovementioned parameters, we examined the importance of soil moisture in layer-1 (SM), stratiform rain (SR) from nonconvective rains and soil temperature in layer-1 (ST) using WRF model sensitivity for the assessment of the fast movement of isochrones especially during June 2013 and for a comparison of slower moving isochrones of June 2014.

Sensitivity of SM, SR and ST were noted to be a significant factor for controlling hydrology and land–atmosphere interactions (Alfieri et al., 2008; Krishnamurti et al., 2012). Over the monsoonal region, more than 70% of the rain is SR (Krishnan et al., 2011). In Krishnamurti et al. (2012), the following scenario was noted from observations and modeling: An isochrone, as it is advancing north is in fact a new family of clouds parallel to the parent isochrone. The nonconvective rains from cloud anvils of the parent isochrone enhance the soil moisture to assist the formation of new line of clouds. These anvils, accompanied by nonconvective rains, shear to the north of the parent isochrone. This region to the immediate north of the isochrone generally carries very warm surface and surface air temperatures in the planetary boundary layer (PBL), such conditionally unstable environment helps in the formation of new cumulus cloud lines. Keeping such hypothesis in background and predicting fast moving isochrones of June 2013 was an appealing experiment.

2. Model configurations, experiments and datasets
We used the following default physics options of WRF: long-wave radiation scheme – Rapid Radiative Transfer Model (RRTM); short-wave radiation scheme – Dudhia scheme; surface physics Monin–Obukhov and Janjic scheme; land surface model – five-layer thermal diffusion; PBL scheme – Mellor–Yamada–Janjic (MYJ) turbulent kinetic energy (TKE) PBL; convection scheme the so-called Kain–Fritsch (new eta) scheme; and an explicit moisture scheme – WRF six-class graupel scheme (WSM6). We ran WRF model (with nonhydrostatic approach) with a single domain, horizontal resolution of 25 km, 27-vertical levels, 6-h initial and boundary conditions from FNL, and 16 days continuous run while model’s lateral boundary conditions...
were updated at every 6 h. For 3-km resolution WRF with nonhydrometric approach, Goddard microphysics option and cloud resolving model was opted.

From observations, it is noted that a couple of days after the passage of the onset isochrone the value of SM (volumetric cubic meters of water in 1 m$^3$ of soil) jump up from 0.15 to 0.35 of saturation in the forecasts, which accounts to around 13.5% increment of SM. This awareness was used in the design of the proposed sensitivity experiments for the enhancements of SM and SR. However for ST, observations showed that the temperature generally decreased 297 K from 300 K (2 to 2.5 °C), which is 7.5% reduction of ST. Somehow for 2013, in WRF experiments we had to enhance SM (10 cm), SR by 25% and reduce ST (10 cm) by 12%, on the 5 grid points to the north of 1 June isochrone. For comparison, same experiments were performed for June 2014 also. In a series of experiments, we enhanced SM and SR by 15, 20 and 25%, and these are respectively labeled as SM15/SR15, SM20/SR20 and SM25/SR25 respectively; combination of enhanced SM and SR (labeled as SMSR25) and reduced the ST by 12% (ST12). A comprehensive sensitivity study was carried out using modified values of SM25, SR25, SMSR25 and ST12 for both June 2013 and June 2014.

The objective criteria to plot the lines of isochrones for WRF control simulation and experiment simulation are as follows: (1) after onset of monsoon over Kerala, we plotted the isochrones for 2, 5, 8, 11, 14 and 16 June connecting the lines which has rainfall 2.5 mm and more for two consecutive days; and (2) We face the situation of multiple isochrones lines during 14 and 16 June 2014, then the isochrones line is drawn closet to the previous day position.

For observational datasets, we used daily rainfall (mm) from TRMM3B42; monthly and daily datasets of volumetric soil water layer-1 (SWVL1, soil layer 0–7 cm, unit m$^3$m$^{-3}$), low cloud cover (LCC, unit 0–1), soil temperature level-1 (STL1, soil layer 0–7 cm, unit deg-K), and total column water vapor (TCWV, unit kg m$^{-2}$) from ERA Interim (Dee et al., 2011).

3. Prediction of fast moving isochrones: a sensitivity of soil parameters and clouds

The simulation of the passage of isochrones during June 2013 was a challenge, because the monsoonal isochrones (solid green-line) covered India completely within first 16 days of June, after onset of southwest monsoon (Figure 1). Red dashed lines show the climatological isochrones, those cover India in 45 days (1 June to 15 July). Monsoonal isochrones of 2013 recorded the fastest movement of isochrones in almost last 100 years of Indian summer monsoonal rainfall. Monsoonal isochrones of 2013 were always ahead than the normal isochrones over western side of the India while monsoonal isochrones were always lagging behind till June 10 and strangely within 2 days (15–16 June) monsoonal isochrones covered all India.

First, we enhanced the SM and SR by 15%, while ST reduced by 7.5% and found that the northward movement of monsoonal isochrones in WRF experiments is almost similar to the control experiment (Figure S1). Furthermore, we gave a shot to enhance SM and SR by 20% (Figure S2); here the northward movements of isochrones were relatively faster than Figure S1, but could not simulate rainfall over northwestern India. In all these simulations, monsoonal rainfall did not reach to perennial desert region, Madhya Pradesh and western Uttar Pradesh, which shows the land surface model in WRF has dry bias over this region. Another reason may be the prevailing soil is extremely dry over northwest India. Is there something more stored in soil moisture and SR for the fast monsoonal isochrones of 2013?

Finally, we enhanced the SM and SR by 25% and ST reduced by 12% in WRF experiments. Figure 2 shows accumulated rainfall from TRMM3B42, control experiment, SM25, SR25, SMSR25, ST12 experiments for 2–16 June. TRMM3B42 rainfall does not show northward movement of rainfall for 2 June 2013, but from 5–16 June, TRMM3B42 rainfall was always ahead of the IMD isochrones (black line). During 2013, isochrones (green lines) moved faster from 8 to 12 June as compared to the climatological isochrones (red dashed lines, Figure 1). In these experiments through 8 June, the predicted isochrones (red lines) and the IMD isochrones (black lines) were moving northward together over most of its length, except in the eastern flanks where the predicted isochrones moved faster (Figure 2). During 11 and 14 June, the northern flank of the isochrones did not progress, whereas eastern flank one moved ahead of the official IMD isochrones. Rainfall distribution for 14 June from TRMM3B42, control, SM25, SR25, SMSR25 and ST12 shows a band of maximum rainfall, to the immediate south of central India. This band of maximum rainfall between the Arabian Sea and the Bay of Bengal at 20°N is an interesting aspect related to the SM, SR and ST. The central region of India is a region of strong land–atmosphere coupling and thus a favorable source of increased precipitation (Koster et al., 2004). This feature is attributed to the fast movement of monsoonal isochrones from 14 June onward (see Figures S3 and S4). Monsoonal isochrones in the SM25 experiment show (over several regions of India) a faster motion as compared to the control experiment from WRF model.

However, there was a large gap of 3–4 longitude between the observed and the predicted isochrone over Northwest India on 16 June. To look minutely the northern extent of the monsoonal isochrones on 16 June, a zoomed picture is shown at the bottom of Figure 2. We compared WRF control (CNTL) simulation with other WRF simulation experiments. Various noteworthy differences in rainfall found over Rajasthan region, western Uttar Pradesh, Haryana and northern Madhya Pradesh. In terms of magnitude of rainfall all the designed WRF experiments do better than CNTL.
over Uttarakhand, western Uttar Pradesh and Himachal Pradesh. SRSM25 experiment shows the best results among all. To compare slow versus fast moving monsoonal isochrones, we compare WRF simulation experiments between 2013 and 2014. In case of year 2014, IMD monsoon isochrones moved faster than CNTL simulation (Figure S5). For 2014 also, we enhanced SM and SR by 25% and ST reduced by 12% ahead (5 grids points) of the isochrones, model was able to capture rainfall variability with TRMM in all experiments (Figure 3). After 11 June, monsoonal isochrones in WRF experiments simulation were ahead of the CNTL simulation. But, 2014 being a drought year, so in soil there were not much soil moisture in June (Figure 4(a)). On applying same methodology (as in case of June 2013) simulated monsoonal isochrones of 2014 are in sacrosanct with observed isochrones (Figure S3). Amazingly a gap along eastern coast of Indian landmass in the Bay of Bengal is left void in all the WRF experiments of 2014, which were completely filled in all the WRF experiments of 2013. Presence of this gap from 8 June onward may be one of the indications of a slower motion of monsoonal isochrones. These experiments show the dependency of monsoonal isochrones over soil characteristics (moisture and temperature) and stratiform rainfall. Largely, these experiments show the fast movement of June 2013 modeled isochrones compared favorably with the observed isochrones over the interior of India.

4. Spatial variability of soil parameters, clouds and circulation features

4.1. Observational features of soil parameters, clouds and water vapor

Figure 4 shows several observational fields (from ERA Interim), SWVL1 (upto 10 cm below the earth’s surface) (Figure 4(a)–(c)); LCC (Figure 4(d)–(f)); STL1 (Figure 4(g)–(i)), and TCWV (Figure 4(j)–(l)) for June 2012, 2013 and 2014. SWVL1, LCC and TCWV being enhanced over central India around 20° N latitude, while STL1 showed lower values for June
Rapid movement of monsoonal isochrones

Figure 2. Daily accumulated rainfall (mm) from 2, 5, 8, 11, 14 and 16 June 2013 from TRMM3B42 and WRF-ARW model sensitivity experiments (control, enhancing soil moisture by 25%, enhancing stratiform rain by 25%, enhancing soil moisture and stratiform rain by 25% and reducing soil temperature by 12% ahead of the 1 June 2013 onset isochrone). Black line shows the IMD isochrones while red line shows predicted isochrones. Lower panel shows the zoom out part of north-western India for 16 June.

2013. SWVL1 is increased from 0.15 to 0.3 m$^3$ m$^{-3}$, LCC increased from 0.1 to 0.3 unit, STL1 dropped down from 307 to 304 K and TCWV increased from 40 to 60 kg m$^{-2}$. This was one of the reasons why we reduced soil temperature from 7.5 to 12% in case of soil temperature experiment for year 2013. The increased soil moisture and clouds were clearly related to increased rainfall over central India during 14 and 16 June. The line diagrams are plotted for the rectangular box (76–78°E, 12–15°N) over southern India for daily values of SWVL1 (Figure 4(m)), LCC (Figure 4(n)) and STL1 (Figure 4(o)) from 15 May to 30 June 2013. These daily values show sudden increase of volumetric soil water, smooth growth of low cloud cover and drop of soil temperature from 2 June onward. The variability of above parameters confirms the role of the enhanced soil moisture, nonconvective rain and a reduction of soil temperature during the start of summer.
monsoon season of 2013. Furthermore, Figure S3 and S4 show the gradual advancement of soil parameters and nonconvective cloud over central India and their crucial role in land surface modeling in WRF model.

4.2. Observational and model predicted local divergent circulation, Hadley circulation and Buoyancy field

Local divergent circulations and rotational fields at 200 mb gave an added insight for the fast movement of onset isochrones during June 2013. Figure 5 shows the velocity potential and divergent field at 200 mb from observations (Figure 5(a)) and model experiment SM25 (Figure 5(b)). The divergent circulation, this feature increased visibly from 2 to 16 nonconvective rain, which shows a divergent wind along the north and northwest (Figure 5(a)). We examined day by day, observed, directions and amplitudes of the divergent circulations from 2 to 16 June and noted that their orientation and speeds were consistent with the steering of the isochrones toward the northwestward direction. On comparing these observed-based results with the model experiment SM25, the divergent flow was reasonably close to observations over the central longitudes of India confirming a northward steering. However, rotational parts of winds (streamline flows) were almost parallel to the onset isochrones (figure not shown), while rotational flow does not steer the isochrone. Prediction from model shows a stronger divergent circulations field June (Figure 5(b)). The model results did not carry a direction of divergent flow to the northwest direction as a result the model isochrone did not extend up to northwestern India. Figure 5(c) is based on observations, and shows the difference of the velocity potential between Kerala (southernmost end of India) and

Figure 3. Daily accumulated rainfall (mm) from for 2, 5, 8, 11, 14 and 16 June 2014 from TRMM3B42 and WRF-ARW model sensitivity experiments (control, enhancing soil moisture by 25%, enhancing stratiform rain by 25%, enhancing soil moisture and stratiform rain by 25% and reducing soil temperature by 12% ahead of the 1 June 2014 onset isochrone). Black line shows the IMD isochrones while red line shows predicted isochrones.
Rajasthan (northwestern end of India) of the onset monsoonal isochrones for several recent years. That difference is proportional to the mean divergent between Kerala and Northern India. It is interesting to note that the mean northward-directed steering (as measured by this mean 200 hPa level, south to north divergent wind) is increasing in recent years.

In swift, it is noted that the environment ahead of isochrones is being modulated by the clouds, circulation and light rains from the anvils of the tall clouds of the onset isochrone. The slowly enhanced local Hadley circulation has an important role to steer the newly formed cloud elements ahead of isochrones. We examined local Hadley circulation from observations and model experiments for 2 to 16 June 2013. Local Hadley circulation (zonally averaged over 73–90°E) is displayed for 8 and 11 June, which is very active over 10–22°N (Figure 6(a) and (b)). Model predicted local Hadley circulation shows the vertically rising branch from 10 to 15°N on 8 June and 17 to 22°N on 11 June (Figure 6(c) and (d)). Local Hadley circulation for year 2014 is not as strong and well organize as compared to 2013, from WRF experiment SM25 (Figure 6(e) and (f)) for 8 and 11 June. For 2013 model experiments, local Hadley circulation show vertical intensification over several latitudes as is evidenced by stronger divergent winds of the upper troposphere (the return branch of the local Hadley cell), which steers these clouds ahead of isochrones. Eventually newer buoyant elements are initiated ahead of isochrones. Generally buoyant elements are of the order of few kilometers and were difficult to visualize in present experiments with 25 km of resolution. As a result, model experiments were carried out at a horizontal resolution of 3 km in order to examine the time history of Buoyancy. These buoyant elements grew from 8 to 11 June over entire Indian landmass (Figure 6(g) and (h)). The growth of buoyant elements is indicative of the spread of convection over a wide area and a faster northward motion of the isochrones.

5. Concluding remarks and discussions

This research work dialogues about the importance of soil parameters and clouds in WRF simulations for the movement of monsoonal isochrones over Indian region. Two cases of unlike monsoonal isochrones movement were considered to compare and conclude. The modeling shows that the experiments SM25 and SR25 are the promising among the other experiments where we modified soil moisture, nonconvective clouds and soil temperature respectively. The modifications help in the
Figure 5. Mean of velocity potential filed from June 2 to 16 (*10^7 m^2 s^{-1}) at 200 mb from (a) observation, (b) model experiment (SM25), (c) velocity potential difference between (*10^7 m^2 s^{-1} at 200 mb) Jaisalmer [Rajasthan, (71°E, 27°N)] and Trivandrum [Kerala, (77°E, 8.5°N)].

formation of a new line of convection that becomes the new position of the isochrone. That enhancement of soil moisture for the 2013 must have grown from spring season rains and also from the anvil rains of the parent isochrone. This moistening of the soil immediately ahead of the parent isochrone favored the formation of new clouds that grew in a conditionally unstable environment.

The central issue on fast versus slow meridional motion of the monsoonal isochrone appears to be strongly related to the upper branch of the local Hadley Cell over India. These divergent winds are directed from south to north and play an important role in the northward steering of the onset isochrone. The enhancement of the local Hadley cell appears to be related to this enhanced convection along the onset isochrone that contributed to a fast steering northward and the establishment of the monsoon onset over most of India in a much shorter time compared to the climatological progress. The message that emerges from this study is that for real-time forecasts of this major societal scientific issue, monitoring of soil moisture and incorporation of nonconvective rain within a real-time high resolution nonhydrostatic cloud-resolving model may be necessary to address the march of the isochrones. Afterward, we planned to carry out a large number of sensitivity experiments using pixel-level soil moisture data from Navy satellite and asymmetry in the cloud cover across the isochrones. New study will be possible by using HRLDAS and 4DVAR components of WRF model. We suggest following steps, in the context of possible real-time application of this finding: (1) For
the accurate prediction of monsoonal isochrones an acquisition of high-resolution soil moisture datasets on real time from ISRO facilities [e.g. Agro Metrological (AGROMET) Towers] is required; (2) Real-time availability of GPM precipitation and radar-based vertical structure of hydrometeors (for definition of anvils and nonconvective rains) is important; and (3) There may be a need for real-time postprocessing of the model output to map the local Hadley cell and the divergent winds that steer the isochrones.
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Supporting information

The following supporting information is available:

Figure S1. Daily accumulated rainfall (mm) from for 2, 5, 8, 11, 14 and 16 June 2013 from TRMM3B42 and WRF-ARW model sensitivity experiments (control, enhancing soil moisture by 15%, enhancing stratiform rain by 15%, enhancing soil moisture and stratiform rain by 15% and reducing soil temperature by 7.5% ahead of the 1 June 2013 onset isochrone).

Figure S2. Daily accumulated rainfall (mm day\(^{-1}\)) from for 2, 5, 8, 11, 14 and 16 June 2013 from TRMM3B42 and WRF-ARW model sensitivity experiments (control, enhancing soil moisture by 20%, enhancing stratiform rain by 20% ahead of the 1 June 2013 onset isochrone).

Figure S3. ERA Interim volumetric soil moisture layer-1 for 2013: (a) 2–5 June, (b) 2–10 June, (c) 2–16 June, (d) to (f) except for low-level clouds, (g) to (i) except for soil temperature layer-1.

Figure S4. ARW-WRF sensitivity experiment of enhancing soil moisture by 25% ahead of the 1 June 2013 onset isochrone: (a) total soil moisture layer-1, 2–5 June; (b) total soil moisture layer-1, 2–10 June; (c) total soil moisture layer-1, 2–16 June; (d) total cloud fraction 2–5 June; (e) total cloud fraction 2–10 June; (f) total cloud fraction 2–16 June from 1000 to 100 mb; (g) average soil temperature layer-1, 2–5 June; (h) average soil temperature layer-1, 2–10 June; (i) average soil temperature layer-1, 2–16 June.

Figure S5. The IMD onset isochrones for year June 2014, a year of slower monsoonal isochrones.

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