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Possible relation between land surface feedback and the post-landfall structure of monsoon depressions

Hsin-I Chang,[1] Dev Niyogi,[1] Anil Kumar,[1,2,3,4] C. M. Kishtawal,[5] Jimy Dudhia,[2] Fei Chen,[2] U. C. Mohanty,[6] and Marshall Shepherd[7]

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[1] The effect of pre-storm land surface on the monsoon depressions (MDs) is studied. The Weather Research Forecast (WRF) model was configured with two nested domains to explore the sensitivity of MDs to antecedent soil moisture and land surface representation for selected three landfalling MDs during August 2006. Results indicate that WRF had good ability to simulate the MDs, and the post landfall model response was sensitive to antecedent soil moisture and modestly dependent on land surface representations. This was verified by reviewing the climatology of 125 MDs (1970–2003) which revealed that if the surface received heavier rainfall a week ahead of MD landfall, the inland intensity was maintained for a longer duration. The gradient in surface heat fluxes as the depression made landfall affected the evolution of the MDs over India. In particular, warmer, wetter (cooler, drier) land surface can intensify (weaken) the landfalling MDs over the Indian monsoon region. **Citation:** Chang, H.-I., D. Niyogi, A. Kumar, C. M. Kishtawal, J. Dudhia, F. Chen, U. C. Mohanty, and M. Shepherd (2009), Possible relation between land surface feedback and the post-landfall structure of monsoon depressions, *Geophys. Res. Lett.*, *36*, L15826, doi:10.1029/2009GL037781.

1. Introduction

[2] A monsoon depression (MD) over the Indian monsoon region (IMR) is a weak cyclonic disturbance formed over the Bay of Bengal that moves northwestward into the Indian sub-continent. The occurrence of MDs is considered a dominant factor for the total rainfall received over the IMR.

[3] The offshore evolution of MDs is well studied [e.g., *Goswami*, 1987]. However, as the MD approaches land, there is poor understanding about the land – atmosphere interactions [*Vinodkumar et al.*, 2009]. We seek to examine the effect of pre-storm land surface processes as MDs make landfall over the IMR. The research hypothesis is that even though MDs are dictated by synoptic feedbacks, land surface representation and the pre-storm soil moisture condition over the warm IMR will affect the landfalling MD.

2. Study Period and Numerical Experiments

[4] We selected three consecutive landfalling MDs that occurred in August 2006: MD1 (August 2–7), MD2 (August 11–15), and MD3 (August 15–20). MD1 was a large (~500 km) and intense tropical system. A deep depression (988 mb central pressure) was observed on August 3 (MD1), which weakened to a low pressure system (995 mb) after 48h. The system had a long inland track and caused widespread flooding over northeast India, before dissipating over northwest India. MD2 formed as a low-pressure system over the northwest Bay of Bengal on August 11. The system though short-lived, led to isolated heavy rains over most of India. MD3 formed on August 16 and moved northwestward.

[5] There is no research-grade surface-flux or radar/profiler observations archived over the study region. The Indian Meteorological Department (IMD) monitoring forms the backbone of available observations. Eleven surface stations and sounding sites (Figure S1) were used for the model verification and analysis of the results.[8] These stations were selected on the basis of proximity to the storm tracks and data availability. These were supplemented by TRMM Precipitation Analysis (TMPA) [*Huffman et al.*, 2007].

[6] We performed experiments using the Weather Research and Forecasting model (WRF2.2-ARW). We tested different parameterizations over IMR [*Chang et al.*, 2009]. Present study uses two nested domains (30 km, 10 km grid spacing; Figure S1) with the YSU PBL scheme, Grell-Devenyi convective parameterization, RRTM longwave and Dudhia shortwave radiation. 6-hourly 1° NCEP global final analysis provided the model initial and boundary conditions.

[7] The approach was to assess the impact of the land surface feedback, if any, on the three MDs. The WRF model was run with three different land surface schemes: Noah, Slab and Noah-GEM. The Slab model [*Dudhia*, 1996] has no explicit vegetation representation and only soil temperature is estimated prognostically, while soil moisture is a function of land use category only. The Noah model [*Chen and Dudhia*, 2001] has prognostic soil moisture/soil temperature equations and a moderately complex vegetation representation. Noah-GEM [*Niyogi et al.*, 2009] is more complex than Noah with a photosynthesis-based canopy resistance formulation. In this study, the Noah run is the control, while the Slab and

[1]Department of Agronomy and Department of Earth and Atmospheric Sciences, Purdue University, West Lafayette, Indiana, USA.
[2]National Center for Atmospheric Research, Boulder, Colorado, USA.
[3]Now at Hydrological Sciences Branch, NASA Goddard Space Flight Center, Greenbelt, Maryland, USA.
[4]Now at Earth System Science Interdisciplinary Center, University of Maryland, College Park, Maryland, USA.
[5]Indian Space Research Organization, Ahmedabad, India.
[6]Indian Institute of Technology, New Delhi, India.
[7]Department of Geography, University of Georgia, Athens, Georgia, USA.

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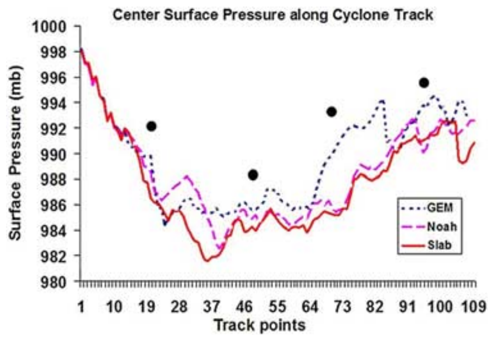

Figure 1. MD1 simulated storm center pressure from Noah, Noah-GEM, and Slab runs. Black dots indicate observed station pressure.

Noah-GEM runs are considered for sensitivity analysis. The model results were then used to test the hypothesis regarding the role of pre-storm land surface conditions such as antecedent soil moisture, in affecting the post-landfall structures of MDs.

3. Results

[8] The model results were compared with observations and against each other to assess the impact of land surface processes on the simulation of landfalling MDs. The atmospheric temperature profiles for all three LSM-WRF runs compared well with the observations (differences within observation error bars and typically ~1K; Figure S2). Though there were larger variations in simulated winds for different runs (~5 to 10 m/s), the model was able to successfully simulate anomalous events such as low level jets that were observed at a few coastal stations. The model results also agreed well with observed daily surface temperature data available from different IMD sites.

[9] Figure S3 shows the TRMM-MPA and WRF simulated rainfall from Noah, Slab and Noah-GEM runs for August 3 (landfall), August 4 and August 5 for MD1. The model reproduced the regional rainfall distribution and timing of the landfall reasonably well for all three LSM runs for MD1. The actual amount of peak rainfall was under predicted (115 mm as compared to 320 mm). There were also some notable discrepancies over the Western Ghats [cf. *Chang et al.*, 2009]. However, it should be noted that the TRMM MPA has been shown to significantly overestimate heavy rainfall rates at sub-monthly scales [*Su et al.*, 2008]. Furthermore, the translation speed of simulated storms was faster compared to observation (mean bias ~3 m/s). The model rainfall hotspot appeared to be generally northwest and more widespread as compared to the TRMM-MPA. The most significant rainfall differences for all the three runs were found along the tracks of the storms. The rainfall amounts were statistically similar ($p = 0.37$) for Noah and Noah-GEM while the Slab run produced significantly ($p = 0.18$) higher rainfall along the track (~5 to 10 mm). Similar results were obtained for MD2 and MD3.

[10] We also analyzed surface pressure and potential vorticity for the different runs during the pre, and post landfall phases of storms. The Slab run simulated the low pressure center about 50 km southeast of the Noah run 24h post landfall, while Noah, Slab and Noah-GEM runs appeared to be west of observation. The spatial and temporal patterns were generally similar for all the runs except immediately after landfall and along the storm track.

[11] A time series of the MD1 central surface pressure is shown in Figure 1. The Slab run simulated the lowest minimum surface pressure (MSP) around 981 mb, and Noah-GEM had higher MSP (985 mb) than Noah LSM (983 mb). MSP values from Noah-GEM were closest to the observation. We noted less sensitivity of the central pressure to different LSMs for MD2 and MD3, which were relatively weaker than MD1. However, in general, Slab resulted in slightly lower central pressure (~2 mb for MD1, ~0.5 mb for MD2 and MD3) as compared to Noah and Noah-GEM.

[12] Simulated tracks for the three MDs were analyzed next (Figure S4). For the three MD cases, the 24h post landfall track errors were: 163 km, 142 km, and 130 km for Slab, Noah and Noah-GEM, respectively. While the track error appears to be higher for Slab, as compared to Noah/Noah-GEM, there was considerable variability and thus no clear impact of land surface schemes on the inland MD track can be identified. As an example, for MD3, Noah-GEM simulated landfall location closest to observation (45 km) as compared to Noah (62 km) and Slab (85 km), and the track error varied as the storm moved inland. These errors need to be interpreted cautiously as the observations themselves can have typical errors of 50 to 75 km (IMD Operational Group, personal communication, 2008).

4. Discussion

[13] The results provide some common findings which are summarized here. MDs are large scale systems, and the synoptic forcings clearly dominate their evolution and structure. Yet, as the MDs made landfall, there were noticeable differences in the storm structure and rainfall due to the land surface feedbacks.

[14] Figure 2 shows the typical daytime surface latent heat flux (LHF) for the three LSMs. The flux gradients were larger between southern and central India in Noah and Noah-GEM runs as compared to Slab. Statistical analysis indicates significant difference between Slab and Noah latent heat fluxes, but less difference between Noah and Noah-GEM. The differences in the heat flux gradient can be important reasons for the differences in the dynamical response seen for the WRF runs with the three LSM runs. Horizontal flux divergence from the three LSM schemes was also analyzed for coastal and inland region (figure not shown). While some results indicated stronger gradients when using Noah or Noah-GEM, the results showed high variability and were inconclusive. The Slab runs for all three MDs also simulated highest soil temperature for most stations due to the bare soil condition. Figure S5 shows the typical soil temperature diurnal variation over an interior station (Bhopal), indicating daytime soil temperature for Slab simulation 3–5 K above Noah and Noah-GEM. The daytime temperature difference is important since it affects surface evaporation.

[15] The potential impact of pre-storm surface conditions on the post-landfall structure of MD was analyzed next. Tropical systems weaken rapidly after landfall due to the lack of surface moisture fluxes. *Dastoor and Krishnamurti* [1991] reviewed the role of soil wetness on a Bay of Bengal MD and suggested that the extremely dry land surface could

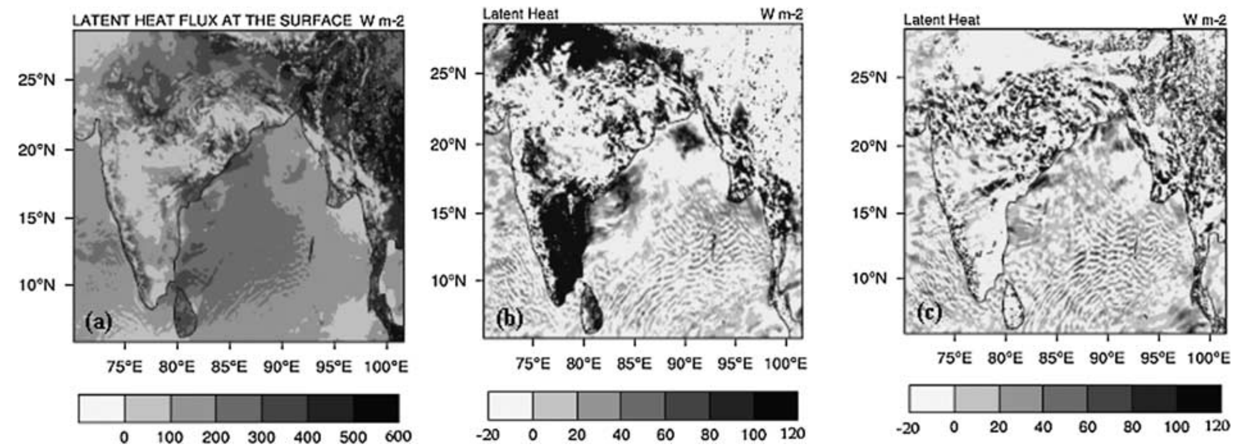

Figure 2. Surface latent heat flux (W m^{-2}) at 06Z (11:30 LT), August 5, from (a) Noah, (b) Slab minus Noah, and (c) Noah-GEM minus Noah WRF runs. Statistical analysis indicates Slab minus Noah results show significant differences, but less difference between Noah and Noah-GEM.

stall the storm motion, while an extremely wet land surface could weaken the storm, but produce widespread rains. *Emanuel et al.* [2008] recently examined re-intensification of a tropical cyclone over sandy soils in northern Australia. They concluded that the large vertical heat fluxes from hot sandy soil, and the enhanced thermal diffusivity as a result of the inland precipitation could strengthen the storm post landfall.

[16] Figure S6 shows typical model results for the effect of antecedent land surface response on the MD structure. The results are shown for Noah LSM, but are generally similar for the Slab and Noah-GEM runs as well. As expected, for the multiscale systems, the relations between surface and atmospheric conditions show variability among different MD cases and locations. However, there is also similarity in the results suggesting a relation between antecedent land surface conditions and the post-landfall storm structure. For example, all model points along the storm track showed higher winds with wetter soil conditions. Similarly, higher soil temperature corresponded with lower MSPs and higher wind speed in all analyses, while the inverse relationship between pre-storm soil temperature and the storm MSP appears to be valid for nearly two-thirds of the data points. That is, for warmer land surface, the landfalling systems appears to be more intense. An example of this relationship is shown over Calcutta for MD2 in Figure S6a. For low LHF or SHF values, there was no apparent relation between the heat fluxes and the storm intensity for all three MDs. When the LHF values were above $\sim$100 W/m^2 or higher, there was a modest positive relation between increasing LHF and higher surface winds (Figure S6b). There is large scatter among different stations, but the results suggest high antecedent LHF may lead to lower surface pressure (Figure S6c). We also noted lower surface pressure caused by higher antecedent soil moisture for all the selected model points/stations (Figure S6d). We found similar results for MD2 with an exception of one model point near a coastal site (Calcutta), where we found higher central pressure for wetter soil.

[17] The lower surface pressure – higher soil moisture relation could be due to two confounding features. One is the possibility that indeed there is a lower surface pressure for higher antecedent soil moisture conditions; and a second possibility could be the result of low pressure system moving inland and causing rainfall and increased soil moisture. To diagnose this we analyzed the antecedent soil moisture and pressure relationship using the simulated time series of rainfall, soil moisture and pressure (Figure S7). Results suggest the possibility of antecedent soil moisture causing lower surface pressure and the subsequent rainfall enhancement. This is further confirmed following the inverse relations between 6h antecedent soil moisture and surface pressure (Figure S8) for each TD.

[18] To further understand the soil moisture-rainfall feedback mechanism, we developed two additional experiments. In the first experiment, the overall soil moisture was reduced by 50% for the second domain ('dry soil run'). Results indicated that higher antecedent soil moisture is related to stronger depressions (Figure 3, top). To confirm the results are indicative of pre-storm antecedent soil moisture (and not the impact of storm induced rain), we removed the rainfall impact on soil moisture, and this also showed a small impact on the surface pressure. Results in Figure 3 (bottom) reaffirmed that higher antecedent soil moisture conditions lead to lower surface pressure. Although the rainfall from the system itself also contributes slightly to the deepening ($\sim$0.5 mb), the contribution from the pre-storm soil moisture seems to be significantly larger (2–3 mb) than that due to storm precipitation. These results were also analyzed for the Noah control run, dry soil run and no-rain run at inland locations. An illustrative center pressure time series is shown in Figure S9; higher surface pressures were simulated in the dry soil run. These results further show that the pre-storm soil moisture conditions affect the characteristics of landfalling depressions in the IMR.

[19] These findings strengthen the idea presented by *Dastoor and Krishnamurti* [1991] and *Emanuel et al.* [2008] that as the tropical systems make landfall over warmer and wetter land surface, the increased surface feedback may strengthen some storms, as compared to cooler and drier land conditions. This is likely due to the increased convective latent heating for warmer, moist surface. To assess if such impact can be noted in the observed MD climatology, we analyzed the tracks of all 125 MDs that formed between 1970 and 2003 (Figure 4a). The inland duration for each MD was

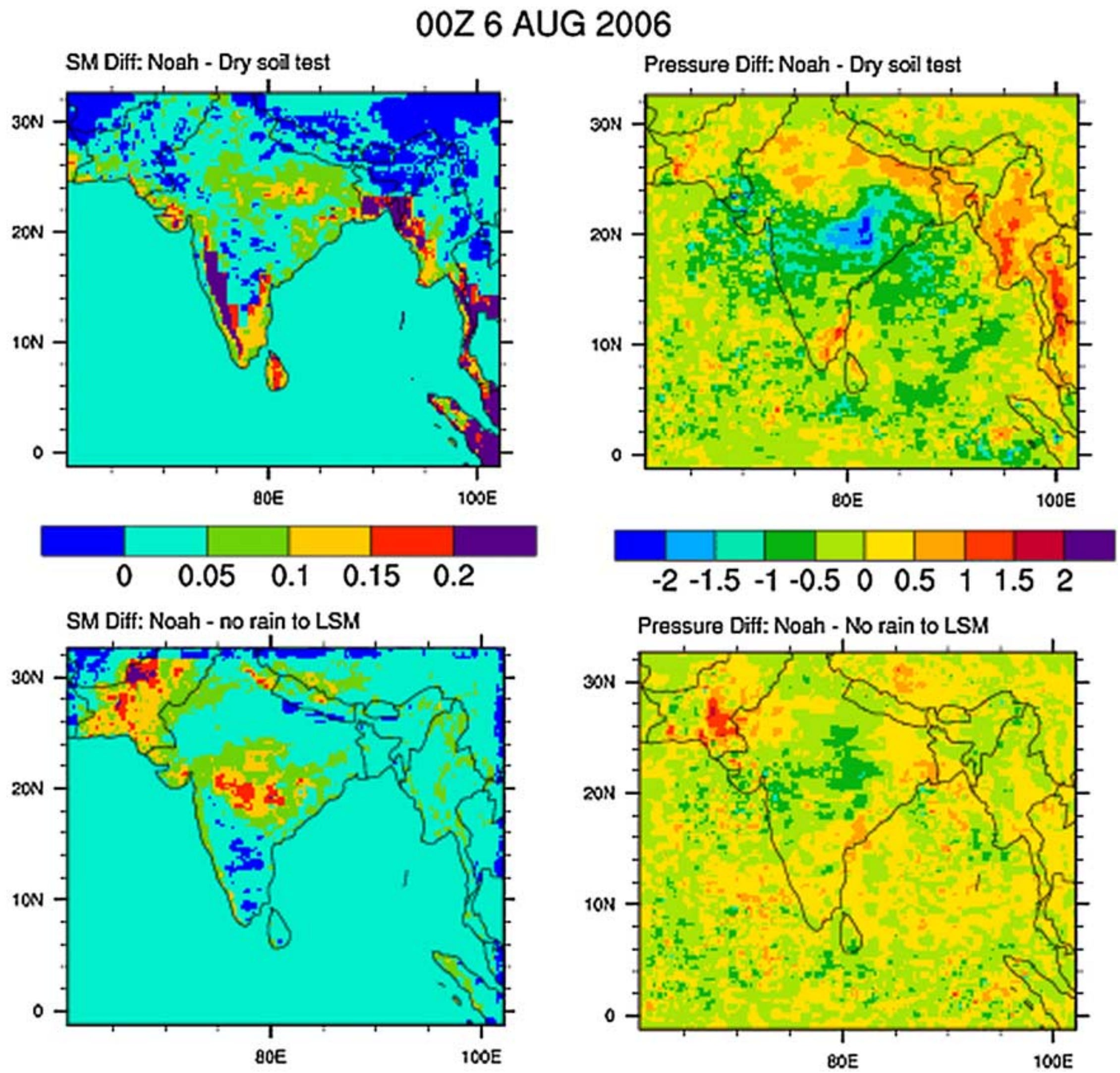

Figure 3. Soil moisture and surface pressure difference plots for (top) control and dry soil run and (bottom) control and no-rain run. Results indicate wetter antecedent soil conditions lead to lower surface pressure for the landfalling monsoon depression.

computed using a high resolution land-sea mask. Gridded analysis (1°) of daily-observed IMD rainfall [*Rajeevan et al.*, 2006] was used to compute the 7-day averages of pre-storm rainfall for each MD. The pre-storm rainfall is used as a surrogate for antecedent soil wetness due to the lack of observed soil moisture data. Figures 4b–4c shows the mean patterns of pre-storm rainfall for long-lasting (inland life span > 72 h) and short-lived (inland life span < 30 h) MDs for the period of analysis. The average rainfall difference between long-lasting and short-lived MDs is more, in the northeastern India, where MDs typically make landfall (Figure 4d). Using the bootstrap method of significance analysis [*Efron*, 1982], we worked out that the difference of antecedent precipitation for long-lasting and short-lived monsoon depressions (Figure 4d) is significant at 90% confidence level. The rainfall patterns and their differences clearly indicate that antecedent ground wetness, particularly along the main corridor of MDs over central India is important for the survival and the development of landfalling monsoon depression (Figure S10).

5. Conclusions

[20] Our results highlight the ability of the WRF modeling system in simulating the MDs over the IMR, especially in the first 24h during and after landfall. The model results showed variability for the land surface scheme used, but in general, the WRF system was able to reproduce the surface and vertical structure well.

[21] Even for these large scale synoptically driven systems, the antecedent land surface can affect the associated rainfall and to some extent the intensity of the landfalling monsoon depressions.

[22] Each of the three LSM runs captured the variability in the central pressure well. The track error was between 60 km to 110 km during landfall for all the runs. The track error was slightly reduced when Noah or Noah-GEM was used but no

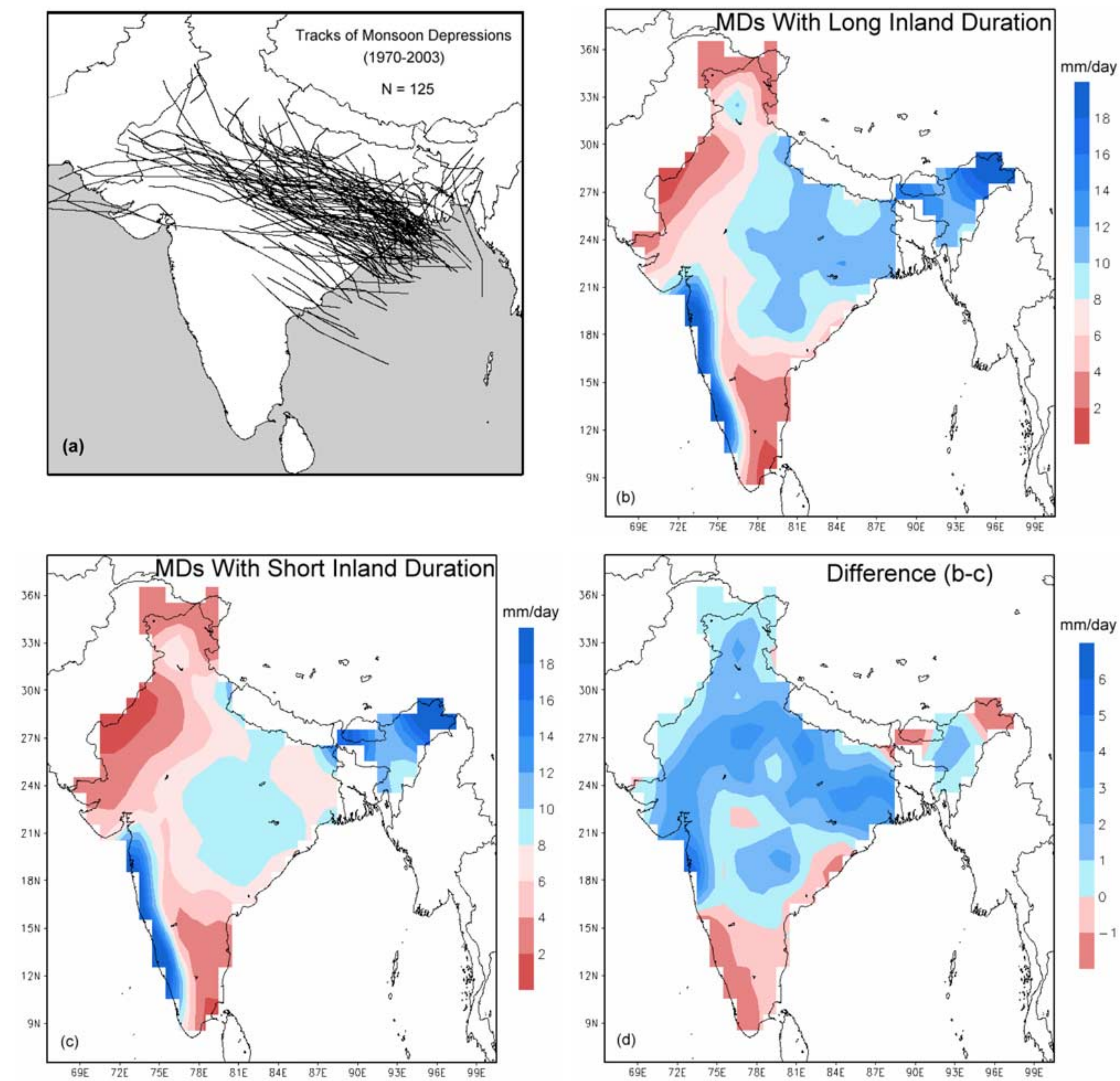

Figure 4. Observation and analysis of 125 MDs formed between 1970 and 2003: (a) best track estimates, (b) mean pre-storm rainfall for long-lasting MDs (inland life span > 72 h), (c) mean pre-storm rainfall short-lived MDs (inland life span < 30 h) for the period of analysis, and (d) rainfall difference between Figures 4b and 4c. Boot strap analysis indicates there are significant differences in the antecedent precipitation for long-lasting and short-lived monsoon depressions.

clear sensitivity of the MD track to land surface schemes could be identified. The wind fields for the landfalling MDs showed modest sensitivity to the land surface. While WRF model captured the TRMM-MPA and rain gauge observed rainfall distribution well, there were notable differences in the rainfall amounts along the storm track for the different LSM runs. Noah and Noah-GEM runs simulated more concentrated precipitation patterns than the Slab run. The results suggest a possibility of some modest improvement when the simpler Slab model was replaced by Noah or Noah-GEM LSM (Figure S11).

[23] The paper also investigated the relation of antecedent soil moisture and landfalling MD intensity. There was large variability in the relations, yet the majority of the results cautiously point to the possibility that pre-storm soil moisture condition could provide useful guidance regarding the post-landfall structure of the MDs. In particular, the conclusion that wetter, warmer land surface can lead to more intense landfalling storms seems to be possibly a general conclusion consistent with the results from *Dastoor and Krishnamurti* [1991] and *Emanuel et al.* [2008]. A climatological review of the 125 landfalling MDs showed the MD intensity was maintained for a longer duration inland if the land surface received heavier antecedent rainfall. Our findings need to be investigated further with more detailed models and observations. Whether the role of land surface is important through

out the monsoon season or there is a preferential impact during early or late monsoon seasons, or during monsoon break, also remains to be investigated. The study thus suggests a possibility that enhanced land surface representation can improve the simulation of landfalling tropical storms over the IMR; and that for wetter, warmer surface conditions, more intense MDs can occur.

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H.-I. Chang and D. Niyogi, Department of Agronomy and Department of Earth and Atmospheric Sciences, Purdue University, West Lafayette, IN 47907, USA. (dniyogi@purdue.edu)

F. Chen and J. Dudhia, National Center for Atmospheric Research, Boulder, P.O. Box 3000, CO 80307, USA.

C. M. Kishtawal, Indian Space Research Organization, Ahmedabad 380015, India.

A. Kumar, Code 614.3, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA.

U. C. Mohanty, Indian Institute of Technology, New Delhi 110016, India.

M. Shepherd, Department of Geography, University of Georgia, Athens, GA 30602, USA.