Understanding the Global Distribution of Monsoon Depressions

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LONG-TERM GOALS

This project aims to improve the understanding of cyclonic storms called monsoon depressions, which play an important role in the meteorology of the tropical and subtropical eastern hemisphere and serve as precursors for typhoons in the Indian and Western Pacific Oceans. The work undertaken here serves as part of a broader effort to better understand and predict tropical cyclogenesis and the variability of monsoon climates in Asia, Australia, Africa, and the Americas.

OBJECTIVES

Synoptic low pressure systems embedded in monsoon circulations play a central role in the meteorology of the tropical Indian and western Pacific oceans during local summer, producing a large part of the rainfall of the Indian and Australian monsoons and producing enhanced surface wind variability over oceans (Yoon and Chen, 2005; Davidson and Holland, 1987). These monsoon low pressure systems, of which the more intense occurrences are called monsoon depressions, can also evolve into typhoons and are strongly correlated with dominant patterns of tropical intraseasonal variability such as the Madden-Julian oscillation (Goswami et al., 2003). Yet despite the importance of these low pressure systems, the mechanisms responsible for their formation, intensification, and propagation are not understood (e.g. Beattie and Elsberry, 2010). Furthermore, no climatology of these storms exists for regions outside of India.

This project aims to:

- document the frequency and geographic distribution of monsoon depressions in the Indian and western Pacific Oceans (both north and south of the equator),
- determine which environmental parameters (e.g. wind shear, sea surface temperature) control genesis of monsoon depressions,
- examine how the dynamical structure of monsoon depressions varies regionally and throughout the storm lifecycle, and
- assess and further develop theories for storm formation and structure.

APPROACH

This study builds understanding of the dynamics of monsoon depressions through three main tasks. In the first task, a global database of the distribution of observed monsoon depressions is constructed, as only some of these storms are included in existing best-track archives of tropical cyclones. In the second task, a genesis potential index used for tropical cyclones is objectively adapted to monsoon depressions, providing a statistical description of the association of depression occurrence with environmental parameters such as wind shear and humidity. The third task will examine the dynamical structure and evolution of monsoon depressions using idealized cloud-system resolving models together with observational composites based on the climatology compiled in the first phase of the project. These dynamical studies will be strongly constrained by observations, using the statistical properties of the genesis index to verify that the idealized model systems behave in a statistically similar fashion to observations as a function of environmental parameters.

Key individuals are:

> William Boos, Principal Investigator and Assistant Professor at Yale University, directs the work flow of the project and supervises the other personnel. He is performing the idealized model studies and the assessment and development of dynamical theories.
>
> John Hurley, postdoctoral associate at Yale University, is compiling the depression climatology and associated statistics, and will produce observational composites.
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> Sarah Ditchek, undergraduate intern at Yale University, is adapting existing genesis potential indices to monsoon depressions.

WORK COMPLETED

Funding for this project started four months before the writing of this report. In that time the following work was completed:

1. *Depression climatology:* The TRACK program, which is an automated feature tracking algorithm developed by Hodges (1995), has been configured to identify and track the locations of cyclonic vorticity maxima in the ERA-Interim reanalysis. Vortex tracks exceeding a specified threshold of relative vorticity, surface pressure, and surface wind speed were compiled for the tropical and subtropical Northern Hemisphere for 1989-2010 (the same task is in progress for the Southern Hemisphere). An existing monsoon depression climatology that exists for India in paper form only was digitized for comparison with our results.

2. *Genesis potential index:* Our first planned task was to perform a best-fit of the functional form of the genesis potential index of Emanuel and Nolan (2004) to monsoon depressions. One parameter that is part of the Emanuel-Nolan index is potential intensity, but monsoon depressions sometimes originate over land where sea surface temperature (SST) and thus potential intensity are undefined. For this reason, we derived an alternative thermodynamic parameter called the “relative moist static energy” that is defined over both land and ocean.

3. *Dynamical studies with idealized models:* The Weather Research and Forecast (WRF) model was configured to simulate a monsoonal basic state on a zonally-symmetric beta-plane with an entirely

oceanic lower boundary having prescribed SST. Model results are not included in this report as analysis has only just begun.

RESULTS

(N.B.: Only preliminary results are presented, as the project has been active for just four months.)

1. Depression climatology

While best-track archives do contain tracks of some monsoon depressions, they seem to be missing a substantial fraction of the full distribution, as illustrated in Fig. 1 by a comparison of tracks from the Joint Typhoon Warning Center (JTWC) for 1999 with tracks from a climatology of Indian monsoon depressions (Sikka 2006) which was digitized as part of this project. Over India and the Bay of Bengal, the JTWC archive contains one storm, while the Sikka archive contains 13 low pressure systems, about half of which are of depression intensity. Automated identification of cyclonic vortices in the ERA-Interim reanalysis seems to successfully identify some of the depressions in the Bay of Bengal, including one which originated over land in northeastern India. Weaker storms in the ERA-Interim data set were purposefully excluded by enforcing a minimum threshold for storm vorticity, surface pressure anomaly, and wind speed during the identification process.

Examination of the distribution of genesis points for the full period of the ERA-Interim dataset (1989-2010) shows that genesis points for low pressure systems in the Bay of Bengal are part of a larger distribution that stretches from the Arabian Peninsula to the Western Pacific (Fig. 2). In future work we will attempt to distinguish between monsoon depressions and classical tropical cyclones, and to characterize the statistical properties of this distribution of genesis points. Cyclonic vortices in the Southern Hemisphere will also be identified.

2. Genesis potential index

A genesis potential index provides a statistical description of the association of storm genesis with environmental parameters such as humidity and large-scale wind characteristics. The task of adapting the Emanuel and Nolan (2004) genesis index to monsoon depressions is complicated by the fact that depressions sometimes originate over land; potential intensity, which is one of the inputs to the Emanuel-Nolan index, is undefined over land. Alternate attempts to define a tropical cyclone genesis index (e.g. Tippett et al. 2011) have found that relative SST performs comparably with potential intensity as a predictor for genesis. We define a quantity called "relative moist static energy" as the difference between the moist static energy (MSE) of surface air minus the tropical-mean MSE. This quantity has the advantage of being defined over land while corresponding quite closely to relative SST over ocean (Figs. 3 and 4). Like relative SST, relative moist static energy is expected to act as a rough measure of convective available potential energy (CAPE) but with the added advantages of being defined over land and accounting for the influence of land surfaces on tropical free-tropospheric temperatures. While our immediate goal is to use relative moist static energy in a genesis index for monsoon depressions, it may have broader use as a simple global index of convective potential.

Work to define a genesis index for monsoon depressions in terms of relative moist static energy and other variables is in progress.

IMPACT/APPLICATIONS

Future results from this project are expected to have applications in weather and climate prediction on a variety of time scales:

Prediction on synoptic time scales: Studies of model skill for monsoon depression forecasting have mostly proceeded empirically, with previous authors finding sensitivity of skill to model resolution, convective physics, and initial conditions (e.g. Routray et al., 2010). Greater theoretical understanding of the mechanisms governing monsoon depressions may thus guide the improvement of forecast models. The genesis potential index developed by this study is also expected to be useful in synoptic forecasting, providing greater understanding of the influence of large-scale parameters on depression occurrence.

Prediction on intraseasonal time scales: Intraseasonal variability in the South Asian summer monsoon strongly modulates the occurrence frequency and tracks of monsoon depressions in the Indian region (e.g. Chen and Weng, 1999). Production of a depression climatology will allow for assessment of whether similar modulation of depression behavior occurs near Australia and in the western Pacific. Knowledge of such a relationship could help forecasters use the observed phase of the MJO to improve depression predictions.

Tropical cyclogenesis: Monsoon depressions serve as precursors for tropical cyclones (e.g. McBride and Keenan, 1982). An improved understanding of monsoon depression dynamics is thus expected to contribute to our theoretical understanding of tropical cyclogenesis.

Response to climate shifts: Synoptic activity and extreme rain events in the Indian summer monsoon have increased since the 1950s, but this increase is associated with enhanced activity of weaker low pressure systems and a decline in the activity of more intense systems (e.g. Ajayamohan et al., 2010). The genesis potential index developed in this project is expected to be useful in understanding how future variations in climate might influence depression activity in the broader Asia-Pacific region.

RELATED PROJECTS

Interannual variability of monsoons in a convective quasi-equilibrium framework: In a separate but related project, the PI's group has found a statistically significant relation between interannual variations in monsoon precipitation and the equivalent potential temperature of near-surface air over land. This relationship was found to hold in all of Earth's regional monsoons, and is important because it shows that monsoon rainfall is related not only to SST, as emphasized by previous studies, but also to thermodynamic conditions over land. Since monsoon depressions produce substantial monsoon rainfall in South Asia and Australia, future examination of the interannual variability of monsoon depressions may prove to be interesting and highly relevant.

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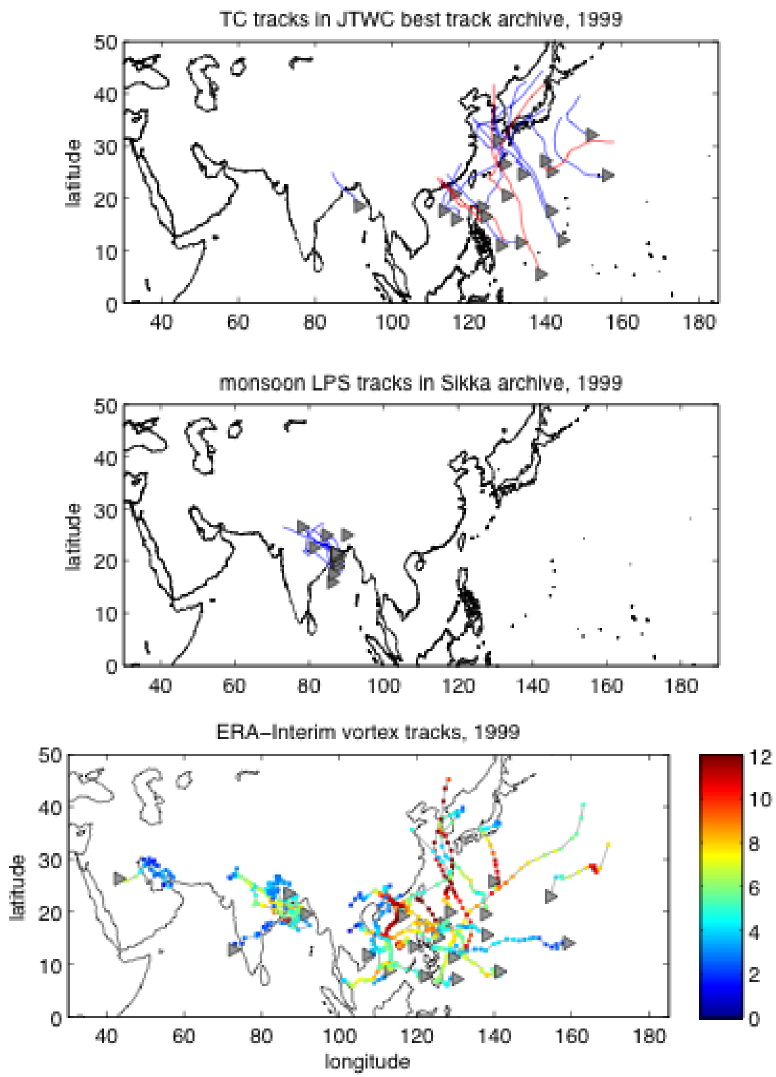

Fig. 1: Cyclonic vortex tracks for 1999. Top: From the JTWC best-track archive. Storms of typhoon intensity are denoted by red lines and weaker storms by blue lines. Triangles denote genesis points. Middle: Tracks from the Sikka (2006) climatology for India. Bottom: Tracks from our identification based on ERA-Interim 850 hPa relative vorticity, using a minimum threshold for vortex strength (not discussed here). Points show 6-hourly vortex centers, with color indicating relative vorticity (in 10^{-5} s^{-1}).

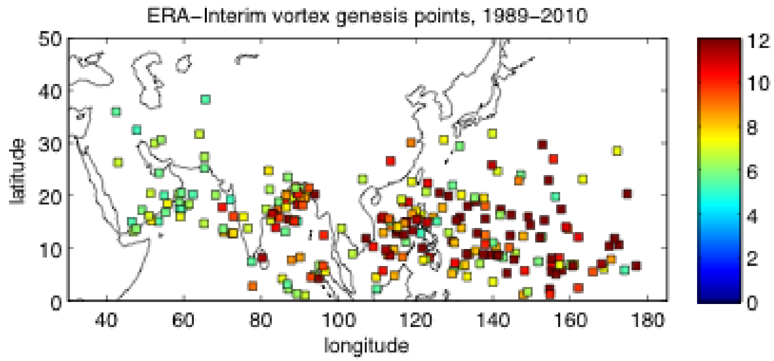

Fig. 2: Genesis sites of vortex tracks for 1989-2010, identified from the ERA-Interim data set using the TRACK algorithm. Color denotes peak relative vorticity (10^{-5} s^{-1}) achieved during the life of the vortex.

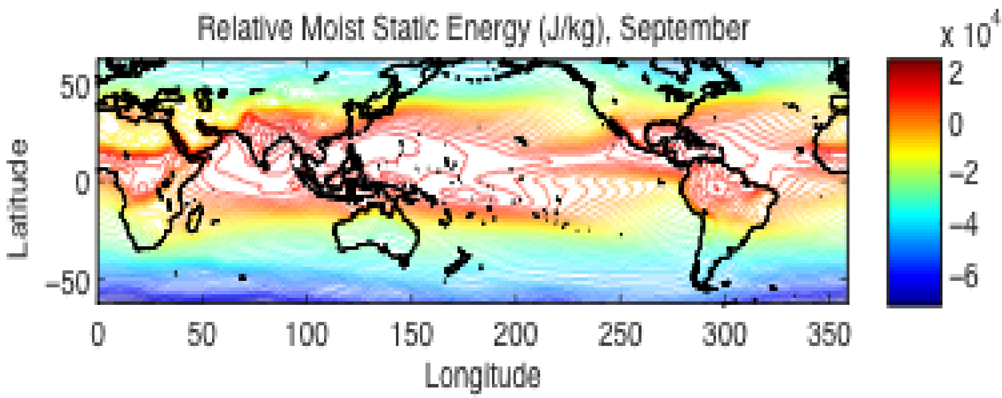

Fig. 3: Climatological mean relative moist static energy for September, from the ERA-40 data set.

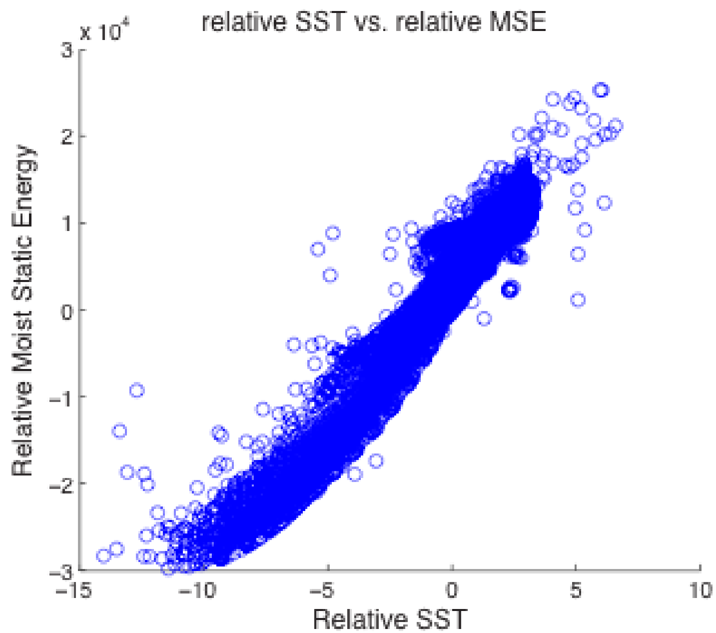

Fig. 4: Relation of relative moist static energy (MSE, in J/kg) to relative sea surface temperature (SST, in K), for the ERA-40 September climatology, demonstrating that relative MSE is a good substitute for relative SST.