LONG-TERM GOALS

This project aimed to improve understanding and observational assessments of atmospheric cyclonic vortices called monsoon depressions, which produce extreme precipitation in the monsoon climates of Asia and Australia and also serve as precursors for typhoons. This work is part of a broader effort to better understand and predict tropical weather and the early stages of tropical cyclogenesis during solstice seasons.

OBJECTIVES

Synoptic low pressure systems embedded in continental-scale monsoon circulations play a central role in the meteorology of the tropical Indian and western Pacific oceans during local summer, producing a large fraction of the total rainfall together with enhanced surface wind variability in the South Asian and Australian monsoons (Yoon and Chen, 2005; Goswami et al., 2003; Davidson and Holland, 1987). The more intense occurrences of these low pressure systems are called monsoon depressions, which frequently evolve into typhoons and on average have peak rain rates of 5 cm/day. 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 aimed to:

- document the global frequency and geographic distribution of monsoon depressions,
- determine which environmental parameters (e.g. wind shear, sea surface temperature) are associated with the genesis of monsoon depressions,
- examine how the dynamical structure of monsoon depressions varies regionally and throughout the storm life cycle, and
- assess and further develop theories for storm formation and structure.

This project was funded from June 1, 2011 through August 29, 2014. All proposed work was completed.
APPROACH

This study built understanding of the dynamics of monsoon depressions through three main tasks. In the first task, a database of observed monsoon depression tracks was constructed, because only some of these storms are included in existing best-track archives of tropical cyclones. In the second task, an objectively derived genesis potential index used for tropical cyclones was 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 examined the dynamical structure and evolution of monsoon depressions using idealized models together with observational composites based on the climatology compiled in the first phase of the project.

Key individuals are:

- William Boos (PI), Assistant Professor at Yale University, directed the project work flow and supervised other personnel. He performed some observational analyses and developed theory.
- John Hurley, postdoctoral associate at Yale, compiled the depression climatology and produced observational composites.
- Naftali Cohen, postdoctoral associate at Yale, analyzed trends in Indian monsoon depressions and conducted observational studies of instability mechanism.
- Varun Murthy, doctoral student at Yale, performed idealized cloud-resolving model studies of monsoon depression spinup.
- Sarah Ditchek, undergraduate intern at Yale, created a genesis potential index to statistically describe the formation of monsoon depressions.

WORK COMPLETED

The following tasks were completed during the 3-year duration of this project:

1. Track dataset: An automated feature tracking algorithm [based on the TRACK program of Hodges (1995)] was used to identify the locations and horizontal trajectories of cyclonic relative vorticity maxima in the global ERA-Interim reanalysis for 1979-2012, with a focus on monsoon regions during solstice seasons. Fig. 1 shows the spatial distribution of boreal summer genesis points and tracks. Composite structures of depression-strength vortices in Africa, South Asia, Australia, the West Pacific, and the Americas were compared.

2. Genesis potential index: A genesis potential index for Indian monsoon depressions was developed, using Poisson regression (Tippett et al. 2011) methodologies and a novel generalization of “relative sea surface temperature” that is defined over land (motivated by the fact that depression genesis sometimes occurs over land).

3. Observationally based dynamical studies: The dynamical structure of monsoon depressions was examined in observational composites and case studies. Theories for the growth and propagation of monsoon depressions were developed.
4. Dynamical study with idealized model: Boundary-forced integrations of the Weather Research and Forecast (WRF) model were conducted in a continental-scale domain in an effort to simulate the spontaneous genesis of monsoon depressions. However, simulated structures were not realistic, perhaps because this model used parameterized convection. Initial-condition runs were subsequently performed using the WRF model at a higher horizontal resolution that allowed for elimination of convective parameterizations (i.e. a cloud-system resolving configuration). The mechanism of growth of an initial seed vortex was studied.

RESULTS

Multiple notable results were obtained during this project. Most of these have been published or at least submitted to refereed journals, and at least two additional manuscripts will be submitted in the next 3-6 months. A subset of these results is described briefly below.

1. **Synoptic-scale vortices produce at least half the total precipitation in most continental monsoon regions.**

2. **Shallow, dry vortices coexist with deep, precipitating vortices in most monsoon regions.** The shallow, dry vortices are found primarily over the desert regions that are adjacent to classic monsoon regions (e.g. over the Sahara, Pakistan and northwestern India, and continental Australia. These dry vortices have potential vorticity confined to a near-surface layer, and vertical structures trapped below 600 hPa. The deep, precipitating vortices have vertical structures that extend to the upper troposphere.

3. **Monsoon depressions in South Asia, Australia, the southwestern Indian Ocean, and the West Pacific all share similar dynamical structures.** This structure consists of a cold core at low levels and a warm core in the middle to upper troposphere, in contrast to canonical tropical cyclones which have a warm core at low levels. While the winds and vorticity peak in the lower troposphere, potential vorticity (PV) has a maximum in the middle troposphere (Fig. 2).

4. **The upstream propagation of Indian monsoon depressions is produced by nonlinear self-advection (i.e. “beta drift”, Fig. 3).** This new finding contrasts sharply with previous hypotheses for propagation that required interaction of precipitating convection with the low-level vorticity field (e.g. Sanders 1984, Chen et al. 2005). Considerable dynamical insight can be gained by viewing monsoon depressions as mid-tropospheric PV maxima instead of lower-tropospheric vorticity maxima (as was traditional).

5. **Storm structures are inconsistent with theories of baroclinic growth, the most widespread idea for the mechanism of depression amplification.** PV maxima are localized in space, which precludes dry baroclinic growth, and PV structures lack the upshear tilts necessary for growth by moist baroclinic instability or nonmodal growth processes.

6. **Genesis of monsoon low pressure systems is strongly associated with several climatological variables.** Genesis is positively associated with mid-tropospheric relative humidity, low-level absolute vorticity, and a bulk measure of convective available potential energy. Genesis is negatively associated with vertical wind shear, which is yet another indication that these storms do not grow by traditional baroclinic instability mechanisms.
IMPACT/APPLICATIONS

Weather and climate model development: The results of this project will allow model simulations of weather in monsoon regions (e.g. the Indian Ocean) to be assessed by comparing their output with our track dataset. The finding that monsoon depressions are mid-tropospheric PV maxima indicates that the fidelity of model convection will be crucial for properly simulating the structure of monsoon depressions. In contrast, given a correct PV structure, simulation of propagation should be straightforward since it depends only on adiabatic self-advection.

Prediction on synoptic time scales: Studies of model skill for monsoon depression forecasting have mostly proceeded empirically, with previous authors finding sensitivity 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. Because of the similar dynamical structure of monsoon depressions across multiple regions, efforts to improve the simulation and prediction of monsoon depressions in one region (e.g. South Asia) are likely to yield improvements in other regions (e.g. the southern Indian Ocean and the West Pacific). The genesis potential index developed by this study may also be useful in synoptic forecasting, providing understanding of how large-scale parameters influence depression occurrence.

Tropical cyclogenesis: Monsoon depressions serve as precursors for tropical cyclones (e.g. McBride and Keenan, 1982). An improved understanding of monsoon depression dynamics thus enhances our theoretical understanding of the early stages of tropical cyclogenesis.

RELATED PROJECTS

Interannual variability of monsoons: We have 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 a thermodynamic variable that is defined over land.

Thermodynamic bias of climate model simulations of monsoons: We have shown that almost all climate models participating in the Coupled Model Intercomparison Project (CMIP) exhibit a common bias in the thermodynamic structure of the South Asian summer monsoon that is caused by poor representation of orography. The highly smoothed topography used in these models allows dry air from the deserts of western Asia to penetrate the monsoon thermal maximum, reducing model upper-tropospheric temperatures and suppressing monsoon precipitation.

REFERENCES


**PUBLICATIONS**

Cohen, N. Y. and W. R. Boos: Has the number of Indian summer monsoon depressions decreased over the last thirty years? *Geophysical Research Letters* [submitted, refereed].


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HONORS/AWARDS/PRIZES

W. R. Boos, 2014 Director’s Award, Yale MacMillan Center for International and Area Studies

W. R. Boos, 2013 CAREER Award, National Science Foundation

W. R. Boos, 2013 Editor’s citation for excellence in refereeing, American Geophysical Union

Fig. 1: Illustration of the global distribution of synoptic-scale monsoon vortices having the intensity of a monsoon depression. Shading shows frequency of genesis for various storm categories for May–Sept. 1979–2012, based on ERA-Interim data (in units of number per summer season within a 500 km radius of each point). Green lines represent individual vortex tracks for the year 2012 (only one year is shown for clarity), with genesis points indicated by diamonds. From Hurley and Boos (in press at Q. J. R. Meteorol. Soc.).
Fig. 2: Comparison of vertical structures of depression-strength vortices in three different monsoon regions. Top panels are for the Indian region, middle panels for the southwestern Indian Ocean, and bottom panels for the northern Australian region. Left column shows latitude-height profiles of potential temperature anomalies (color shading, in K) and zonal wind (contours, dashed negative, in m/s). Right column shows longitude-height profiles of potential vorticity (colors, in PVU) and meridional wind (contours, dashed negative, in m/s). All quantities are storm-centered composite means. Note that depressions in all regions have a low-level cold core; they also have a deep column of potential vorticity extending to the upper troposphere, even though winds and relative vorticity peaks in the lower troposphere.
Fig. 3: Supporting evidence for the assertion that Indian monsoon depressions propagate primarily by adiabatic, nonlinear self-advection (i.e. “beta drift”). Color shading shows potential vorticity (in PVU) and is provided to mark the location of the storm center. Red vectors show the vortex propagation velocity, which is to the northwest at about 2 m/s. That velocity is similar to the total horizontal wind averaged over the vortex center, which is represented by the blue vector. The green vector shows the climatological mean wind, which is strongly eastward at low levels (bottom panel) and very weakly northwestward in the middle troposphere (top panel), and thus would tend to tilt the vortex. Contours show the azimuthally asymmetric horizontal streamfunction; “beta gyres” can be seen that are consistent with idealized models of beta drift.