Fundamental monsoon dynamics:
Aquaplanet monsoons and their response to climate changes

Monsoons are prominent features of the atmospheric tropical circulation, affecting the climate of nearly one quarter of the globe and sustaining more than one half of the human population in regions with rapidly growing economies. With projected increases in population and pressure for food security, understanding how monsoons will change with changing climate is both a priority and a major challenge for climate science: Simulations of monsoons in today's climate by state-of-the-art general circulation models (GCMs) show significant biases, and future projections in the Coupled Model Intercomparison Project Phase 5 (CMIP5) archive remain largely uncertain, with a range of disparaging trends to the end of the 21st Century. Disagreements in the modeled present-day rainfall and projected changes reflect deficiencies in our current understanding of the basic physical and dynamical mechanisms driving monsoons, their seasonal cycle, and their response to anthropogenically induced radiative perturbations. An impressive array of research is being carried out to introduce increasing complexity in the modeling of monsoons, to account for numerous and complex interactions between land, atmosphere, ocean, cryosphere and biosphere. However, theoretically based studies aimed at identifying the fundamental dynamics of monsoons remain few. Filling the existing gap in our understanding of large-scale monsoons and their response to climate changes is the underlying theme of my research endeavors.

A primary tool is a GCM that is idealized both in terms of the lower boundary – a so-called *aquaplanet* – represented by a uniform slab ocean, and the model physics. Using this idealized GCM, I was able to show that monsoons can exist even in the absence of land-sea contrast, prevailingly considered the major driver of monsoons, provided that the lower boundary has low enough thermal inertia. These *aquaplanet* simulations suggest that monsoons, rather than being large-scale sea breeze circulations driven by the contrast in thermal properties between land and ocean, occur as the tropical overturning circulation transitions from an equinox regime, in which the circulation is driven by large-scale eddies of extratropical origin, to a monsoon regime in which the circulation approaches conservation of angular momentum and more directly responds to energy constraints.

The emerging view of monsoons as angular momentum-conserving tropical overturning circulations is in sharp contrast with the traditional interpretation as sea breeze circulations, both in terms of fundamental driving and expected response to radiative perturbations: The traditional sea breeze view emphasizes surface temperature gradients as drivers of winds through pressure gradients in the momentum balance. Increased land-sea temperature contrast with global warming is a robust GCM prediction, which would imply increased monsoon strength. This projection is however not robust in climate models, especially for the Asian monsoon. The view of monsoons as tropical angular momentum-conserving circulations, instead, constrains the circulation strength from an energetic perspective through the top-of-atmosphere energy balance. Under warming, the monsoon precipitation can increase through changes in moisture content (following the Clausius-Clapeyron relationship) even when the circulation weakens.

Using the idealized GCM, we can investigate the response of *aquaplanet* monsoons to radiative perturbations. For instance, we recently studied how these systems respond to changes in orbital

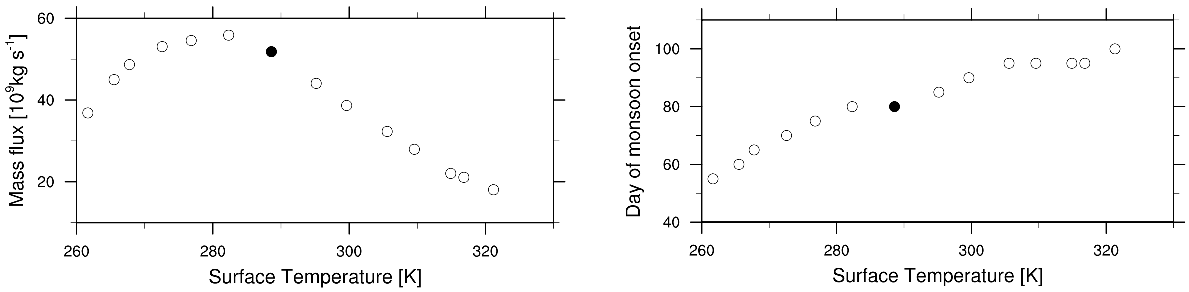

FIGURE 1: Monsoon strength vs global-mean surface temperature (left) and timing of monsoon onset (in julian day) vs global-mean surface temperature (right). Each circle represents a different simulation and the filled circle identifies the simulation of present-day Earth's climate.

precession and showed how, consistent with paleoclimatic records, the annual mean precipitation is greater in the hemisphere in which perihelion occurs in the summer. This happens through a nonlinearity, which does not involve the Clausius-Clapeyron nonlinearity, as previously suggested, but arises because the seasonal cycle of the precession-induced humidity changes is correlated with the seasonal cycle of low-level convergence.

I am currently studying the response of *aquaplanet* monsoons to changes in longwave radiation, in analogy to changes in greenhouse gas concentrations. The idealized GCM allows us to experiment extensively the parameter space and to identify robust key mechanisms in a broad continuum of climates and configurations. I find that, as the climate is warmed, the tropical precipitation increases rapidly with temperature, but the monsoonal circulation behaves non-monotonically, achieving its maximum at a climate slightly colder than present day (Fig. 1, left). Changes in precipitation seasonality also occur, with the monsoon onset being progressively delayed with warming (Fig. 1, right). Previous work discussed how the differing response of land and ocean surfaces with warming could cause a delay in the transition from the dry to the wet season. My results suggest that more fundamental dynamical mechanisms, acting irrespective of land-sea contrast and possibly linked to the increased residence time of atmospheric moisture with warming, might be implicated in these seasonal changes. Results from this work are used to develop metrics to assess the performances and better constrain projections of comprehensive GCMs, as well as to inform observational studies.