Tropical Rainfall: Within-Season Variations

In the tropical belt of the Asian Pacific region, there are rainy spells, between two weeks to a couple of months in duration, that are associated with the tropical intraseasonal oscillations (ISO). The major disturbance of this kind is the Madden-Julian Oscillation (MJO), which typically has a period of 40–50 days and is linked to the deep convection over the Indian Ocean and western Pacific warm pool and accompanied by rain. The MJO is most active from November to May during which time such disturbances move eastward around the globe, weakening over the eastern Pacific, growing somewhat stronger over South America, and weakening again over the Atlantic and Africa, until they return to the Indian Ocean (Madden-Julian 1971, 1972). Included in this category of tropical intraseasonal oscillations are also northward and westward moving disturbances that prevail from May to October and are called the monsoon oscillations.

These disturbances affect human activities and particularly agriculture in the heavily populated Asian continent, and improvements in their forecast would be valuable. Most global general circulation models still have great difficulty in simulating the properties of these tropical oscillations, which originate in complex interactions among many physical processes taking place on different scales of time and space. Modelling these oscillations entails a series of interacting parameterizations of such processes as moisture transport, evaporation, cloud dynamics, convection, and radiation transfer. Uncertainties in the mathematical descriptions of any of these parameterized interactions jeopardize a model's ability to simulate the disturbances. Progress in predicting the wet and dry spells requires a more complete understanding of the mechanisms underlying these complex interactions.

Many studies have already been devoted to developing a theoretical understanding of the MJO. These studies have invoked a broad range of processes and feedback mechanisms to account for the growth and maintenance of the disturbance. The major mechanisms that have been proposed can be summarized as follows: (i) cooperative interaction between convection and atmospheric waves; (ii) instability driven by wind-evaporation feedback or wind-induced surface heat exchange, in which spatial variation in surface heat fluxes associated with variations in surface wind speeds controls the structure of convection; (iii) instability arising from friction-induced moisture-convergence feedback, in which boundary-layer friction organizes convection and couples the equatorial Kelvin and Rossby waves moving eastward; and (iv) cloud-radiation feedback, which results from interactions among convection, radiative heating anomalies, and the surface flux of moisture and sensible heat. The intraseasonal oscillations in the monsoon region are furthermore greatly affected by seasonal variations in the atmospheric circulation and sea surface temperature.

In spite of all the work in this field, many aspects of these oscillations are not well understood and present the scientific community with a challenge. **Bin Wang**, co-leader of the Asian-Australian Monsoon System research team at the IPRC, has developed a model that simulates the major characteristics of both the MJO and the summer monsoon oscillations and provides a unifying framework for these tropical oscillations. Wang considers his model to be relatively simple. It is a time-dependent, primitive-equation model on an equatorial beta-plane that has two free-troposphere levels and a well-mixed planetary boundary layer. Figure 4 highlights the physical processes in his model. At the center of the model are the nonlinear interactions among convective-condensational heating, low-frequency equatorial (Rossby and Kelvin) waves, boundary-layer moist dynamics, and wind-induced heat exchange at the surface. These nonlinear interactions he calls, for short, "convective interaction with dynamics," following Neelin and Yu (1994). Variations in net radiative heating, parameterized as a longwave radiative cooling, are included as a feedback mechanism, and the model allows for the impacts of sea surface temperature and the three-dimensional background atmospheric circulations. Thus, the physics of the model integrate, to varying degrees, all of the mechanisms listed above.

Despite its simplicity, the model is able to reproduce atmospheric disturbances that have features closely resembling those of the observed MJO and monsoon oscillation. The simulated atmospheric disturbances have the following MJO characteristics (Figure 5): an east-west circulation that spans the globe and is coupled to a large complex of convective cells;

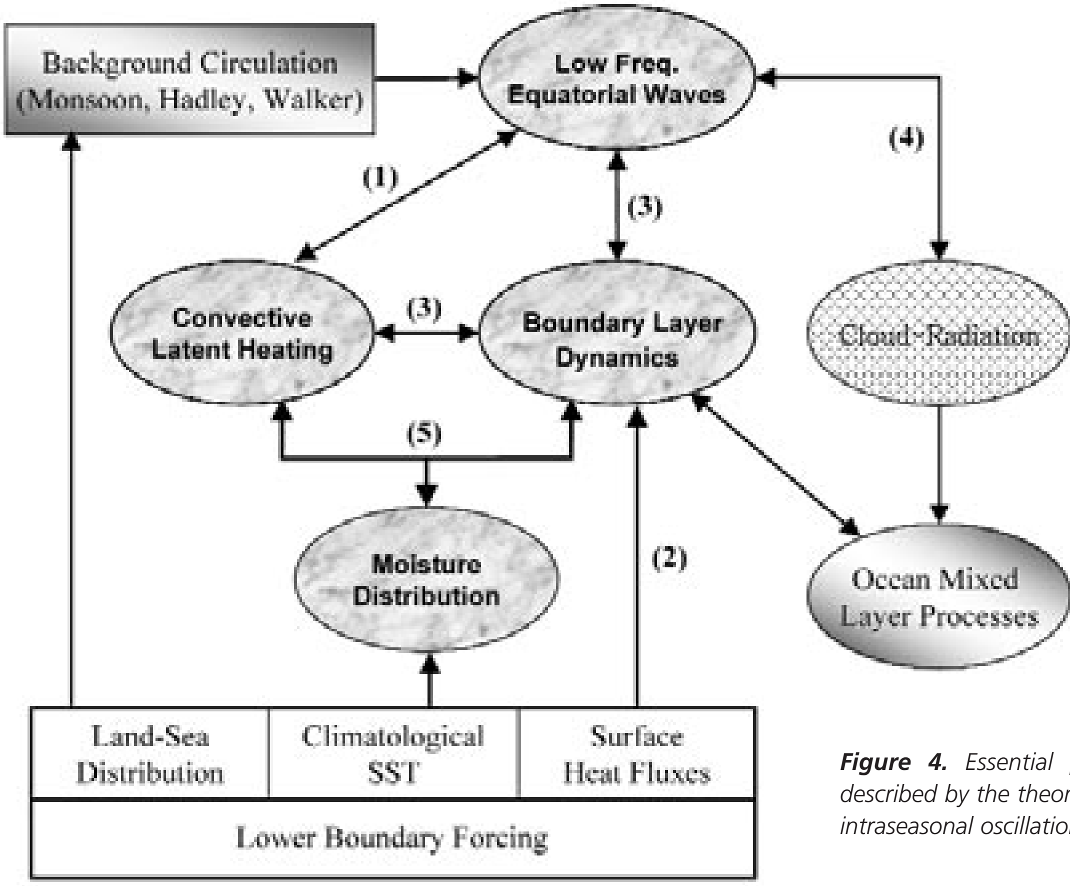

Figure 4. *Essential physical processes described by the theoretical model of the intraseasonal oscillation.*

a baroclinic structure, with winds converging in the boundary layer ahead of the main precipitation; a horizontal circulation consisting of both equatorial Kelvin and Rossby wave components and a slow eastward (about 5 m/s) movement that gives rise to a subseasonal timescale (30–60 days). Given the boundary forcing for the monsoon season, the simulated intraseasonal oscillation also shows appropriate seasonality, with prominent northward propagating and off-equatorial westward propagating disturbances during the summer monsoon. Simulation with Wang's model of this aspect of the tropical oscillation will be described in a later issue of the newsletter. The focus here is on the eastward moving Madden-Julian Oscillation.

The fact that the simulated intraseasonal oscillation has such realistic properties suggests that the essential physical processes represented by the crude parameterizations within the model are also reasonably realistic. Analyses of the simulations can therefore provide insight into the fundamental dynamics of the MJO. Figure 5 shows a schematic of the atmospheric flows in the simulation, once the wet phase of the MJO is established. When SST exceeds a critical value (about 28°C) in the Indian Ocean or in the warm pool, warm moist air rises above 500 mb, and Kelvin waves (blue circulation) are excited. Moving eastward along the equator, these waves leave a low-pressure trough east of the main convection. In this trough, boundary-layer frictional convergence accumulates and stimulates convection east of the major convection region. The convective heating released in the major precipitation region also generates Rossby waves. The most trapped Rossby wave (red circulation) becomes coupled to the Kelvin wave in the following way: Air rises in the two off-equatorial lows of the Rossby wave (R-Low) as well as in the equatorial trough in the region of deep convection that generated the Kelvin wave in the first place. The convergence of air in the region of major convection couples the two waves, strengthening the disturbance. Because the eastward movement of the Kelvin wave is slowed by the westward tendency of the Rossby wave due to meridional variation in the Coriolis force, the coupled Rossby-Kelvin wave takes on the approximate eastward speed of the MJO.

Perhaps the most important finding from analyses of the simulations is the role played by friction-induced convergence in the boundary layer, which links surface heat exchange, the motion of free tropospheric waves, and heating due to con-

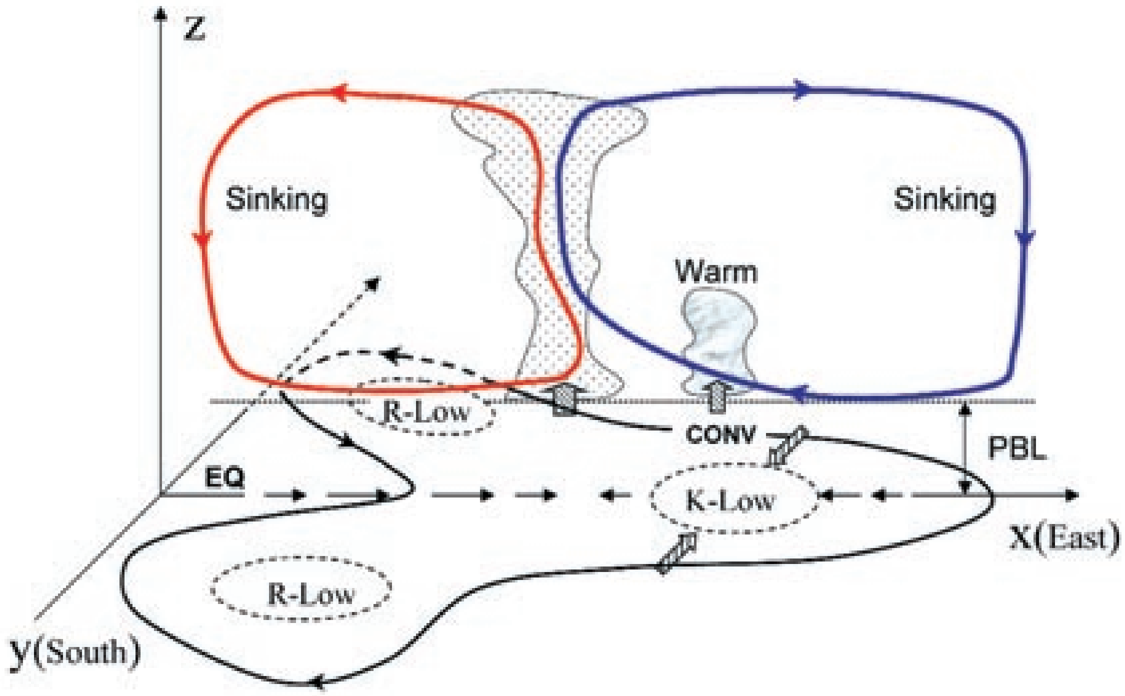

Figure 5. *Schematic structure of frictional moisture feedback thought to occur in the Madden-Julian Oscillation. In the horizontal plane, 'K-low' and 'R-low' represent the low-pressure anomalies associated with the moist equatorial Kelvin and Rossby waves, respectively. Arrows indicate wind directions. In the equatorial vertical plane, the free tropospheric wave circulation is shown. The wave-induced convergence is in phase with the major convection, whereas the frictional moisture convergence in the K-low region precedes the major convection owing mainly to meridional wind convergence.*

densation. What happens is that the returning flow of the eastward moving Kelvin wave warms the region east of the major convection and precipitation region, creating a low-pressure (K-Low) region in the surface layer that results in the convergence of moist air. The moist converging air rises, but condenses before reaching 500 mb. The heat released by condensation now provides energy that is available not only to support the growth of the perturbation, but also to maintain the original perturbation, including the area of deep convection, drawing everything eastward. The eddy available potential energy originating in this convergence is also the reason why the disturbance grows slowly and does not result in a catastrophic conditional instability of the second kind (CISK). Being ahead of the main convective region, the energy for growth of the instability, supplied by evaporative heat flux and the condensational heating associated with the friction-induced moisture convergence, is not converted to kinetic energy for a CISK. Moreover, a portion of the energy is carried away from the convective regions by fast moving, dry Kelvin and Rossby waves, which spread perturbed circulation around the globe, accounting for the planetary circulation scale of the MJO.

The MJO has many time and space scales, and the major drawbacks of the present theoretical model are that its simple representation of diabatic heating cannot deal with the interactions among the scales and that it presumes direct coupling between the MJO disturbance and convection. The current model results suggest that to simulate the MJO realistically, the cumulus parameterization scheme has to let the large-scale low-frequency waves 'feel' the effects of the parameterized convective heating, and it has to have some effect on the parameterized heating either directly (through grid-scale precipitation) or indirectly (through a complete description of the multi-scale interactions). In complex general circulation models, one does not know the correct partitioning between convective and stable precipitation. If all convective heating were consumed by high-frequency disturbances, and if there were no appropriate upward energy transport, how could the model maintain the MJO? Learning how interactions among the various space and time scales and how the up-scale (from meso scale to planetary scale) energy transfer sustains the MJO presents a major challenge, but should shed light on why many current models fail to simulate the MJO.