The role of surface heat fluxes in tropical intraseasonal oscillations

The tropics sustain strong, coherent variations in wind and precipitation on the intraseasonal (30–60 day) timescale. In their active phases, these intraseasonal oscillations are characterized by the slow eastward movement of stronger-than-average precipitation and westerly winds. In northern summer, rainfall and wind anomalies also propagate northward on the intraseasonal timescale over India, southeast and east Asia and the adjacent oceans, pacing the active and break cycles of the monsoons and thus exerting a direct control on the livelihoods of large populations dependent on rain-fed agriculture. We argue that heat fluxes from ocean to atmosphere play a fundamental role in driving the intraseasonal oscillations. We also propose that the current generation of numerical models may enable us to test this and other hypotheses about the dynamics of intraseasonal oscillations more convincingly than has been done in the past.

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In addition to their direct control on local weather, the intraseasonal oscillations (ISOs) have several indirect impacts. They modulate the occurrence of tropical cyclones, not only in the Indian and western Pacific ocean basins but also in the eastern Pacific and Atlantic[1,2], influence weather at extratropical latitudes[3,4] and may also play a role in initiating El Niño events[5]. Prediction of ISOs is thus of great value and has recently begun to be done with some success, using both statistical methods and numerical models[6–8]. Recent intercomparison studies[9,10] show that the state of the art in climate models' ISO simulations has improved significantly compared with a decade earlier, although significant flaws remain.

Understanding of the ISOs, on the other hand, remains disappointingly limited. Many simple models of the most widely studied ISO mode, the eastward-propagating Madden Julian oscillation[11] (MJO), have been constructed in attempts to reveal its fundamental mechanisms[12–14], but there are fundamental differences between them and little agreement on which of them, if any, is correct. The MJO is arguably the most significant mode of atmospheric variability at any subdecadal timescale that remains so unsatisfactorily explained. Why are there coherent modes of variability on the intraseasonal timescale? What is the energy source? Why are they planetary in scale and why does the MJO propagate eastward at around 5 m s^{-1}?

We focus here on the energy source, arguing that evidence, some but not all of it recent, suggests that feedbacks involving turbulent and radiative heat transfer between ocean and atmosphere drive the ISOs.

SURFACE HEAT FLUXES AS THE ENERGY SOURCE OF THE ISOs

The idea that air–sea interaction might provide the energy source for the MJO was first proposed over two decades ago[15,16]. These authors used the quasi-equilibrium framework, which states that cumulus convection, owing its existence to the buoyancy of warm moist air rising from near the surface, acts quickly to eliminate that buoyancy, either by cooling and drying the surface or warming the upper atmosphere, or both[17–19]. Quasi-equilibrium predicts that large-scale disturbances will not develop spontaneously owing to convection alone. However, if a basic-state easterly flow is assumed, quasi-equilibrium predicts that eastward propagating moist Kelvin wave disturbances—modified versions of the dry equatorial Kelvin waves which are fundamental linear modes of a shallow fluid layer on a rotating sphere—will develop owing to another process, namely variations in surface heat fluxes induced by the surface wind variations associated with the disturbance itself. This mechanism was termed wind–evaporation feedback or wind-induced surface heat exchange (WISHE). Disturbances can also develop spontaneously in models of this type (and in more complex models) from the interaction of clouds with electromagnetic radiation[20]. Because of competing effects on the short-wave (solar) and long-wave (terrestrial) parts of the radiation spectrum[21], deep cumulus clouds result in little net loss or gain of energy from the atmosphere to space. Their primary impact is a transfer of energy from ocean to atmosphere, analogously to a surface turbulent flux[22].

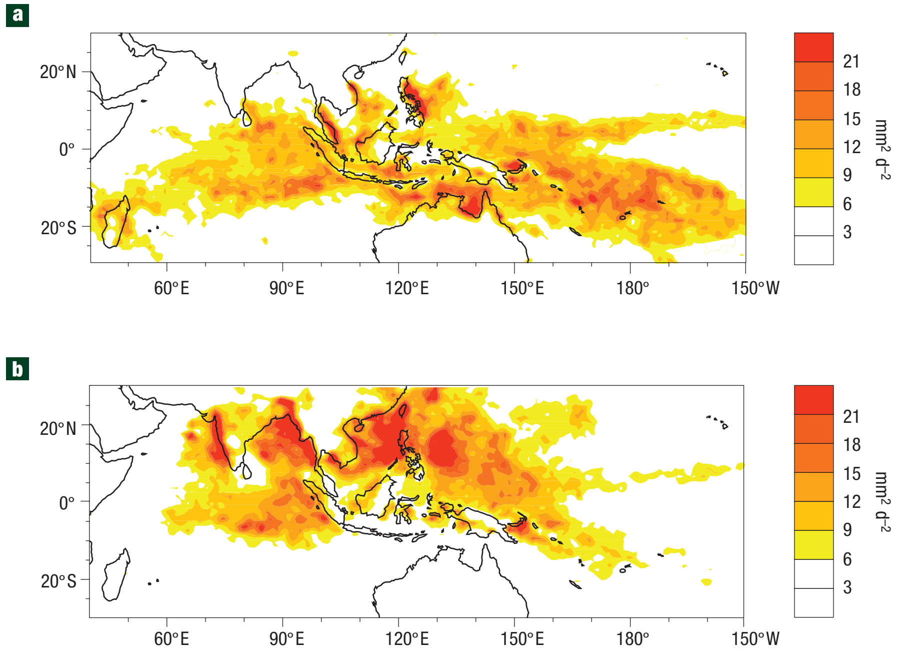

Figure 1 Intraseasonal rainfall variance in the 30–90 day frequency band from the TRMM 3B42 data set (1998–2006). **a**, November–April. **b**, May–October. Bandpass filtering to retain only intraseasonal frequencies was done on daily data using two 60-point non-recursive digital filters with half-power points at 30 and 90 days.

In short, the simplest quasi-equilibrium models predict the emergence of large-scale weather disturbances such as ISOs only when convection interacts with processes, such as turbulent surface fluxes or radiation, that are moist diabatic. A moist diabatic process is one that alters the total entropy (including the component associated with the presence of water substance) of air parcels. This prediction of quasi-equilibrium is in contrast to so-called conditional instability of the second kind (CISK) models[23], which predict the emergence of large-scale disturbances without surface fluxes or radiation. For the MJO, frictional CISK in particular[24,25], in which near-surface circulations driven by surface friction have a crucial role in organizing convection, is a prominent theory that does not involve diabatic processes.

Observations indicate the need for modification of the original WISHE theory in several respects. The MJO is most strongly manifest in regions of mean surface westerlies, and the active phases occur in regions where the total surface wind is westerly[26,27], whereas both mean winds and total surface winds in active phases are easterly in the theory. In addition, spectral analysis[28] shows that the MJO is a distinct phenomenon from the 'convectively coupled Kelvin waves' that the original WISHE theory predicted. Although these observations are at odds with the original WISHE models in detail, they do not disprove the general notion that moist diabatic processes, and specifically radiative and turbulent heat exchange between the ocean and atmosphere, are integral to the ISOs. On the latter issue, the current state of understanding is unclear. We argue here that a substantial and growing body of evidence suggests a fundamental role for air–sea heat transfer in driving the ISOs.

LAND–SEA CONTRASTS IN INTRASEASONAL VARIABILITY

Over the oceans, the ISOs are associated with large variations in net heat flux. The flux from ocean to atmosphere during an active phase is greater than that during a suppressed phase by as much as $100\,\mathrm{W\,m^{-2}}$ or more, of which comparable fractions are radiative and turbulent[29]. These flux anomalies are temporally well correlated with precipitation anomalies in those oceanic regions where ISO convective variance is large[30], and at any given time within those regions the total surface flux is spatially correlated with precipitation. As disturbances propagate eastward or northward, the peak surface flux tends to lag the peak precipitation slightly, indicating that the fluxes are not responsible for the disturbances' propagation even though they may well be essential to their existence.

Over land, the total net heat flux, and thus also its intraseasonal anomalies, are constrained to be small owing to the small effective heat capacity of the land surface. If net surface heat flux variations were important in driving intraseasonal variability in deep convection, the latter variability would be expected to be smaller over land than ocean. This is indeed the case, as shown in Fig. 1, produced using the Tropical Rainfall Measuring Mission (TRMM) 3B42 (ref. 31) data set from 1998 to 2006. Qualitatively similar results are found from other data sets with longer records (not shown), both for precipitation and related quantities such as top-of-atmosphere outgoing long-wave radiation, which is related to high cloudiness[32–34].

Climatological mean precipitation, although having similar large-scale structure to that of the variance, does not show the same land–sea contrasts on small scales (Fig. 2). This is so particularly in Southern Hemisphere summer, when climatological rainfall tends to maximize over the large Indonesian islands[35]. That the magnitude of the intraseasonal variability is not a simple function of the mean suggests that different mechanisms control the two. Orography presumably does influence both, as demonstrated by the tendency of both mean and variance to maximize just to the west (and thus upstream, in westerly monsoon flow) of coastal mountain ranges, especially in northern summer[36]. Nonetheless, we argue that differential surface heat capacity provides a more general explanation than orographic effects for the land–sea contrast in intraseasonal precipitation variance.

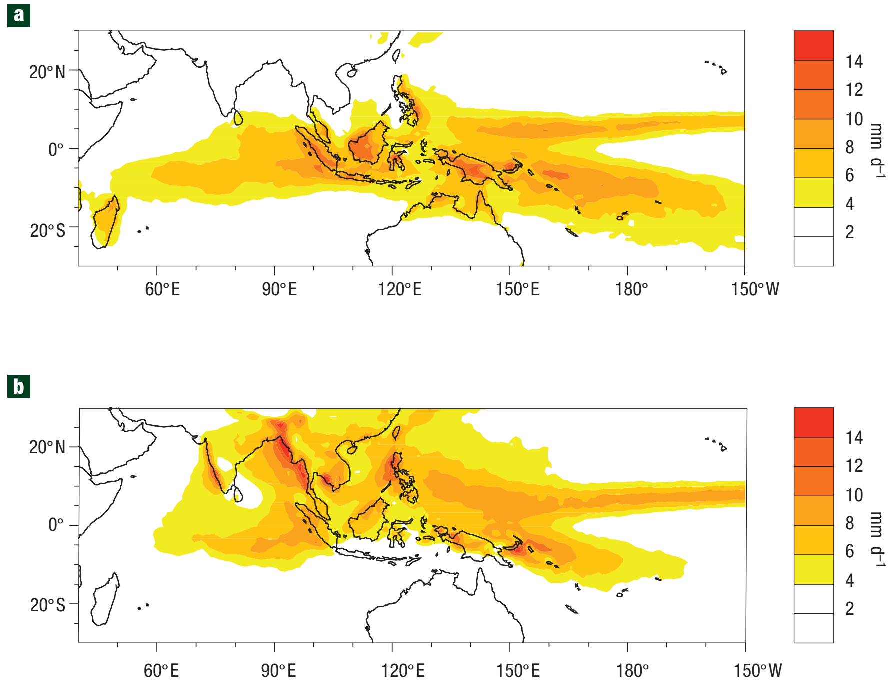

Figure 2 Climatological mean rainfall from the TRMM 3B42 data set (1998–2006). **a**, November–April. **b**, May–October.

Given the large spatial scales of the ISOs as usually defined, the relatively small-scale structures in the variance maps require some interpretation. Other observations have been interpreted to suggest that intraseasonal variations in convection at a point can be thought of as resulting from a local recharge–discharge oscillation[33,37,38]; energy accumulates in the ocean mixed layer and lower troposphere while convection is suppressed, and is then vented to higher altitudes and surrounding regions when convection is active. A simple single-column model based on an implementation of quasi-equilibrium (ref. 39) and parameterized large-scale atmospheric dynamics captures this behaviour[22]. This model generates spontaneous intraseasonal oscillations if air–sea flux feedbacks are sufficiently strong. For weaker feedbacks, oscillations do not occur spontaneously, but forcing on intraseasonal timescales is effective in generating a response. We can think of the large-scale, propagating ISO as providing external forcing, and the single-column dynamics, dependent on the surface properties, as determining the amplitude of the local convective response. Whether free or forced, insufficient surface heat capacity (less than that of a few metres of water) prevents the model from sustaining significant intraseasonal variability, implying a prediction of small intraseasonal variance in convection over land, as observed.

Although convection at a point responds to forcing from the large-scale ISO, the aggregate response of convection over large horizontal areas must sustain the ISO, as the associated convective heating drives the large-scale flow perturbations. Thus, the mechanisms responsible for small-scale variance structure are presumably also relevant to the dynamics of the large-scale ISO itself.

USING MODELS TO TEST MECHANISMS

In numerical models, an individual physical process can be modified or eliminated, enabling direct assessment of the role of that process in the model. Turbulent and radiative fluxes are computed by parameterizations contained in distinct portions of model code. By replacing the turbulent or radiative fluxes obtained from these parameterizations by specified values that do not depend on the model state (ideally, defined instead by annually and spatially varying climatologies computed from long control model integrations), the dynamical feedbacks involving those fluxes are disabled. The same feedbacks can also be disabled by eliminating the heat capacity of the ocean surface, rendering it a 'swamp'. Comparing the ISO in a model with surface flux feedbacks removed with that in the control version of the same model gives a direct estimate of the role of those feedbacks in generating the control model's ISO (ref. 16).

Calculations testing the role of surface turbulent flux feedbacks and radiative feedbacks in this manner have been carried out with a number of models, yielding mixed results. As model simulations of ISOs improve, however, such calculations become more compelling as guides to our understanding of the observed ISOs. In one recent study using a model in which the MJO simulation was state-of-the-art (although still flawed in some respects), the simulated MJO was strongly weakened when surface flux feedbacks were disabled[40]. Similar results (not shown) have been obtained with a recent version of the National Oceanic and Atmospheric Administration Geophysical Fluid Dynamics Laboratory climate model. WISHE has also been shown to be important in an intermediate complexity model, where it acted synergistically with excitation by extratropical storms to generate an ISO (ref. 41).

Although suggestive, results from a small number of models are not entirely convincing. A more comprehensive set of calculations of this sort with a much larger number of models might enable a real step forward in our understanding of ISO dynamics, particularly if similar results are obtained from a large subset of the models, or from the subset in which ISOs most resemble the observed ones. Tests of this kind would be particularly interesting if conducted with recently developed global cloud-resolving models[42] and the multiscale modelling framework[43,44], both of which show exciting promise in the simulation of the ISOs. Surface turbulent momentum fluxes can also be evaluated in the same way as heat fluxes, enabling a direct test of the frictional CISK hypothesis[24,25]. It is of course possible that the ISOs result from a combination of surface fluxes and moist adiabatic mechanisms such as frictional CISK, rather than one by itself.

In the case of the northward-propagating northern summer ISO (ref. 45), general circulation models have been used even less (compared with the MJO) to assess the role of distinct physical processes. In at least one model of intermediate complexity that gives a robust simulation of the northward-propagating ISO, surface flux feedbacks, specifically WISHE, are demonstrably important to the linear instability that produces the mode[46,47]. The northward propagation seems to be controlled by large-scale dynamics[46–48].

OCEAN COUPLING

In addition to influencing the atmosphere, intraseasonal surface heat flux perturbations also induce sea surface temperature anomalies. To the extent that these anomalies then influence the atmosphere, the ISOs are coupled ocean–atmosphere modes. A number of studies have investigated this possibility, as summarized in recent reviews[12–14]. Most (but not all) of these studies are consistent with the view that ocean coupling provides a modest amplification to the ISOs, and slows their propagation[49,50]. The coupling question merits further study, but is secondary to that of the role of surface fluxes. If ocean coupling is important, surface fluxes must also be, because it is only through surface fluxes that the ocean can influence the atmosphere. The converse is not true; surface fluxes can be important while ocean coupling is not, because surface fluxes can vary strongly even if sea surface temperature remains constant. Thus, the role of fluxes is the more fundamental issue.

A PATH TOWARDS SOLVING THE ISO PROBLEM

We have argued that available evidence suggests an important, perhaps fundamental role for atmosphere–ocean heat fluxes, both turbulent and radiative, in driving the ISOs. If this were to be proved correct, it would still not constitute a theory for the ISOs, as the oscillations' scales and structure would still remain to be explained. We would, however, be able to rule out the subset of existing theories in which only moist adiabatic dynamics are involved. Conversely, if surface heat fluxes were to be proved unimportant to the ISOs, we could focus our attention on moist adiabatic theories. Either situation would represent an improvement over the current state of confusion. The division into diabatic and adiabatic mechanisms is justified by analogy to extratropical atmospheric dynamics, where dry adiabatic models of geophysical fluid dynamics have been very successful. The land–sea contrast in intraseasonal precipitation and outgoing long-wave radiation variance also suggests this division, because it would be consistent with an important role for atmosphere–ocean heat exchange.

Numerical models have now improved in their simulations of the ISOs to the point that they may, collectively, enable a more convincing test of specific mechanisms, such as those involving surface fluxes. Reaching a conclusive outcome, if possible at all, requires the execution of simulations designed specifically for this purpose with a large number of models. Carrying out the necessary simulations is straightforward, but can require significant effort, depending on the details of the model code and the user's facility with it. We hope our arguments help to convince modellers that this effort is worthwhile.

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