CHAPTER 6

CONCLUSIONS

"Like most poets, preachers, and metaphysicians, he burst into conclusions at a spark of evidence."

— Henry Seidel Canby on Ralph Waldo Emerson

6.1 Summary

The boreal summer ISO and its impact on and relationship to the South Asian monsoon is the focus of this dissertation. Even though the ISO is typically strongest during the boreal winter and spring seasons (Madden 1986; Hendon and Salby 1994), the boreal summer ISO is found to be a central component of the South Asian monsoon system. The importance of the ISO in determining the large-scale active and break phases over India has long been known (e.g., Yasunari 1979; Singh and Kripalani 1985) and is confirmed here. The ISO is found to be important to understanding South Asian monsoon rainfall in at least two other ways as well: interannual variations of ISO activity are inversely related to the seasonal monsoon strength and the ISO modulates westward propagating synoptic-scale waves.

6.2 Structure and Evolution of the ISO

A wavenumber-frequency spectral analysis of OLR revealed that the northward propagation of convection that is associated with the ISO is accompanied by a concomitant eastward propagation, both along the equator and along Indian subcontinent latitudes. The northward and eastward propagation can be explained by the eastward progression of a northwestward oriented band of convection across the Indian Ocean basin. The equatorial convection, and the associated divergence source, excites a Rossby cell response to the west of the equatorial convection in both the northern and southern hemispheres. The analysis presented here suggests that frictional surface convergence into the low pressure center of the Rossby cell, coupled with the presence of a very moist boundary layer maintained by underlying warm SSTs and advection of moist air by the low-level southwesterly monsoon flow, induces deep off-equatorial convection (see Figs. 3.9 and 3.11).

The northwestward oriented band of convection and its eastward progression is reproduced by a number of methods: by regression with both wavenumber-frequency filtered and anomalous OLR, and by compositing temporally filtered OLR. The wind structure associated with the northwestward oriented band of convection is difficult to interpret due to the complicated heating pattern. The surface frictional convergence leading the off-equatorial convection appears clearly in the analyses when heavily filtered bandpass wind fields are used. However, due to the noisy nature of divergence fields the convergence signal is less clear when the wind fields are not pre-filtered.

The boreal summer ISO exhibits two somewhat different evolutions, or modes, which may be relevant to active and break period forecasting. Both modes exhibit the characteristics of convection coupled to a Kelvin-Rossby wave packet that moves steadily eastward, but the two modes differ in how the convection in the central Indian Ocean develops prior to the mature development of the Kelvin-Rossby wave packet. The SN mode exhibits an initially stationary development of equatorial convection while the EN mode always exhibits eastward propagation of convection anomalies. This study proposes that a potential factor determining the two forms of evolution of convection is the different underlying base states. SN events are more commonly encountered during the beginning of the monsoon season when the SSTs across the equatorial Indian Ocean are at a maximum, whereas EN events typically occur later in the season after the SSTs have cooled somewhat.

6.3 Interannual Variations of the Intraseasonal Oscillation

Two measures that capture the interannual variability of summertime ISO activity over India are developed. The first measure uses the two leading intraseasonal EOF modes that together describe the boreal summer ISO. The second measure extracts the ISO by wavenumber-frequency filtering to the 25–80-day, eastward wavenumber 1–6 band in which ISO spectral power is found to be concentrated. Interannual fluctuations in ISO activity are found to be related to year-to-year changes in the number of active and break periods rather than shifts in the characteristic ISO period. Seasons of high ISO activity, which contain more well-defined active and break periods than seasons of low ISO activity, exhibit significantly more low or ”break” rainfall days than seasons devoid of ISO activity, particularly over land. A somewhat tangential result, which requires further investigation, is that interannual fluctuations in convection over India appear to be uncorrelated to interannual fluctuations of convection over the Bay of Bengal. It is possible that the absence of an increase in low rainfall days during seasons of high ISO activity over the Bay of Bengal may be a factor. Interannual fluctuations of ISO activity do not exhibit a strong relationship with interannual variations in rainfall over the oceans but do exhibit an inverse relationship with interannual variations of rainfall over land (see Fig. 4.20).

The relationship between ENSO and the South Asian monsoon is well documented and reasonably robust (e.g., Webster and Yang 1992) with warm ENSO years typically related to weak monsoon years and vice versa. The similarly inverse relationship between ISO activity and monsoon strength points to a possible relationship between the phase of ENSO and summertime ISO activity. However, correlations between summertime ISO activity and ENSO or any other global SST anomalies are low. The lack of any clear relationship between ISO activity and global SST anomalies (see also Slingo *et al.* 1999; Hendon *et al.* 1999) implies that interannual variations of ISO activity are either internally generated or are related to interannual changes in land surface boundary conditions. Hendon (1999) argues that a weak Australian monsoon may enhance wintertime ISO activity by shifting the mean convection distribution closer to the equator which presumably is a more favorable condition for ISO formation (e.g., Wang and Li 1994; Salby *et al.* 1994). This hypothesis may hold true during northern summer with a weak continental Indian monsoon permitting stronger ISO activity. But, the deepest off-equatorial monsoon convection during summer is located over the Bay of Bengal (see Fig. 1.3) where interannual changes in OLR are relatively unresponsive to interannual shifts in ISO activity (see Fig. 4.20). Therefore, it would appear that some strong summertime ISO activity seasons are also marked by off-equatorial convection that theoretically would inhibit ISO activity. This conflicting evidence suggests that the interannual variations of ISO activity may *not* be forced by the strength of the monsoon. This result may be of significance in terms of forecasting potential of seasonal monsoon rainfall (see Section 6.5 for further discussion).

6.4 Modulation of Synoptic-Scale Waves

The canonical intraseasonal sequence of events described in Section 5.5 summarizes the primary results regarding modulation of synoptic-scale waves. The ISO modulates the westward propagating synoptic-scale waves, such as monsoon depressions, that are the source of a sizeable fraction of the total monsoon rainfall. The modulation affects the South Asian monsoon region in two ways. During the active ISO phase over India, the ISO acts as an envelope of westward propagating synoptic-scale wave disturbances which is a result that has been observed before (Murakami 1984; Krishnamurti *et al.* 1985) and was reproduced in modeling studies (Lau and Peng 1990). During the suppressed ISO phase (i.e., during a break period over India) the active ISO convection is located over the western Pacific. The ISO convection excites synoptic-scale waves in that area. These disturbances can subsequently propagate westward across Southeast Asia, generating heavy precipitation during an otherwise dry period.

The modulation of westward propagating disturbances by the active phase of the ISO deserves some more attention in relation to the theory of Lau and Peng (1990) that was introduced in Section 5.1. Lau and Peng found, via a linear stability analysis of quasi-geostrophic motion, that the interaction between the large scale monsoon flow, specifically the mean easterly vertical wind shear and the latent heating associated with the equatorial passing of the ISO convection, induces unstable westward propagating baroclinic disturbances. The results presented here corroborate Lau and Peng's model results. Lau and Peng go on to hypothesize that the excitement of the westward propagating disturbances drives the rapid northward shift in mean convection, since, when the disturbances are viewed in a time-averaged sense, they depict a northward shift of the ITCZ. However, in Section 3.3 it was shown that the northward movement of ISO convection appears to be the result of large-scale frictional moisture convergence into the off-equatorial Rossby cells that flank the equatorial ISO convection. Wang and Rui (1990) observed that a single northward propagating event is composed of a number of tropical storms, monsoon depressions, and other synoptic-scale disturbances, each one contributing to the overall movement and character of the oscillation but not fully determining either the movement or strength. Therefore, it seems likely that the two mechanisms, excitement of synoptic-scale disturbances and large-scale frictional moisture convergence, work in concert to govern the evolution of any individual northward propagating event.

The timescale of the northern summer ISO appears to be shorter at around 35 days compared to the timescale of the ISO during northern winter which is centered at about 45–50 days (Hartmann *et al.* 1992). In an effort to explain the different ISO periods between summer and winter, Wang and Xie (1997) proposed a theory, supported by model results, that says that as ISO convection dissipates near the dateline and the Kelvin-Rossby wave packet decouples from the convection, Rossby waves emanate from the region and propagate westward towards the Indian subcontinent. According to Wang and Xie's theory, when the Rossby waves reach the Indian monsoon region, they amplify and excite convection at the equator yielding a new ISO and effectively generating a 30–35 day period. Such a sequence does not occur during winter because the lack of an easterly vertical wind shear does not support the amplification of the westward propagating Rossby waves. It is somewhat unclear whether or not the results shown here support this theory. Westward propagating disturbances, excited by the ISO in the western Pacific, *do* propagate onto the Indian subcontinent. However, this sequence does not occur during every ISO and is not clearly linked to the initiation of a new ISO at the equator. In addition, the synoptic-scale disturbances appear to be initiated by the interaction between equatorial convection and the easterly vertical wind shear associated with the ISO and not by decoupling of the Kelvin-Rossby wave packet from the convection as it dissipates at the dateline. Nevertheless, possible links between this study and the modeling results of Wang and Xie should be explored further.

6.5 Implications for Prediction

A fundamental implication of this study is that in order for accurate simulations or forecasts of the South Asian monsoon to be made, models must accurately portray the summertime ISO. This requirement is clearly important for skillful medium-range forecasting of active and break periods of rainfall.

The long timescale of the ISO suggests that skillful forecasts should theoretically be possible beyond the 7 days traditionally considered to be the maximum range for dynamical forecasts. Chen and Alpert (1990) demonstrated that when the ISO amplitude is large, NCEP model forecast skill of ISO propagation and amplitude were quite good out to about 10 days. Hendon *et al.* (1999) showed that the NCEP Medium Range Forecast model was unable to sustain the convectively coupled tropical circulation anomalies associated with the ISO beyond about 5 days. Forecast skill was found, consequently, to be better when the ISO was inactive rather than active.

Cadet and Daniel (1988) attempted to exploit the long timescale to make long-range empirical predictions of active and break periods but were met with limited success. Recently, Waliser *et al.* (1999) and Lo and Hendon (1999) have attempted to apply empirical techniques to extend the useful forecast range. The statistical schemes are based on band pass filtered data and the principal components of leading EOFs, respectively, and both exhibit skill out to about 15 days. The summertime forecasts for the Waliser *et al.* (1999) scheme exhibited skill across the northern Indian Ocean and Indian subcontinent as well as in the western Pacific. The Lo and Hendon (1999) scheme was not applied to the summer season, although in theory it should work similarly, assuming you choose the appropriate EOFs such as those described in Section 4.2.

If either dynamic or empirical forecast models improve to the point that the ISO, and the seasonality of the ISO, are well simulated, the inclusion of information in an empirical model or the accurate representation in a dynamical model of the two distinct summertime ISO evolutions could serve to modestly enhance the forecast skill by more accurately pinpointing the timing of active or break period initiation.

The relatively strong relationship between seasonal ISO activity and South Asian monsoon behavior has potentially important ramifications for prediction of seasonal monsoon strength. It would appear that long-range forecast models would require the ability to reasonably simulate not only ENSO but also the interannual variations of ISO activity to accurately predict summer monsoon strength. Presumably, models that do not support realistic ISO activity will exhibit less skill predicting weak monsoons because that is when ISO activity is typically heightened. To this point, though, most GCMs either do not reasonably sustain ISOs or they underestimate its strength (Slingo *et al.* 1996). Furthermore, as was shown in this study, the source of the interannual variations of ISO activity remains unclear, although it appears to be unrelated to any global SST anomalies. The fact that summertime ISO activity is sometimes enhanced during seasons when Bay of Bengal convection, i.e. off-equatorial convection, is normal or above normal suggests that the ISO activity is not dependent on the state of the monsoon but rather plays an active role in determining seasonal monsoon strength. Since no known surface tropical boundary conditions, at least contemporaneous boundary conditions, exhibit a significant relationship with ISO activity, it would seem that the interannual variations of ISO activity may be mainly chaotic and hence largely unpredictable. However, the summertime ISO activity indices exhibit significant biennial variability which suggests that interannual variations of ISO activity may not be not chaotic and that the tropospheric biennial oscillation may somehow be involved although it is not clear in what manner.

6.6 Future Work

A number of the results discussed in this study could be investigated further with models. Of particular interest is the hypothesis that the boundary layer frictional convergence into the low pressure center of an off-equatorial Rossby cell is responsible for the northwestward oriented band of convection. Wang and Xie's intermediate model, which faithfully produces summertime ISOs that resemble those observed, contains only basic equatorial wave dynamics interacting with tropical boundary layer processes and parameterized convective heating. This type of intermediate model would be a powerful tool for investigating the fundamental processes that govern the summertime ISO evolution.

Another interesting topic of future investigation is the influence of interannual variability of synoptic-scale wave activity. The number of depressions per season exhibits significant interannual variability which may be tied to ENSO (Chang and Weng 1999). As was shown in Chapter 5, the ISO modulates the formation of monsoon depressions and their westward-propagating predecessors. Furthermore, the ISO exhibits significant interannual variability in its strength. This raises a number of interesting questions. Do seasons of weak ISO activity exhibit fewer monsoon depressions and vice versa? If so, assuming that more monsoon depressions corresponds to enhanced rainfall, how does this relate to the results shown here that ISO activity is inversely proportional to monsoon rainfall?

The source of the interannual variations of ISO activity remains unknown and warrants further investigation, especially considering the potential implications for seasonal monsoon prediction. The biennial nature of the ISO activity indices suggests that an examination of the relationship between the ISO and the TBO could be fruitful. This could be related to the much larger research topic of scale interaction.

6.6.1 JASMINE The composite results of Section 3.4.2 show an interesting oscillation in Indian Ocean SST that is related to the ISO. These results suggest that the ISO may be a coupled ocean-atmosphere mode of variability. Furthermore, a recent study by (Webster *et al.* 1999) indicates that the Indian Ocean may contain its own form of coupled ocean-atmosphere modes of interannual variability. A recent modeling study on the heat balance of the Indian Ocean revealed significant fluctuations in meridional heat transport on ISO-timescales (Loschnigg and Webster 1999). In addition, Wu *et al.* (1999) show that the timing of the first northward propagating ISO is an important factor determining the monsoon onset.

These observations, among others, led to the Joint Air-Sea Monsoon INteraction Experiment (JASMINE) that took place from April 8 to June 7, 1999 in the Bay of Bengal on board the NOAA Ship the Ronald H. Brown. A primary goal of the field experiment is to investigate the basic physics that underpins the 30–40-day variability of the monsoon with an emphasis on the coupled variability.

A time-latitude section of OLR retrieved from the stationary Meteosat-5 satellite during the JASMINE period is shown in Fig. 6.1. The black line shows the ship's latitude over the course of the experiment. Two intensive observing periods were completed, the first during a dry and calm period and the latter during a very wet and disturbed period. A northward propagating envelope of convection is apparent which coincided with the onset of the monsoon and resembles the northward propagating modes described in this study. Another interesting feature seen in Fig. 6.1 is the modulation of the diurnal cycle by the northward propagating system with rapid southward propagating storms occurring daily throughout the active period.

The fortuitous weather patterns during the field experiment permitted intense observations of atmospheric and oceanic conditions during both the suppressed and enhanced convective phases of what appears to be an ISO. Consequently, the JASMINE dataset should provide an excellent opportunity to investigate the complex coupled atmosphere-ocean physical processes associated with what appears to be a well-defined ISO cycle.

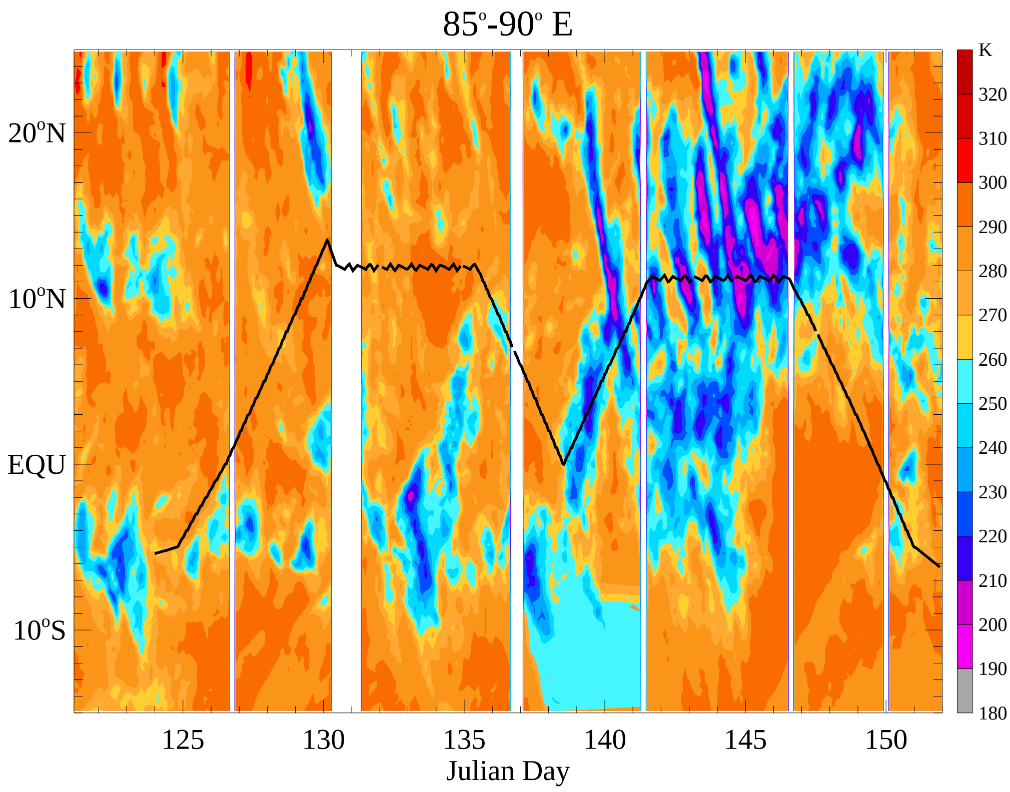

Figure 6.1. Time-latitude section of Meteosat-5 brightness temperature along 85°–90°E during JASMINE. The Ronald H. Brown ship track is superimposed with a solid black line.

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