# CHAPTER 10: THE IMPACTS OF SOUTHEAST ASIAN DEFORESTATION: (II) LARGE-SCALE CIRCULATION CHANGES

## 10.1: Introduction

In the preceding chapter, the modelled impact of Southeast Asian deforestation on local physical processes was considered. Evidence was presented not only of local climate change, but also of impacts at the regional scale. The main emphasis in this chapter is on the influence of Southeast Asian deforestation on the larger-scale climate system. The sensitivity of the large-scale climate, and the potential for the Southeast Asian deforestation to generate influences outside the deforested region, will be explored.

As has been shown, unexpected effects, such as an increase in cloud, precipitation and even evaporation in January over the study area despite the reduction in the net radiative energy over the land surface and open sea, are all indicators that there are likely external influences onto the deforested region. Such effects are not directly caused by the local land-surface changes, but represent an indirect response to events outside of the deforested region. By conservation of mass, the changes in fluxes within the atmospheric column in the deforested region could influence the regional and global circulation. In return, large-scale feedback might occur from the regional and global circulations which could influence the climatic changes in the deforested region. In the context of Southeast Asian deforestation, the question is whether the influence from the regional and global circulation changes is strong enough to dominate local processes which are more directly related to the land surface changes.

This chapter is also structured to investigate the hypothesised climatic impacts given in the earlier analysis reported in Chapter 5. The three region deforestation approach that provides these hypotheses differs from the current ensemble approach with its single region deforestation. Nevertheless, the hypotheses derived are still valid to serve as a guide in the current investigation so that the results obtained from the new approach can be systematically analysed in order to understand better the role of deforestation in altering the character of the atmospheric circulation.

## 10.2: Remote Impacts Caused by Southeast Asian Deforestation

### *10.2.1: The Walker and Hadley circulation changes*

One likely outcome of tropical deforestation is a reduction in vertical ascent over the deforested region caused by the following linked processes: first, an imposed increase in surface albedo leads to the net loss of energy to the column; second, a decrease in net surface radiation is prompted by higher surface temperatures caused by smaller turbulent exchanges; and finally, a reduction in evaporation results from the imposed decreases in canopy extent and vegetation roughness length. This, in turn, might affect the components of either the Walker or the Hadley circulations through changes in vertical motion.

The above mentioned possibility is first assessed by considering the changes in the vertical velocity (Pa $s^{-1}$) over the deforested regions. For both January and July, latitudinal cross-sections are used to capture the cells of the Walker circulation in both winter and summer respectively by taking meridional averages of vertical velocity from 15$^{o}$S to 15$^{o}$N, composited from the 10-case ensemble. In addition, composite longitudinal cross-sections are also used to depict the latitudinal movement of the ITCZ or monsoon trough in the Southeast Asian deforested region, corresponding to the Hadley circulation, by taking zonal averages of the vertical velocity from 90$^{o}$E to 150$^{o}$E.

#### *a. The Walker circulation changes*

The control ensembles (Figures 10.1a and 10.2a) show the cells of the Walker circulation very clearly in both months, but with different positions and intensity. In both seasons there is large-scale ascent over the Amazon Basin (~50$^{o}$W), over the western Pacific (~140$^{o}$E-180$^{o}$E) and central Indian Ocean (~60$^{o}$E). Additionally, two ascending limbs appear in January

(Figure 10.1a). One appears over tropical Africa (~25$^o$E) and another one over eastern or maritime Southeast Asia (~120$^o$E-140$^o$E). There is a distinct descending limb covering continental Southeast Asia (~90$^o$E-120$^o$E) in January. The July cross-section does not show a distinct ascending limb over eastern or maritime Southeast Asia. Rather, there is a wide ascending area in July extending from the western Pacific to the central Indian Ocean, with two relatively stronger ascending flanks over the western Pacific and the central Indian Ocean. The ascending limb over tropical Africa does not appear in the July cross-section (Figure 10.2a). The two ascents over the Amazon and over the western Pacific are significantly weaker in July than in January because the ITCZ's position during this time of the year is not within the area captured by the meridional area-average.

The effects of deforestation can be assessed by direct comparison of the vertical velocity range between the control and deforestation experiment. In January, the ascent over the western Pacific is somewhat diminished, but the ascent over the eastern or maritime Southeast Asia is strengthened. At the same time, the descending limb covering continental Southeast Asia is diminished following deforestation. Interestingly, the opposite sign of change occurs in January between Southeast Asia and western Pacific Ocean following deforestation. Although the ascent over the entire Southeast Asia is weakened in July, the ascent over the western Pacific does not change following deforestation.

Difference plots (Figures 10.1c and 10.2c) are not necessarily straightforward to interpret as the sign of the differences depends upon the signs of the vertical velocities in the control and deforestation experiments. Nevertheless, the plots can be used as a useful pointer to the regions of largest change. In January, as depicted by the difference plot (Figure 10.1c), the largest changes (in both signs) appear over a region extending from the central Indian Ocean to the eastern/maritime Southeast Asia and the western Pacific. This indicates clearly the extent of the changes in the circulation during the winter period following deforestation. Though very weak changes in vertical velocity still occur in other parts of the globe, it seems that these changes are within the normal variability range (including changes over other tropical forest regions such as the Amazon Basin and tropical Africa where deforestation is not imposed in the perturbed simulations). On comparison between the January and July difference plot, it is clear that the effect of deforestation on the vertical velocity is greater in January than in July; the ascent is stronger in the January control climate.

From the control, deforestation and difference plots, the important points obtained from the analysis can be summarised as follows.

(i) The local circulation in the region of Southeast Asia and western Pacific in January as simulated by the current control ensemble appears to be more realistic than the previous simulation by the NCAR Community Climate Model (CCM1-Oz) as presented in Chapter 5. The current control ensemble seems to capture another "sub-Walker circulation" between maritime Southeast Asia and continental Southeast Asia. This suggests the existence of smaller-scale circulations in the region through which continental Southeast Asia is associated with subsidence or a descending limb and maritime Southeast Asia is associated with ascent. This behaviour corresponds with the land-sea contrast during this winter season, when the landmass as well as low-level atmosphere is much colder than maritime Southeast Asia surrounded by the ocean. The use of higher resolution in the current model as well as the ensemble approach are the most likely reasons for the ability to capture this smaller scale circulation.

(ii) In January, the major impact of deforestation on the Walker circulation as suggested by this model experiment is essentially to change the structure of the cell over the region covering the western Pacific Ocean and Southeast Asia. While ascent is increased over maritime Southeast Asia, the ascent over the western Pacific and the descent over continental Southeast Asia are both decreased. Consequently, the peak ascent over the western Pacific which dominates before deforestation shifts over to the maritime Southeast Asia region after deforestation. At the same time, the descent over continental Southeast Asia is diminished. All those changes would modify the larger-scale Walker circulation in the region, as well as the smaller scale circulation over Southeast Asia mentioned above. Deforestation, therefore, perturbs the winter monsoon system in the region by: (a) increasing ascent strength over maritime Southeast Asia; (b) decreasing descent strength over continental Southeast Asia; and (c) decreasing ascent strength over the western Pacific. The combined effect of (a) and (b) causes the strengthening of winter monsoon over the whole of Southeast Asia.

(iii) In July, on the other hand, the major impact of deforestation on the Walker circulation is the strengthening of the ascent over a broad area from the central Indian Ocean to continental Southeast Asia. Deforestation, therefore, perturbs the summer monsoon system in those regions by increasing ascent over the Indian Ocean, the Bay of Bengal, the Indian subcontinent and continental Southeast Asia. The summer monsoon over this region is strengthened following deforestation. The slight decrease in ascent over maritime Southeast Asia in July is most likely due to the influence of the local land-surface changes following deforestation, resulting from a more dominant land-atmosphere interaction during summer over the land area in the region. This agrees with results reported in the preceding chapter; the July surface hydrological change on land indicates a decrease in evaporation and precipitation (cf. Table 9.2) as well as the amount of cloud over land (cf. Table 9.3).

### *b. The Hadley circulation changes*

Figure 10.3 depicts the Hadley circulation in January as captured by a cross-section defined by a meridional average of vertical velocity from 90$^o$E to 150$^o$E (to cover the deforested region). From the control ensemble (Figure 10.3a), there is an ascending limb associated with the ITCZ at 10$^o$S. After deforestation, the upwelling in the ITCZ in January (Figure 10.3b) is strengthened and at the same time the two descending limbs in both subtropical regions are strengthened somewhat. The increasing strength of the descending limbs over the subtropics can be seen clearly from the difference plot (Figure 10.3c). All the above changes show that the strength of the Hadley circulations in both hemispheres is increased following deforestation.

In July, the Hadley circulation characteristics are illustrated in Figure 10.4. From the control results (Figure 10.4a), we can see an ascending limb associated with the summer monsoon trough at about 15$^o$N. Following deforestation, in July, there is an increase in the strength of the upwelling as well as a slightly southward shift of the upwelling limb centre (Figure 10.4b). Consequently, just to the north of the equator (~5$^o$N), at the edge of the main upwelling limb, the strength of the upward vertical velocity is increased. All those changes can be interpreted as a southward shift in the summer monsoon and, at the same time, a strengthening of the monsoon. Overall, the strength of the Southern Hemisphere Hadley cell is increased following deforestation as the descending limb in the Southern Hemisphere subtropics (~30$^{o}$S) is also strengthened. These changes are clearly seen in the difference plot (Figure 10.4c). The zonal average vertical velocity (over 90$^{o}$E to 150$^{o}$E), however, does not capture the Northern Hemisphere Hadley cell in July. The mean climatological position of this cell is located outside the averaging area. In fact, the mean climatological position of the summer monsoon trough is not fully captured within the averaging area as the major part of the trough is located to the west near the Bay of Bengal and northern Indian subcontinent.

In both January and July, effects of deforestation extend outside the deforested region. The plots (Figures 10.3 and 10.4) illustrate, though, that the effects do not extend outside about 30$^{o}$N to 30$^{o}$S, i.e. they are limited to the subtropical region. The three region deforestation experiments analysed in Chapter 5, indicated some effects extending outside the subtropical region.

### *10.2.2: Southeast Asian-scale circulation changes*

#### *10.2.2.1: Mean sea level pressure and surface vertical velocity*

The changes in the mean sea level pressure (MSLP) field are first examined to give some idea of how the Southeast Asia-scale monsoon circulations respond to deforestation. Because the changes in MSLP are small compared to year-to-year variability, no changes are locally significant. Nevertheless, coupled with other parameters, the changes do provide meaningful signals and good indicators of the atmospheric circulation perturbation.

In January (Figure 10.5a), in terms of the common synoptic systems, four notable changes in MSLP occur: -

i. Over the west Pacific Ocean east of Philippines, where the increase in MSLP could be associated with intensification of the sub-tropical ridge over this region;

ii. Over the northwest Pacific southeast of Japan, when the reduction in MSLP could be linked with the intensification of the cyclogenesis or frontal systems in that area or an increase in the frequency of the quasi-stationary mid-latitude trough here;

iii. Over a wide area from the east Indian Ocean south of Indonesia to the western Pacific, where the MSLP reduction could be associated with intensification of the monsoon trough and the well-known ITCZ; and

iv. Over the Asian continent, the increase in the MSLP due to a colder land-mass during this winter month may cause a stronger winter monsoon over Southeast Asia region.

In July (Figure 10.5b), there are also regions where common synoptic systems are affected: -

i. The decrease in the MSLP over the Indian subcontinent and Bay of Bengal during this month could be related to intensification of the summer monsoon trough.

ii. The increase in MSLP from the Philippines extending northeastward over the Pacific past the dateline and northward over Japan which could be associated with intensification of the sub-tropical high over this area.

iii. Over the Pacific to the east of Japan, MSLP is reduced and this could be related to a more intense/more frequent quasi-stationary mid-latitude trough.

Differences in the surface vertical velocity field between the deforested and the control are now examined to see how the changes are related to the Southeast Asia-scale monsoon circulations and how they correspond to the changes in the MSLP discussed above. Figures 10.6 and 10.7 illustrate the differences in vertical velocity near the surface for January and July, respectively. The surface characteristics of the regional circulation of the atmosphere over this region are simulated satisfactorily by the control ensemble results (Figures 10.6a and 10.7a). The potential areas of ascent and descent are correctly captured in both seasons.

During the winter monsoon in January, some obvious vertical velocity changes near the surface, which are statistically significant, occur over Southeast Asia and its neighbouring areas following deforestation (Figure 10.6c). The areas around the northern South China Sea, the Indian Ocean (east-west band between $5^{o}$S to $10^{o}$S) and the Western Pacific to the north of New Guinea experience a significant enhancement of the upward vertical velocity. The area over the western Pacific to the east of Philippines (centred at $140^{o}$E and $13^{o}$N) experiences a significant suppression of the upward motion. Overall, Figure 10.6 indicates an enhancement of upward vertical velocity over the monsoon or near equatorial trough area, suggesting that this monsoon trough is strengthening following deforestation. The changes stated above corresponds well with the changes depicted in the longitudinal and latitudinal cross-sections of vertical velocity discussed earlier and agree well with the changes in MSLP discussed above.

During the summer monsoon in July, statistically significant changes over some important areas such as the summer monsoon trough can be seen clearly in Figure 10.7. The area centred on the Bay of Bengal is associated with the axis of the summer monsoon trough. The difference chart indicates a differential change occurs over this region following deforestation (Figure 10.7c). Though not statistically significant the land area centred on Bangladesh experiences a suppression of upward motion, and the area over the Bay of Bengal experiences a significant enhancement of upward vertical velocity. These modifications may be interpreted as an enhancement of the summer monsoon branch over the Bay of Bengal and a weakening of the monsoon branch over Bangladesh. This differential change corresponds to the southward shift of the upwelling limb in the longitudinal cross-section discussed earlier (cf. Section 10.2.1b). Another area which experiences a significant change is the area located over the north Pacific Ocean, east of Japan, near the dateline (centred on $170^{o}$E and $35^{o}$N). The control ensemble (Figure 10.7a) shows upward motion over the northwest part of the said area which can be associated with the dominant low pressure systems of the area. The southeast part of this area, closer to the dateline, indicates subsidence which is associated with the subtropical high pressure systems.

The character of the changes in the vertical velocity fields in this analysis of single region deforestation is in the opposite sense compared to the previous three region deforestation results analysed in Chapter 5. The previous analysis shows a slight diminishing of the upward vertical velocity over the monsoon trough within the Southeast Asian region. Not only do the single region deforestation results indicate an increase in the strength of the monsoon, but the changes over continental Southeast Asia are also different compared to the three region deforestation case. Again, we consider that the effect on the Southeast Asia circulation in

Zhang *et al*. (1996b) is complicated by external influences resulting from deforestation elsewhere in the tropics.

#### *10.2.2.2: Low and upper level velocity potential*

Velocity potential, superimposed with divergent wind vectors at 850 hPa and 200 hPa, can effectively describe motion in the lower and upper troposphere, effectively illustrating the large-scale divergent flow of the atmospheric circulation. The pattern on the large-scale divergent flow is much clearer and easier to interpret in these fields, rather than in the normal divergence field.

In January, the control ensemble results show convergent flow over Southeast Asia in the lower troposphere (Figure 10.8a), while divergent flow occurs over the Indian subcontinent and the rest of the Asian continent at this level. At higher levels in the troposphere (Figure 10.9a), this picture is reversed as divergent flow prevails over Southeast Asia and Pacific Ocean, and convergent flow covers most of the Asian continent and Indian subcontinent. The changes following deforestation can be seen in the difference charts (Figures 10.8c and 10.9c). After deforestation, large increases in low-level velocity potential occur over the Indian Ocean and Southeast Asia, so that the convergent flow over the Southeast Asia and Indian Ocean is enhanced. An area to the east of Philippines over the west Pacific Ocean (centred at $15^{o}$N and $135^{O}$E) experiences a slight decrease in low-level velocity potential, so that the convergent flow here is decreased. Changes of opposite sign occur in the upper troposphere with increased divergent flow over Southeast Asia and the Indian Ocean, but divergent flow over the area to the east of Philippines over the west Pacific Ocean reduced. The changes over the Indian Ocean to the south of Indonesia are statistically significant at the 5% level (Figures 10.8c and 10.9c).

In July, the control ensemble results show convergent flow exists throughout the whole of the Asian continent and the adjacent oceans in the lower troposphere (Figure 10.10a), and a reversed flow occurs in the upper troposphere (Figure 10.11a). After deforestation, large increases in low-level velocity potential occur over the Indian subcontinent and continental

Southeast Asian region (centred at the north of Indian Ocean/Bay of Bengal), so that the convergent flow over this region is increased (Figure 10.10c). Overall, the whole of the Asia continent and the adjacent oceans experience an increase in velocity potential and convergent flow. Again, changes of opposite sign occur in the upper troposphere (Figure 10.11c) with a large increase in divergent flow over the Indian subcontinent and continental Southeast Asia. The changes over the Indian subcontinent and continental Southeast Asia (at the lower level) and over the south of the Bay of Bengal (at the upper level) are statistically significant at the 5% level. In addition, the decrease in velocity potential and, therefore, increase in divergent flow over Australia at the upper level are also statistically significant.

Combining the changes in the velocity potential at low and high levels, it is possible to relate the changes with the vertical velocity results: (i) the disturbance over Southeast Asia in January, indicating an increase in ascending motion, and the disturbance over the west Pacific Ocean in the same month, indicating a decrease in the ascending motion, in agreement with the vertical velocity analysis, demonstrate a change in the Walker circulation; and (ii) the disturbances over the Indian Ocean, Bay of Bengal, Indian subcontinent and continental Southeast Asia in July, indicating an increase in ascending motion, are also in agreement with the Walker circulation changes found in the earlier analysis of vertical velocity. From the responses shown so far, it would appear that Southeast Asian deforestation is affecting the large-scale atmospheric dynamic structure over the tropics and extratropics of the region.

#### *10.2.2.3: Middle level stream function*

To further examine the simulated large-scale impacts induced by Southeast Asian deforestation, changes in the stream function and non-divergent winds in the middle troposphere (500 hPa) are presented in Figures 10.12 and 10.13 for January and July, respectively.

In January, as shown by the composite chart from the control ensemble simulations (Figure 10.12a), one of the most important synoptic features is the influence of anticyclonic circulations at this level of non-divergence. The anticyclonic system extends from the southern Indian subcontinent through the northern part of Southeast Asia over the west Pacific Ocean. The most intense anticyclonic cell occurs over the west Pacific Ocean. A broad and strong zonal westerly area of non-divergent winds covers the north of the anticyclonic system and relatively weak and variable non-divergent winds cover most of Southeast Asia and the eastern Indian Ocean. To the south of Southeast Asia, covering north of Australia and extending to the west Pacific, a cyclonic system is clearly shown by the non-divergent winds.

Following deforestation (Figure 10.12b), the anticyclonic system is diminished, with a breakdown of the anticyclonic flow pattern over continental Southeast Asia and a weaker anticyclonic cell over the western Pacific Ocean. The changes in the stream function and non-divergent winds are clearly seen in the difference chart (Figure 10.12c). Note that the scale of the non-divergent wind vector is enhanced in the difference chart for clarity. Though the field over only a small part of Southeast Asia shows statistically significant changes, the most important difference for the Southeast Asia region is the penetration of the middle level trough from the Asian continent. This indicates a strengthening of the winter monsoon as colder and denser air from the Asia continent pushes southward as well as downward to lower levels. The colder and denser air moving over relatively warmer surface air would effectively enhance instability over Southeast Asia during this winter season. This condition would then in turn produce much stronger monsoonal activity with an increase in convective cloudiness, as demonstrated in Chapter 9. Other changes worth mentioning occur over the east of the Indian Ocean, and a few parts of the west Pacific Ocean. The area over the eastern Indian Ocean extending to the west of northern Australia is affected by statistically significant increases in the stream function and the non-divergent flow becomes more cyclonic after deforestation. The changes at this middle level could be related to the intensification of the ITCZ below, corresponding with the earlier analysis of other fields at the surface level. Similarly, the changes over the west Pacific Ocean are closely related to the surface changes there as discussed earlier

In July, as shown by the composite chart from the control ensemble simulations (Figure 10.13a), two important synoptic features are: the influence of the anticyclonic circulation over the western Pacific ocean extending westward to the north South China Sea; and a strong cyclonic system over the Indian subcontinent/Bay of Bengal region. Following deforestation, the two systems seem to be intensified (Figure 10.13b). The changes are more clearly seen in the difference chart (Figure 10.13c). Over the western Pacific to the east of Japan (centred at 165°E and 30°N), the stream function is significantly increased and the flow becomes more anticyclonic. Between Japan and the centre of the anticyclone system, it seems that the cyclonic flow at 500 hPa which is associated with a frontal system is enhanced. This change corresponds to the changes in the vertical velocity and velocity potential fields discussed earlier. In addition, there is a decrease in the stream function over the Indian subcontinent/Bay of Bengal (which also extends over Sumatra, Peninsular Malaysia and southern Indochina), but the decrease is not statistically significant. The change, however, could still be considered to be important in terms of modifying the circulation over this region. An increase in the cyclonic/anticyclonic flow at 500 hPa indicates an intensification of the cyclonic/anticyclonic system over a certain area. The intensification of the cyclonic system over the Indian subcontinent and the vicinity shows that the summer monsoon is strengthened following deforestation. On the other hand, the intensification of the anticyclonic system over the west Pacific Ocean and the vicinity shows that the atmosphere becomes more stable in this area. All the above-mentioned changes confirm the changes shown earlier in the MSLP and surface vertical velocity. Again, all can be regarded as indicators that the Southeast Asian deforestation could induce large-scale circulation changes.

## 10.3: The Role of Southeast Asian Vegetation in the Large-scale Circulation

In comparison with previous GCM studies reviewed in Chapter 4 and 5, this study seems to disagree on the sign of the change in the large-scale circulation following deforestation. The current results indicate a strengthening of the winter and summer monsoon over the deforested region and its neighbouring areas, but the previous reviewed results indicate a weakening of the monsoons or shifting of both monsoons to the east. In this section, the modelled change in boundary layer entropy (Chapter 8) is examined to throw light on why the monsoon circulations are strengthened.

### *10.3.1: Impact on the dynamics of monsoon circulations*

Eltahir and Gong (1996) report on the mechanism of floods and droughts over West Africa, based on the results of earlier studies by Held and Hou (1980), Lindzen and Hou (1988), Plumb and Hou (1992), Emanuel (1995) and others (see discussion in Chapter 4). Eltahir and Gong (1996) suggested that rainfall variability over the West Africa region is a manifestation of large-scale ocean-atmosphere-land interaction. According to their theory, the dynamics of wet and dry years over West Africa are governed not only by land-atmosphere interaction or ocean-atmosphere interaction considered independently, but the critical factor to consider is the meridional gradient of boundary layer conditions between the land region and the Atlantic Ocean. The measure that was proposed to describe these conditions over land and the ocean was the meridional gradient of moist entropy (or moist static energy). Eltahir and Gong (1996) argued that a flat meridional entropy distribution cannot drive the regional circulation and a relatively large gradient should force a strong monsoon flow, the main rainfall-producing system in the Sahel region. For a meridional circulation to develop over any tropical region off the equator, the absolute vorticity near the tropopause has to reach a threshold value of zero. For a moist atmosphere that satisfies a quasi-equilibrium balance between moist convection and radiative forcing, the absolute vorticity at upper tropospheric levels is a function of latitude and the meridional distribution of boundary layer entropy.

To support their theory, Eltahir and Gong (1996) presented observations of entropy and wind over West Africa during the monsoon seasons of the relatively wet year of 1958 and the relatively dry year of 1960. The observations presented are consistent with the proposed relation between boundary layer entropy and the monsoon circulation: a large meridional gradient of boundary layer entropy means a healthy (strong) monsoon, and relatively wet conditions over the Sahel region were observed in 1958; a nearly flat distribution of entropy, very weak circulation, and relatively dry conditions were observed in 1960.

The theory presented by Eltahir and Gong (1996) can be applied to this study of changes in the monsoon circulations in the context of Southeast Asia. Here, the critical factor to be considered is the meridional gradient of boundary layer conditions between the land and the Pacific Ocean and the Indian Ocean. Analysis of the boundary layer entropy distribution using the results from the current study will be presented for both January and July in the next section. To obtain a better understanding regarding the mechanisms involved, the meridional and zonal distribution of the surface moisture flux, precipitation, and moisture convergence, as well as the meridional distribution of the net surface radiative flux are also presented as these control the boundary layer entropy distribution (see Chapter 8). The analyses of the above parameters are based on composites from the 10-case ensemble. To correspond with the study area, the meridional distributions are obtained by taking zonal averages from 90$^{o}$E to 150$^{o}$E and meridionally averages from 10$^{o}$S to 20$^{o}$N.

### *a. Effects on the winter monsoon (January)*

Figure 10.14 show the meridional distribution of the surface moisture flux, precipitation, and moisture convergence for January. Note that the use of the term "surface moisture flux" in this section is synonymous with "surface evaporation." The surface moisture flux difference between the deforestation and the control results is not very clear in the region of perturbation, increasing between 10$^{o}$S to 15$^{o}$N and decreasing between 15$^{o}$N to 20$^{o}$N (Figure 10.14a). These contrasting changes most likely correspond to opposing changes over ocean and land areas. However, the maximum surface moisture flux and its negative change around 15$^{o}$N-20$^{o}$N following deforestation could be associated with the changes in land surface properties over this region. The maximum precipitation in the deforestation experiment at 10$^{o}$S (Figure 10.14b) is higher than the precipitation maximum in the control and there are substantial positive changes from 10$^{o}$S to 10$^{o}$N following deforestation. However, there is a decrease in precipitation over the northern region between 10$^{o}$N to 20$^{o}$N. Moisture convergence can be used to measure the strength of the monsoon circulation. The changes in moisture convergence seem to follow quite closely the precipitation changes. After deforestation, moisture convergence between 10$^{o}$S to 15$^{o}$N (Figure 10.14c) is higher than in the control case implying a stronger circulation in this region. Over the northern region between 10$^{o}$N and 20$^{o}$N, the moisture convergence is decreased following deforestation suggesting that the monsoon strength is weakened in this region.

Figure 10.16 shows the zonal distribution of surface moisture flux, precipitation and moisture convergence in January. There is a small overall decrease in the surface moisture flux after deforestation between 100$^o$E to 150$^o$E (Figure 10.16a). Complying with the meridional distribution, this negative change can be associated with the change in land surface properties over continental Southeast Asia. The changes in precipitation following deforestation are positive over continental Southeast Asia and negative over the west Pacific Ocean (Figure 10.16b). As in the meridional case, the changes in moisture convergence are closely related to the precipitation changes. It is important to note that while the moisture convergence over the west Pacific Ocean is decreased following deforestation, the maximum moisture convergence which is located over the Southeast Asian region in the control is increased. This suggests that the strength of the winter monsoon is increased in the Southeast Asia region, while it is decreased over the west Pacific region. The zonal distributions of the moisture flux and precipitation suggest that the main source of moisture that brings maximum precipitation over the Southeast Asia region comes from the west Pacific Ocean.

Figure 10.18 show the meridional distribution of net down surface radiation in January over open sea, land and both sea and land, as shown in Panels (c), (f) and (i), respectively. By convention, downward fluxes are defined as positive, and upward fluxes as negative. It is clear that within the perturbed region, particularly over land, the net radiative flux after deforestation is smaller than that of the control case. In general, the degradation of the vegetation cover considered in isolation will induce an increase of albedo and a decrease of surface water availability. The increase of surface albedo will decrease the surface solar (SW) radiative flux. On the other hand, the decrease of surface water availability will decrease the surface moisture flux and tend to heat up the land surface resulting in larger outgoing LW radiative flux. In addition, the decrease in the surface water availability also reduces the surface moisture flux over land areas over continental Southeast Asia. This introduces less water vapour into the atmosphere over land. Figure 10.18 also contains the net down surface SW radiative flux (Figure 10.18a, d and g) and net down surface LW radiative flux (Figure 10.18b, e and h). For the case of deforestation, particularly over land areas, both SW and LW components contribute to the decrease in net surface radiation.

The reduction in net surface radiation should result in a similar reduction of the surface entropy flux in the deforested region, hence reducing the boundary layer entropy there. Figure 10.20a shows the meridional distribution of boundary layer entropy in terms of boundary layer potential temperature, Π, for the control and deforestation experiments in January. Despite the net surface radiation being decreased, it seems that the boundary layer entropy over Southeast Asia between the equator and $10^{o}$N is slightly increased. This is most likely due to the dominant increase in latent heat released in the boundary layer following an increase in moisture transport from outside, hence, increase in precipitation over this region as discussed in Chapter 9, rather than from the local surface changes as argued by Eltahir and Gong (1996). The highest gradient in the boundary layer entropy in winter (January) is between the Northern Hemisphere middle latitudes and the tropics. This is associated with the strength of the winter monsoon which is controlled primarily by the Siberian High, the source region of the monsoon. Meridionally, the boundary layer entropy gradient seems to increase slightly in the Northern Hemisphere after deforestation indicating a strengthening of the monsoon during this time of the year.

It is clear that the changes in the zonal and meridional distributions discussed so far are not large. To examine statistical significance, Figure 10.21a shows the spatial distribution of the changes in boundary layer entropy in terms of the changes in boundary layer potential temperature, Π, in January with significant changes at the 5% level marked. Clearly, there are negative changes in the boundary layer entropy over continental Asia including the northern continental Southeast Asia. On the other hand, most of Southeast Asia and the western Pacific Ocean experience positive changes in boundary layer entropy. As the results, the meridional gradient of boundary layer entropy is increased. Significant changes in the boundary layer entropy seem to take place over certain areas outside the study area suggesting large-scale atmospheric feedbacks occur following deforestation.

### *a. Effects on the summer monsoon (July)*

Figure 10.15 shows the meridional distribution of the surface moisture flux, precipitation, and moisture convergence for July. In the region of perturbation, only small differences in the surface moisture flux are observed between the deforestation and the control cases (Figure 10.15a). The maximum precipitation in the control experiment at around 15$^o$N to 20$^o$N is shifted slightly southward (Figure 10.15b). This may well be due to the corresponding southward shift of the summer monsoon trough. A positive change in precipitation occurs from 10$^o$S to 15$^o$N. Again, the changes in moisture convergence follow quite closely the changes in precipitation. After deforestation, moisture convergence between 10$^o$S to 15$^o$N (Figure 10.15c) is higher than the value in the control case implying a stronger circulation in this region. Figure 10.17 show the zonal distribution of surface moisture flux, precipitation and moisture convergence in July. There are no significant changes in the surface moisture flux in the perturbation region between 90$^o$E to 150$^o$E (Figure 10.17a). Large positive changes of precipitation around 90$^o$E correspond to the increase in monsoonal rainfall over this region (Figure 10.17b). As in the meridional case, the changes in moisture convergence are closely related to the precipitation changes.

Figure 10.19 shows the meridional distribution of net down surface radiation in July over open sea, land and both, as shown in Panel (c), (f) and (i), respectively. It is clear that within the perturbation region, particularly over land, the net radiative flux following deforestation is smaller than that of the control case. For the case of deforestation, it seems that the SW fluxes (Figure 10.19a, d and g) dominate in contribution to the decrease in net surface radiation. The LW fluxes (Figure 10.19b, e and h) seem not to contribute much to the decrease in net surface radiation.

Figure 10.20b shows the meridional distribution of boundary layer entropy in terms of boundary layer potential temperature, $\Pi$, for the control and deforestation experiments in July. There is no marked change in the boundary layer entropy over the deforested region latitudes. The highest gradient in the boundary layer entropy in summer (July) is between the Southern Hemisphere middle latitudes and the tropics. This is associated with the strength of the summer monsoon during this time of the year. Meridionally, the boundary layer entropy gradient seems to increase slightly in the Southern Hemisphere after deforestation indicating a slight strengthening of the summer monsoon during this time of the year.

Figure 10.21b shows the spatial distribution of the changes in boundary layer entropy in terms of the changes in boundary layer potential temperature, Π, in July. Clearly, there are significant negative changes in the boundary layer entropy over Australia. On the other hand, areas under the influence of summer monsoon trough, from Indian subcontinent extending over the Bay of Bengal to continental Southeast Asia experience a slight positive change in the boundary layer entropy. As the results, on the larger scale, indicate the meridional gradient of boundary layer entropy is slightly increased implying a slight increase in summer monsoon circulation. Again, significant changes in the boundary layer entropy over some areas outside the study area suggest large-scale atmospheric feedbacks occur following deforestation.

## 10.4: The Change in Large-scale Atmospheric Circulation

### *10.4.1: The mechanism relating Southeast Asian deforestation and the change in large-scale atmospheric circulation*

In this final section, the results of this analysis are drawn together into a coherent explanation of why the regional monsoonal circulation responds to the local change in climate induced by deforestation. As shown in the Chapter 9, Southeast Asian deforestation causes an overall increase in the surface temperature in the simulations (Figure 9.18). As a result of the increase in surface temperature, a thermally direct convergent circulation in the boundary layer is created. This is enhanced by the moisture convergence over the deforested region. Both reinforce the existing monsoon convergence over the deforested region. The increase in cloud and precipitation is the result of the enhancement of the convergent circulation in the boundary layer over the deforested region. All the above, subject to large-scale feedbacks, modify the large-scale boundary layer entropy, increasing the meridional gradient of boundary layer entropy. Hence, the whole mechanism results in a strengthening of the large-scale monsoon circulation. The mechanism that relates the local impacts of Southeast Asian deforestation to the strengthening of the large-scale monsoon circulation over the region is illustrated in Figure 10.22.

As discussed previously, external moisture being transported into the deforested region is more significant than internal water recycling in the context of Southeast Asia. The competing responses, as suggested by Eltahir and Bras (1993), between a thermally direct converging circulation in the boundary layer driven by the increase in the surface temperature versus a diverging circulation in the boundary layer due to the corresponding decrease in rainfall and latent heating are, virtually, not present in the context of Southeast Asian deforestation. In fact, following deforestation, the convergent circulation caused by the local increase in temperature tends to reinforce the existing convergence caused by the external monsoon forcing, therefore enhancing the overall convergence over the deforested region. This situation occurs in both monsoon periods, in January and July, but a clearer signal can be detected during the winter monsoon in January. By mass continuity, the increase in ascent above the deforested regions cause changes beyond the areas of disturbance. There must be either a decrease in ascent or an increase in descent elsewhere and broader disturbance in the general circulation. For example, when looking at the Walker circulation changes in Section 10.2, we have seen that ascent over the western Pacific has diminished in January following deforestation (cf. Figure10.1). Similarly, in July, an increase in ascent over the Indian subcontinent/Bay of Bengal longitudes is balanced by a decrease in ascent to the west (cf. Figure10.2). This change is supported by the changes in other parameters, such as velocity potential, stream function, MSLP as well as surface vertical velocity.

### *10.4.2: The current analyses versus the hypotheses*

Finally, the current results are checked against the two hypotheses defined in Chapter 5 based on the results of the three region deforestation experiment of the NCAR Community Climate Model. The two hypotheses are: -

i. that deforestation can, in general, modify the circulation pattern over this region during the summer and winter monsoon seasons, by shifting the monsoon trough of both seasons to the east; and
ii. that deforestation can, more specifically, produce significant changes to the signals over the Indian Ocean and west Pacific Ocean by: (a) weakening both the summer monsoon trough over the Indian subcontinent and the winter monsoon trough over the Southeast

Asia region; and (b) strengthening both the effect of the summer and the winter monsoon over the western part of the west Pacific Ocean, adjacent to Southeast Asia region.

With reference to Hypothesis (i), it is found that the current single region deforestation perturbation in Southeast Asia can modify the circulation pattern over this region during the summer and winter monsoon seasons. However, the shifting of the monsoon trough of both seasons to the east is not detected in the current results. Rather, a potential southward shift of the summer monsoon does occur after deforestation, but there is no significant shift in the winter monsoon.

Regarding Hypothesis ii(a), it is true that significant changes over the Indian Ocean and west Pacific Ocean do take place following deforestation. However, the changes behave in an opposite direction since both the summer monsoon trough over the Indian subcontinent and the winter monsoon trough over the Southeast Asia region are strengthened, not weakened. Hypothesis ii(b) can also be rejected, as there are no evidence of the strengthening of either the effect of summer monsoon or winter monsoon over the western part of the west Pacific. In fact, there is evidence that the effect of the winter monsoon over the west Pacific Ocean is weakened, opposing this hypothesis.

The two hypotheses, therefore, can be rejected under the state of single region deforestation in Southeast Asia. It cannot, however, be overemphasised that the results of this hypothesis testing should be interpreted carefully since the three region deforestation forcing differs from the current approach based on single region deforestation. As remarked in the introductory notes, the hypotheses derived primarily serve as a guide in the current investigation so that the results obtained from the new approach could be systematically analysed. The two different forcings could be expected to induce different responses, in terms of both the climate and the atmospheric circulation. Deforestation in more than one region may produce widespread interactions, either damping or reinforcing locally-generated disturbances through global-scale interaction.

In the context of the Southeast Asia region, the results from the current analysis have answered the question of whether or not Southeast Asia deforestation can alter the character of the local monsoons. The results have successfully shown the extent to which the monsoon penetrates different parts of the region and delineated how the continental, maritime and the adjacent oceanic areas are affected by regional deforestation. But can regional deforestation affect the global-scale circulation?

Analysis of the global velocity potential fields is used to examine the model-simulated global impacts induced by Southeast Asian deforestation. Figures 10.23 and 10.24 illustrate changes in the velocity potential at low level (850 hPa) and upper level (200 hPa) on the planetary-scale for January and July, respectively. The changing patterns of the velocity potential indicate that the greatest effect following Southeast Asian deforestation is over the deforested region and its neighbouring areas, though there are also smaller changes over places further from this region. In January, Southeast Asia and its surrounding areas are most affected (Figures 10.23c and 10.23d); the changes in low level convergence and upper level divergence are the greatest over this region corresponding to the increase in winter monsoon strength. In July, according to the low level velocity potential, areas centred over the Bay of Bengal seem to receive the most impact at the surface after deforestation compared to other places on the whole globe (Figure 10.24c). These changes are closely related to the intensification of the summer monsoon as indicated by the significant increase in convergence.

Although the most affected locations are confined within the deforested region and nearby areas, there are weak signals over distant areas, away from the deforested region. For example, the changes in velocity potential in January indicate that remote effects occur over the northern region of South America (Figures 10.23c and 10.23d), though the changes are not as great as over Southeast Asia. Similarly in July, changes over western Africa are quite marked (Figures 10.24c and 110.24d). All these remote changes suggest the existence of so-called teleconnections between the changes in land surface over the deforested region and atmospheric perturbations on the planetary-scale, perhaps relating to the regional changes in the Walker and Hadley circulations. However, the dominant effects lie within or close to the deforested area and it would be unwise to place the same level of confidence in these remote teleconnections which could well arise solely by chance. It is, in any case, unlikely that remote teleconnections would develop fully within the 60-day integration period and in the absence of full ocean-atmosphere interaction.

## 10.5: Conclusions

This chapter has examined the large-scale implications of Southeast Asian deforestation. The impact of deforestation extends beyond the deforested region by changing the regional atmospheric circulation. Southeast Asian deforestation has, in particular, been seen to affect the regional monsoon circulation, strengthening these flows in both winter and summer. Changes in the Walker and Hadley circulations have also been identified as an important consequence of deforestation. The Walker circulation is affected not only over the deforested region but also over the tropical oceans, the west Pacific Ocean and Indian Ocean in particular. Meanwhile, changes in the Hadley circulation cause disturbances in the meridional moisture transport between the tropical region and the mid- and high latitudes. Both the changes in the Walker circulation and in the Hadley circulation may provide some explanation for the changes in the broader general circulation simulated over the extratropical regions.

A mechanism has been proposed to account for how large-scale deforestation in Southeast Asia modifies the atmospheric circulation in this region. This mechanism suggests that as a result of the increase in surface temperature, a thermally direct convergent circulation in the boundary layer is created and enhanced by the moisture convergence over the deforested region. Both reinforce the existing monsoon convergence over the deforested region and, under large-scale feedbacks, modify the large-scale boundary layer entropy, causing an increase in the meridional gradient of boundary layer entropy and underpinning the strengthening of the large-scale monsoon circulation (cf. Figure 10.22).