CHAPTER 4: GENERAL CIRCULATION MODEL SIMULATIONS OF TROPICAL DEFORESTATION

4.1: Introduction

In this chapter, previous simulations of the effects of deforestation on climate using general circulation model (GCM) are reviewed and conclusions are drawn for the present study. An early version of this review has been published in Wan Azli Wan Hassan *et al.* (1996). The effects of the removal of large areas of tropical forest on local, regional and global climate have received considerable attention from climate analysts and modellers. As discussed in the previous chapter, it is widely recognised that continuing removal of these forests will add carbon to the atmosphere through biomass burning, thereby enhancing the greenhouse effect, as well as disturbing greenhouse gas budgets in other ways. In addition, the clearing of these forests also modifies climatically-important properties of the land surface such as surface albedo, evaporation rate and surface roughness. In this way, deforestation alters the amount of radiation reflected and absorbed at the earth's surface and, therefore, directly affects the radiation budget. The radiation budget is also indirectly affected by the changes in the hydrological cycle over areas of forest clearance.

In terms of greenhouse gas emissions, destruction of the world's forests is releasing, on balance, 1.6 " 1.0 billion tonnes of carbon per year (Houghton *et al.*, 1994; 1995) and is thus the most important anthropogenic carbon source after the combustion of fossil fuels. It is still very difficult to produce an accurate estimate of the carbon balance due to the complexity of the carbon cycle and the inadequacy of the available data. Because of this, none of the climate model studies reported so far has attempted to include effects on the carbon budget and hence the radiation balance in deforestation experiments, focussing instead on the direct and indirect effects of changes in land surface characteristics. Neither has any study attempted to simulate the gradual changes that, in reality, occur as tropical forest is removed and replaced. Instead, modellers have concentrated on comparing the long-term mean situation before and after an imposed deforestation, assessing effects on the radiation budget and the hydrological cycle.

On the basis of previous work discussed in Chapter 2, it can be concluded that replacing the tropical forest with grassland leads to three main changes in land surface properties and consequent effects on the local atmosphere:

(i) the increased surface albedo directly causes a reduction in the surface net radiation balance;

(ii) the reduction in the leaf area and stem area of the ambient vegetation reduces its water-holding capacity and causes decreased interception of precipitation and reduced transpiration; and

(iii) the relatively short and smooth grasslands have a lower surface roughness than forest and are, therefore, associated with lower surface friction.

The impact that these changes have on the broader climate can be difficult to unravel. For example, there are complex feedback processes involved in relating changes in surface evaporation to changes in total precipitation. These interactions involve increased surface albedo, reduced canopy interception and lower roughness length following deforestation and result in a number of modifications to the energy and moisture budget of the overlying atmospheric column and hence effects on surface temperature and precipitation (Figure 4.1).

A number of different kinds of climate models have been applied in order to identify the effects of deforestation on local, regional and global climate. Of these models, the most sophisticated form is the General Circulation Model (GCM) which provides a full three-dimensional representation of the climate system. Though they still possess many uncertainties, GCMs represent the best integration of the present level of understanding and development in meteorological science. Coupled with an ocean model, they can now produce realistic simulations of global climate change. In fact, even using the most complex model, quantitative estimation of the effects of large changes in terrestrial ecosystems on climate is a difficult task. The state of the climate system is determined by complex interactions between dynamical processes in the atmosphere and thermodynamic processes at the earth-atmosphere interface. For this reason, some authors have concluded that earlier, less sophisticated model studies on the effects of deforestation on climate were generally inconclusive, giving, at times, conflicting results (Salati and Nobre, 1991; Nobre *et al*., 1991).

4.2: Modelling Tropical Deforestation: Overview of the Early Experiments

As reviewed in Henderson-Sellers (1987), early modelling studies of tropical deforestation were of two types, either simple energy-balance box models, providing only a crude representation of the world's geography, or low-resolution, three-dimensional GCMs.

Potter *et al*. (1975), for example, used the Lawrence Livermore global two-dimensional statistical/dynamical zonal energy-balance box model of the atmosphere to investigate the climatic effect of tropical rain forest removal. They found general global cooling and, overall, a net reduction in global precipitation, resulting from a large reduction in tropical precipitation almost balanced by an increase in sub-tropical precipitation. Lettau *et al*. (1979) focussed on the Amazonian region using an energy-balance box model. They used hydrological and mean regional wind data to assess the possible impact of tropical deforestation on regional climate and predicted increases in both local temperature and rainfall. In the first deforestation experiment with a GCM, Henderson-Sellers and Gornitz (1984) used the Goddard Institute for Space Studies (GISS) model and attempted to maximize the possible impact of tropical deforestation by simulating the effects of extensive land cover change in the Amazon region. In the model, a total area of 494 million hectares of tropical moist forest was replaced by grass. The study predicted decrease precipitation with no significant temperature change, results similar to those of Potter *et al*. (1975) for the Amazonian region. The features, perturbation and results for the above experiments are summarised in Table 4.1.

Henderson-Sellers (1987) identifies some common themes that can be drawn from these early results. First, the results show changes in the surface hydrology are at least as important as changes in the surface albedo. Second, the results are sensitive to the parameterizations (descriptions and formulations of key climate processes) inherent in the models and to the information input to the models regarding land surface characteristics. Finally, while the local meteorological disturbance may be very large, the results of these early experiments are in dispute with regard to whether to expect detectable climatic change in any areas remote from the perturbation region.

4.3: General Circulation Model Simulations of Tropical Deforestation: A Historical Review

With more detailed land surface parameterization schemes and interacting thermodynamic, hydrodynamic and radiative processes, GCMs can now be used effectively for climate modelling as well as operational numerical weather prediction. The land surface and other parameterization schemes, which were highly simplistic in the early models, have been gradually improved. Currently, climate experiments with GCMs are normally run in coupled ocean-atmosphere mode, with at least a mixed-layer slab ocean. Previously, the simulation of ocean processes was crude and this seriously limited the realism and reliability of the early experiments. The new generation of GCMs has the potential for an effective examination of the consequences of the change in land surface boundary conditions following deforestation.

In the past two decades, the number of GCM experiments undertaken to study specifically the climatic effects of tropical deforestation has been limited. Most studies have tried to estimate the impact likely to occur as a result of tropical deforestation by maximizing the changes in surface characteristics (such as the area and the nature of the change) considered important to climate. These early simulations were designed to draw out the local- to regional-scale climate change following deforestation, and simulations of Amazonian deforestation typified modelling of these changes. Some model studies emphasized the importance of surface albedo, and others stressed the role of changes in surface roughness length and soil water capacity (i.e. the hydrological cycle) using improved canopy representation. Only recently have deforestation experiments been extended to Southeast Asia and tropical Africa in an attempt to understand the global climate response, with particular emphasis on the role of the large-scale dynamics of the climate system.

Ten major deforestation experiments using GCMs are now reviewed, to compare their features and perturbations, major developments and results. Starting with the first such experiment by Henderson-Seller and Gornitz (1984), we examine the development of model simulation of deforestation impacts by then considering studies by Dickinson and Henderson-Sellers (1988),

Lean and Warrilow (1989), Shukla *et al*. (1990), Mylne and Rowntree (1992), Lean and Rowntree (1993), Henderson-Sellers *et al.* (1993), Polcher and Laval (1994a,b), McGuffie *et al.*

(1995) and Zhang *et al.* (1996a,b).

4.3.1: Features and perturbations

The models used and the main features of the experimental design used in these ten studies are first described. Henderson-Sellers and Gornitz (1984) used the Goddard Institute for Space Studies (GISS) finite difference model, with low spatial resolution (8^o latitude by 10^o longitude), to simulate large-scale clearing of the Brazilian Amazon forest by assuming its replacement with a grass/crop cover. The magnitude of this deforestation was said to be equivalent to 35-50 years of deforestation at the global rate estimated in 1984. A ten-year simulation was undertaken and the results from the last five years was compared with the last five years of a 20-year control run.

Dickinson and Henderson-Sellers (1988) used the CCMOB version of the National Center for Atmospheric Research Community Climate Model (NCAR-CCM), coupled with a biophysically based land-surface parameterization scheme [Biosphere-Atmosphere Transfer Scheme (BATS)]. This spectral model had a rhomboidal truncation at total wavenumber 15, approximately equivalent to a resolution of 4.5^o latitude by 7.5^o longitude. (Spectral refers to the manner in which processes in the horizontal are modelled in a “wave number” rather than latitude/longitude coordinate system, in keeping with the wave-like nature of the large-scale atmospheric circulation.) In their deforestation experiment, all the grid cells with vegetation classified as evergreen broadleaf tree in South America were modified to new vegetation having the characteristics of impoverished scrub-grassland, typical of deforested regions in Amazonia. At each of the modified grid locations, the soil texture was modified to that of finer type and the soil colour to that of a lighter type. A 13-month integration, initialized from the second year of a three-year control simulation, was undertaken giving a one-year simulation of deforestation.

Lean and Warrilow (1989) used the finite grid model of the United Kingdom Meteorological Office (UKMO) with a spatial resolution of 2.5^o latitude by 3.75^o longitude. They altered the surface characteristics, using the 1^o x 1^o land-surface points from the Wilson and Henderson-Sellers (1985) data set, by replacing tropical forest or savannah with tropical pasture and integrated for three years for both the control and deforestation experiment.

Shukla *et al.* (1990) [also reported by Nobre *et al.* (1991)] used the Center for Ocean-Land-Atmosphere Interactions GCM (COLA-GCM), a modified version of the National Meteorological Center (NMC) global spectral model (R40), with a resolution of 1.8° latitude by 2.8° longitude. They modelled deforestation by changing a number of physical parameters in the Simple Biosphere (SiB) land-surface scheme [described by Sellers *et al.* (1986)]. Two one-year integrations, for control and deforestation, were carried out for the whole of the Amazon Basin.

Mylne and Rowntree (1992) worked with the same UKMO finite grid GCM used by Lean and Warrilow (1989), but with a simpler land-surface scheme. They used a simple "bucket hydrology" to predict the soil moisture content of a single soil layer. Their experiments were designed to modify only the land-surface albedo, rather than simulate the effect of a full-scale deforestation. The albedo in two regions was modified; the Amazon and tropical Africa. Their control experiment imposed an albedo of 0.2 over all snow-free land with an eight-year integration time and compared the results with two other experiments with a nine-month integration time. One was a "forest" experiment that had a snow-free albedo dependant on the vegetation and soil data sets, and the other was a "woodland" experiment, where snow-free land with a tropical forest albedo was replaced by an albedo appropriate for grassland.

Lean and Rowntree (1993) used the same version of the UKMO finite grid GCM as Lean and Warrilow (1989) and Mylne and Rowntree (1992) to run experiments incorporating an improved representation of micrometeorological processes within the forest. Their three-year control and deforestation experiments provide a comprehensive analysis of simulated climate following the replacement of Amazonian forest by pasture.

Henderson-Sellers *et al.* (1993) used an updated version of CCM1 (CCM1-Oz). This is the NCAR spectral (R15) model at a resolution of 4.5° latitude by 7.5° longitude, coupled with a biophysically-based land-surface parameterization scheme, a modified version of BATS (BATS1e). With a mixed layer slab ocean, Henderson-Sellers *et al.* conducted six-year control and deforestation experiments for three regions: the northern Amazon Basin, the southern Amazon Basin and Southeast Asia. In the deforestation experiments, the ecotype was changed from tropical moist forest to scrub grassland, the soil texture made finer and the soil colour made lighter. The six-year integration time was designed to accommodate an adequate time scale response to tropical deforestation, so that the climate is at full equilibrium rather than in transient response mode. The authors suggested that previous simulations, particularly those with a complex land-surface scheme, had relatively short integration times that did not allow the climate system to achieve a new equilibrium following a perturbation. Whether or not six years is adequate for equilibrium to be reached is an interesting point which is returned to later in this review.

The LMD (Laboratoire de Météorologie Dynamique) grid-point GCM model with a 2.0^o latitude by 5.6^o longitude resolution coupled with the SECHIBA (Schématisation des Echanges Hydriques à 1'Interface entre le Biosphére et 1'Atmosphére) parameterization scheme was used by Polcher and Laval (1994a,b) for a global tropical deforestation experiment including South America (Amazonia), Southeast Asia (Indonesia) and tropical Africa. For the deforested case, the values in a vegetation parameter set associated with tropical rain forests were replaced with those for grassland in the tropical belt. The integration time for the control and deforestation in Polcher and Laval (1994a) was 13.5 months. In their other experiment, Polcher and Laval (1994b) used a longer integration - 11 years - for the control and deforestation to facilitate statistical analysis.

Following a similar approach to Henderson-Sellers *et al.* (1993), another experiment using a modified version of the CCM1 model (CCM1-Oz) at wavenumber 15 (R15) truncation (equivalent to a 4.5^o latitude by 7.5^o longitude resolution) was carried out by McGuffie *et al.* (1995). This experiment also incorporated BATS1e, a mixed-layer slab ocean and a three-layer sea-ice model. A 14-year control integration was used, followed by a six-year deforestation experiment in which the tropical wet forest throughout the Amazon Basin, Southeast Asia and tropical Africa was replaced by scrub grassland.

Finally, the work by Zhang *et al.* (1996a,b) represents an extension of the experimental design and analysis of McGuffie *et al.* (1995), using the same model (CCM1-Oz) and land-surface parameterization scheme (BATS1e). However, their simulation times were longer, with a 25-year control integration and an 11-year perturbation integration in which the tropical forests in the Amazon Basin, Southeast Asia, and tropical African region were modified to grassland. Whereas Zhang *et al.* (1996a) focus their report on a detailed process-based analysis of the local changes within the forest region resulting from deforestation, the companion paper reports an evaluation of regional to global-scale changes in climate resulting from deforestation (Zhang *et al*., 1996b).

Table 4.2 summarizes the major features of the experiments described in this section and Table 4.3 documents major improvements in model formulation that have occurred, providing an indication of fruitful areas for further improvement.

4.3.2: Principal findings and discussion

4.3.2.1: Impact of deforestation on local and regional climate

All ten experiments covered the Amazon Basin and we can, therefore, make a comparison of local to regional climatic changes following deforestation based on their results. The findings are summarized in Table 4.4. There is some consistency as far as discernible impacts on local and regional climate are concerned despite the considerable differences in the GCM dynamical structures, land surface representation, ocean and cloud description and the length of the simulations. With some exceptions, most of the impacts on climate are outside the range of natural variability. Nevertheless, there are many uncertainties with respect to the magnitude and direction of changes. The simulations, especially those employing different land-surface schemes, give different results for the effect of tropical deforestation on local climate.

The experiments of Henderson-Sellers and Gornitz (1984) and Mylne and Rowntree (1993) did not find an overall significant change in temperature over Amazonia. The experiment reported by Mylne and Rowntree (1993) found an annual average change in temperature of -0.11^{o} C. Both Henderson-Sellers and Gornitz (1984) and Mylne and Rowntree (1993) did identify considerable decreases in annual average precipitation, evaporation and moisture flux convergence on a local to regional scale, similar to most of the other experiments. In general, moisture flux convergence decreases in the Amazon, where the reduction in evaporation is less than the reduction in precipitation. Only the Dickinson and Henderson-Sellers (1988) and Polcher and Laval (1994a) results were somewhat inconsistent with those from other experiments.

All the simulations that covered Southeast Asia (Henderson-Sellers *et al*., 1993; Polcher and Laval, 1994b; McGuffie *et al.*, 1995; Zhang *et al.*, 1996a) showed only minor impacts on local and regional climate resulting from deforestation in this region. Overall, the regional climatic impacts of deforestation were smaller over Southeast Asia than over the Amazon. In some cases, the responses were reversed. Because of the monsoon circulation over Southeast Asia and the warm ocean temperatures, especially in the western Pacific Ocean, the impacts of deforestation in Southeast Asia differ from those in the Amazon. The results of Zhang *et al.* (1996a) suggest that the Southeast Asia monsoon is much less sensitive to deforestation than the low-level flow over South America. McGuffie *et al.* (1995) do, though, describe a possible impact on the monsoon system over Southeast Asia. For Southeast Asia, all results showed that total precipitation and evaporation are very little affected by the imposed deforestation. In terms of temperature, the change was different from that over the Amazon Basin, with Southeast Asia exhibiting discernible decreases in ground surface temperature following deforestation (Henderson-Sellers *et al*., 1993; McGuffie *et al.*, 1995; Zhang *et al.*, 1996a).

As indicated by Henderson-Sellers *et al.* (1993), and supported by subsequent studies (e.g. Polcher and Laval, 1994b; McGuffie *et al.*,1995; Zhang *et al.*,1996a), investigation of precipitation is difficult in the context of deforestation in Southeast Asia due to the very high annual rainfall. This is particularly a problem in the wet season. There is strong forcing of rainfall by orographic uplift and a ready supply of moisture from the adjacent tropical ocean. The tropical forest plays a lesser role in producing the high rainfall over Southeast Asia region than in the Amazon region, rendering identification of deforestation-induced change difficult. Although the experiments show that some point values of precipitation over Southeast Asia alter in the deforested case, there was no clear change to the basic spatial pattern of rainfall as only a few of the point deviations are statistically significant. Similarly, reductions in total precipitation exist almost throughout the year but, with only a few statistically significant, there is no significant seasonal impact following deforestation (Henderson-Sellers *et al*., 1993; McGuffie *et al.,* 1995; Zhang *et al.,* 1996a). For example, Henderson-Sellers *et al*. (1993) found a significant decrease in precipitation in only two of the wet season months (June and July).

In most experiments, deforestation in tropical Africa also led to only minor effects on local and regional climate in this region compared with the effect over the Amazon (Polcher and Laval, 1994b; McGuffie *et al.,* 1995; Zhang *et al.,* 1996a). On the other hand, Mylne and Rowntree (1992) found that percentage climate changes over tropical Africa were even greater than over the Amazon Basin. Zhang *et al.* (1996a) showed that deforestation in Africa results in cooling of the land surface, similar to the simulations in Southeast Asia where the ground surface temperature decreased slightly.

The nature of the changes in albedo, roughness length and surface hydrological characteristics used in defining the deforestation process are very important in determining the local to regional effects of tropical deforestation. These model experiments show that the impacts simulated in response to tropical deforestation in the Amazon Basin, Southeast Asia and tropical Africa are regionally dependent. This occurs because the response to deforestation is determined by the nature of the local climate system and atmospheric circulation.

4.3.2.2: Impact of deforestation on global climate

The first GCM experiment of Henderson-Sellers and Gornitz (1984)**,** designed specifically to investigate global teleconnections, did not suggest any discernible modification of global climate despite the exaggerated nature of the input perturbation (cf. Table 4.1). It may be that any model with a land surface that neglects the canopy hydrology, such as this, cannot successfully represent changes in regional and global circulation. Some of the later GCM simulations (e.g. Shukla *et al.,*1990; Henderson-Sellers *et al*., 1993) hinted that climatic disturbances distant from the areas

of tropical deforestation may occur. Impacts on the general circulation of the atmosphere can be detected in the longitudinal Walker and latitudinal Hadley circulations of lower latitudes. These conclusions are supported by the very latest model experiments which do suggest that tropical deforestation may excite large-scale or global scale atmospheric impacts. With a coupled atmosphere and biosphere to give a more realistic canopy hydrology, and improved experimental design such as longer integration times, the more recent model simulations have a credibility perhaps lacking in some of the earlier experiments.

The results of McGuffie *et al.* (1995) and Zhang *et al.* (1996a, b), encompassing deforestation of all three regions (Amazonia, tropical Africa and Southeast Asia), are particularly interesting in the context of global climate. McGuffie *et al.* (1995), as well as describing impacts on the monsoon system over Southeast Asia following deforestation, find small but statistically significant changes in climate in middle and high latitudes. Modification of the model surface parameters to simulate tropical deforestation produces significant modifications of both the Hadley and Walker circulations (Figure 4.2), which are associated with changes distant from the region of deforestation. Zhang *et al.* (1996b) proposed a mechanism for the spread of disturbances arising from tropical deforestation to middle and high latitudes based on Rossby wave propagation. This is similar to the mechanisms associated with the extratropical influence of ENSO events which facilitate the dispersion of the tropical disturbances to high latitudes. Hence, Zhang *et al.* (1996b) not only suggest that it is possible for tropical deforestation to produce global-scale impacts, but offer a mechanism to explain how this might occur.

4.4: Improving Model Simulations of the Effects of Tropical Deforestation

In assessing the results discussed above it must be remembered that there are inherent uncertainties in these simulations which may affect both the magnitude and the direction of the predicted consequences of tropical deforestation. These shortcomings need to be addressed through the refinement of both models and experimental designs. The need to improve modelling of the effects of tropical deforestation has received much attention from modellers. For example, as stated by McGuffie and Henderson-Sellers (1997), future challenges include the simulation of the dynamic processes associated with vegetation destruction and (potential) regeneration.

One major criticism of previous studies is that they are all unrealistic in terms of the change in land cover used to force the model. Despite the word “simulation” used here and in the original publications in describing previous model experiments, all of these experiments were strictly "sensitivity" rather than true simulation experiments. This is because all of the studies tried to generate an unequivocal model response, or estimate the maximum impact likely to occur as a result of tropical deforestation, by maximizing the perturbation to land surface boundary condition (i.e. surface vegetation, soil moisture, albedo, etc.). These perturbations were, in fact, much larger than the observed changes. Simulation experiments should be conducted by imposing a known and realistic, i.e. observed, perturbation on the model. Land cover change, particularly in the tropics, has been shown to be a dynamic process involving loss of forest partly offset by rapid regrowth of secondary vegetation (Turner *et al.*, 1993). For example, based on a simulation and field measurement for deforested sites in northern Thailand, Giambelluca *et al.* (1996) have discovered that secondary vegetation increasingly resembles the original forest cover. According to Giambelluca *et al.* (1997), aggregation of surface properties necessary in GCMs is known to be a major source of uncertainty in model results. Obviously, previous GCM deforestation experiments were not based on a realistic change in vegetation parameters. Indeed, if such large-scale deforestation were to actually take place, large changes in the oceanic circulation and sea surface temperature anomalies are likely to emanate (Sud *et al.*, 1996).

Considering this same point from a different perspective, it is fair to say that the GCM experiments undertaken to date reveal a great deal about the sensitivity of each model to changes in its particular land surface boundary conditions following deforestation. Yet the models are probably not yet suited to climate prediction *per se* and, without much further development, cannot provide information at a resolution appropriate to environmental monitoring and management.

Prominent amongst the many challenges facing modellers wanting to use GCMs as a more reliable tool to study the impacts of tropical deforestation are the development of improved biophysical models and new techniques for regional climate assessment. For example, the next generation of land-surface parameterizations should include more comprehensive models of micro-climate. In the longer-term, complete interactive links to biogeochemistry and terrestrial ecology could be usefully incorporated into such models, permitting simulation of time-dependent deforestation and regeneration as well as the analysis of trace gas contributions to the change in the radiation balance.

Finally, there are critical issues of scale to be considered. The limited integration time of many previous experiments is a shortcoming that is only slowly being addressed and does render many results open to doubt. Longer integration times are essential in climate-oriented studies. Given technical constraints, this requirement may cut across a parallel need to improve the spatial resolution of the model experiments. The limited spatial resolution of even the most sophisticated GCM is a serious deficiency when the key concern lies in analysing deforestation-related processes which, at the outset, have a characteristic spatial scale well below that of the models and have to be parameterized.

4.5: Summary

Large-scale conversion of tropical forests into pastures or crops is likely to change the local microclimate of those regions and may produce regional- or even global-scale impacts. A historical review of general circulation model (GCM) simulations of the climate effects of tropical deforestation is given in this chapter. The purposes is to compare the different features, perturbations, major developments and results of these experiments. Comparisons reveal that, in the case of Amazon Basin deforestation, there is some agreement in terms of discernible impacts on local and regional climate despite the considerable differences in model dynamical structures, land surface representation, ocean and cloud description, and also the length of the simulations. However, many uncertainties exist with respect to the magnitude and direction of changes depicted in the model results. The impacts simulated in response to tropical deforestation in the Amazon Basin, Southeast Asia and tropical Africa differed and the changes in response to deforestation in Southeast Asia and tropical Africa were smaller than resulting from Amazonian land cover change region. Recent simulations have shown that alteration of the model surface parameters following deforestation produces significant modifications of both the Hadley and Walker circulations, resulting in changes distant from the region of deforestation and the possibility of global-scale impacts.