

# Coupling A Biosphere-Atmosphere Transfer Scheme with A Mesoscale Atmospheric Model: A Case Study in Deforestation

by  
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Submitted to the Department of Civil and Environmental Engineering  
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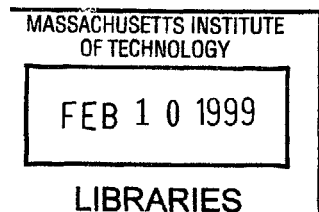
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## Abstract

The land surface influences the lower atmosphere and thus impacts the whole atmospheric circulation. The quality of land surface parameterizations in atmospheric circulation models should influence the quality of their simulations. Our effort is focused on coupling a comprehensive biosphere-atmosphere transfer scheme (BATS) with the Fifth-Generation NCAR/Penn State Mesoscale Model (MM5V2). The focus is on the role of vegetation in the energy and water budgets. The results show that by coupling the two models, we can get more realistic simulations of the lower atmosphere, the vegetation and the soil.

Four numerical experiments are performed over the Amazonia region using the coupled MM5V2-BATS driven by the data obtained from NCAR land use data archive. The first two experiments are used to evaluate the coupled model's performance in the Amazon region. Following the two experiments, a deforestation experiment and a control experiment are carried out. The control experiment is driven by the observed data while the deforestation experiment assumes that the all the domain is deforested and is completely covered by savannah. The results indicate that Amazonia deforestation produces less rainfall, less latent heat flux, more sensible heat flux and warmer surface and canopy temperatures.

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# Chapter 1

## Introduction

### 1.1 Scope

In order to address global environmental problems, the earth must be viewed as a whole system which includes atmosphere, biosphere and lithosphere. They interact with each other through physical, chemical and biological processes. The purpose of this study is to investigate the interactions between the atmosphere and the biosphere using numerical simulations. The earth's land surface plays a key role in the energy and water balances of the earth system. The land surface is spatially heterogeneous, characterized by land cover such as forest, grass, crop and desert. It also varies temporally. The land covers' properties are dependent on the season of the year. The atmosphere responds in many ways to the variable conditions of the land surface.

The land surface characteristics control the electromagnetic energy reflected, absorbed and emitted by the earth. The net solar radiation reflected by the land surface is determined by the surface albedo which is dependent on the vegetation type and the states of the soil and vegetation. The outgoing infrared radiation from the land surface to the overlying atmosphere is controlled by the surface temperature and emissivity. The surface roughness and vegetation characteristics and soil properties affect the turbulent energy fluxes in the planetary boundary layer. The structure of the atmospheric planetary boundary layer is controlled by the sensible and latent heat fluxes and by momentum flux from the land

surface. In turn, the states of the soil and the vegetation are affected by the atmosphere near the ground. The energy received at the surface will modify the states of soil and vegetation. The properties of soil and vegetation play a very important role in partitioning the net incoming radiation into sensible and latent heat flux. From the point of view of water transfer, the vegetation directly affects the rainfall interception and infiltration, evaporation and surface and ground water runoff. Therefore, the interaction between the atmosphere and land surface is very complicated.

Scientists have been trying to improve the descriptions of the hydrologic processes in the numerical models of the atmosphere. A large volume of research is focused on large scale models. For example, many general circulation models (GCMs) now include more and more detailed descriptions of the hydrologic processes. The results of the model simulations indicate that the hydrologic processes in the land surface play an important role in the atmosphere-land-ocean system. Many efforts are focused on the impact of the natural variability of land cover on the weather or climate. Other efforts are geared to understand human impact on climate such as that caused by deforestation and desertification. This study seeks to improve our understanding of the role of hydrology in the atmosphere-land interaction system in the Amazon basin by coupling a biosphere-atmosphere transfer scheme to a mesoscale atmospheric model and to investigate the impact of the present and future deforestation on the hydrologic processes and regional climate in the Amazon basin. The Amazon basin is important because it covers about six million squared kilometers and is a unique region which plays a significant role in the net global energy partition of sensible and latent heat fluxes. The Amazon river accounts for 20 percent of global runoff. The land cover change of this unique region will definitely impact the hydrologic processes and climate regionally and globally.

This study includes three parts. The first part includes a review and statement of the motivations of this study. The second part includes the descriptions of the NCAR/Penn State mesoscale atmospheric model MM5V2 and the Biosphere-Atmosphere Transfer Scheme and detailed description of the coupling procedure. This is the main part of the thesis. In the last part the coupled land-atmosphere model is used to study the impact of the change in vegetation/land cover, especially deforestation on the climate and hydrological processes in

the Amazon basin.

## 1.2 Outline

This thesis includes seven chapters. Chapter 2 is a review of relevant studies and the motivation and objectives of this study. The overall approach is described. Chapter 3 is the description of the atmospheric model used in this study. Chapter 4 describes the biosphere-atmosphere transfer scheme which is to be coupled to the atmospheric model. Chapter 5 describes the motivations for the coupling and describes the process and method of coupling the two models. Chapter 6 assesses the performance of the coupled atmosphere-land model by designing two numerical simulation experiments in the Amazon basin. Following the two experiments, a deforestation experiment and a control experiment are carried out. The deforestation experiment assumes that the tropical rainforest is replaced by savannah. Chapter 7 summarizes the numerical simulations and presents the conclusions from this study. Future studies are suggested.

# Chapter 2

## Literature Review

### 2.1 Historical Perspective

The sea surface temperature(SST) particularly in the tropics, is the most important determinant of seasonal to inter-annual climate variability. Second in importance is the influence of soil moisture and vegetation on the energy, moisture and momentum transfers between the atmosphere and the land surface.

Charney(1973) describes the dynamics of droughts in terms of the interactions, via surface albedo of the atmosphere and the land cover of the Sahel in North Africa. The loss of the vegetation cover in the desert increases the surface albedo which increases the reflected solar radiation at the surface leading to a reduction in net incoming radiation at the surface. A reduction in net radiation will cool the surface. The cooling affects the overlying atmospheric circulations in such a way as to reduce rainfall which further decreases the vegetation cover in the region. Charney's mechanism has been developed for studying the feedback of the biosphere to atmosphere in desert or semi-desert regions. His hypothesis is strictly based on radiative energy, without considering the role of water in the mechanism. However, can it be used to explain the interactions of biosphere-atmosphere in a warm and humid climate where atmospheric water vapor content is significant, e.g. in the Amazon tropical rainforest?

After Charney pointed out the issue of atmosphere-biosphere interactions, numerous studies have evaluated the sensitivity of atmospheric circulation to different surface forcings

by using one-, two- and three-dimensional global or mesoscale atmospheric models.

The first General Circulation Models(GCMs) in the 1970s treated the land surface as a simple reservoir of water and energy. The first parameterizations had no dependence on any observed data. In the 1980s, GCMs began to include land surface models which described the functions of soil and vegetation. At the end of the last decade there were increasing number of studies trying to improve and validate land surface parameterizations. Satellites now provide more realistic descriptions of global land cover for GCMs studies, which helps scientists recognize the importance of spatial heterogeneities and the important role of vegetation in water transfer and carbon dioxide assimilation(recent reviews include Dickinson, 1995a and b). There is growing need for developing more complete and realistic land surface parameterizations.

Surface parameterizations have evolved significantly during the last two decades. Deardorff(1977) proposed the use of a budget equation for the soil-surface moisture content. Evaporation and precipitation were included in the water balance in the soil. The equation allows for precipitation to saturate the soil, and then for evaporation to occur at its potential rate for some time. A plant module which includes a heat-balance equation for a single canopy layer, in addition to a heat-balance equation solved for the atmosphere-land surface interface, was also developed by Deardorff (1978). Carlson and Boland (1978) designed a one-dimensional model to simulate surface temperature and heat flux. McCumber and Pielke(1981) developed a bare-soil parameterization scheme, which included a multi-level soil layer, and 11 types of soil.

The Biosphere-Atmosphere Transfer Scheme(BATS) was developed by Dickinson(1984) and Dickinson et al.(1986). BATS is a surface-physics/soil-hydrology parameterization scheme which includes three soil layers, partial vegetation cover and time-dependent surface characteristics. Taconet et al. (1986) developed a vegetation and soil model, which contained a parameterization scheme of the energy and water transfers within the canopy(following Deardorff, 1978). The simple biosphere model(SiB) of Sellers et al.(1986 and 1992) was designed to provide a biophysically realistic description of processes that control the transfer of radiation, sensible heat, latent heat, and momentum between the terrestrial surface and the atmosphere. SiB was more complicated and required more input parameters than

the other equivalent land surface parameterizations. Wetzel and Chang(1988) presented a model of evapotranspiration from a natural heterogeneous surface, which assumed that the area-averaged soil moisture and vegetation coverage are known. A parameterization of land-surface processes developed by Noilhan and Planton(1989) was designed to achieve an accurate description of the main physical processes using the least number of prescribed parameters. The model considered the effect of gravity only when it calculated the ground-surface moisture.

Avissar and Pielke(1989) developed a parameterization of subgrid-scale effects, where each heterogeneous grid cell was divided into several homogeneous subgrid classes. For each of these subgrid classes, a complicated micrometeorological model of the soil-vegetation-atmosphere system was developed to calculate the surface temperature and the surface heat fluxes into the atmosphere. The surface heat fluxes for the grid cell were obtained by averaging the fluxes from the subgrid classes according to their distribution.

Bonan(1995) developed a land surface model(LSM) which simulated the energy, water, and momentum balance of the soil-vegetation-atmosphere system and operated globally with geographically prescribed vegetation and soil characteristics. Foley et al.(1996) developed an integrated biosphere simulator(IBIS) to describe the land surface processes, canopy physiology, vegetation phenology, terrestrial carbon balance and vegetation dynamics. This model provided a more dynamic and holistic framework to study the issues of global ecology and biosphere-atmosphere interactions.

Because of uncertainty of the accuracy of specifying the numerous surface parameters, scientists have examined in detail their impact on the overlying atmosphere. Deardorff(1978) found that soil moisture has a major influence on the characteristics of the surface heat fluxes which lead to significant impact on the planetary boundary layer. Carlson and Boland(1978) showed that moisture availability and thermal inertial are the surface parameters most responsible for the horizontal variation of the atmospheric temperature. Using their high-resolution PBL scheme, Zhang and Anthes(1982) found that the structure of the PBL during the daytime is most sensitive to the surface moisture availability and the roughness length. The one dimensional model of Colby(1984) showed that soil moisture has the greatest effect on the partitioning of energy between sensible and latent heat fluxes. Wetzel and



Chang(1988) concluded that the soil moisture and the fractional vegetation cover are the most important factors which affect the regional evapotranspiration. Segal(1989) studied the impact of very wet soil and canopy temperature on the surface sensible heat flux and the structure of the planetary boundary layer and found that the Bowen ratio over saturated or very wet surface is affected mostly by the surface temperature. Pinty et al.(1989) pointed out that the most sensitive parameter in the vegetation parameterization is the leaf stomatal resistance, which controls the Bowen ratio at the surface. They also found that the accuracy of the soil moisture data directly determines the accuracy of the surface predictions made by a mesoscale model. Giorgi(1989) used a two-dimensional mesoscale model coupled with BATS and found that the interception by the canopy foliage and the evaporation produced a sharp decrease in the canopy temperature when the precipitation began. Using a single vegetation canopy in a parameterization of land surface processes, Mahfouf and Jacquemin(1989) concluded that the interception of rainfall by vegetation strongly affected the water budget at the land surface.

Accuracy of description of the surface characteristic in each grid cell in a model is essential to predict the surface temperature and fluxes. The surface characteristics include the amount of moisture in the soil, the surface albedo and roughness length, the soil thermal properties, etc. In BATS, Dickinson(1984) divided each grid cell into vegetation and bare soil subareas, each with distinguishing characteristics. Avissar and Mahrer(1988) regrouped the similar homogeneous land patches at different places inside each grid cell into subgrid classes. Then, for each one of the subgrid classes, a group of specific surface parameters are defined. The total energy transferred between the atmosphere and the land surface from each grid cell is calculated by averaging according to the distribution of the subgrid classes. This kind of parameterization of subgrid-scale heterogeneity would represent the surface forcing more accurately.

Recently most GCMs contain a land surface model which represents the biophysical interactions between land surfaces and the overlying atmosphere. Common land surface models include BATS of Dickinson et al.(1986), SiB of Sellers et al.(1986, 1992), LSX of Pollard and Thompson(1995) and LSM of Bonan(1995). The Biosphere-Atmosphere Transfer Scheme(BATS) was originally developed to be coupled with the NCAR Community Cli-

mate Model(CCM). The current version of BATS is a piece of software with about four thousand lines of code that can run as an off-line version or coupled to an atmospheric model. Giorgi(1989) coupled a two-dimensional regional atmospheric model MM4 with BATS. Lakhtakia(1993) coupled a one-dimensional NCAR/Penn State mesoscale model with BATS. Their studies showed that coupling BATS in the atmospheric models can improve the simulation of the surface fluxes and therefore enhance the description of the evolution of the planetary boundary layer.

## 2.2 Motivation and goal

The Fifth-Generation NCAR/Penn State mesoscale atmospheric model MM5V2 is the latest in a series that developed from a mesoscale model used by Anthes at Penn State University in the early 70's that was later documented by Anthes and Warner (1978). The model can be applied to study a broad range of atmospheric phenomena. The model has many options for precipitation physics, planetary boundary layer processes and atmospheric radiation.

There are four types of planetary boundary schemes available in MM5V2. A surface processes parameterization is included in all of them. The surface module contains 13 vegetation categories and use energy balance equations to predict the ground temperature. The surface fluxes and momentum are calculated in the planetary boundary layer schemes. Two kinds of methods are used to calculate the surface fluxes in the PBL schemes. One is bulk-aerodynamic theory following Deardorff(1972) which is used in the bulk-aerodynamic PBL scheme. The other is similarity theory which calculates the surface fluxes in terms of the friction velocity. This method is applied in the high-resolution Blackadar PBL scheme(Blackadar, 1766, 1979; Zhang and Anthes, 1982). In both cases, the surface characteristics in each grid cell are spatially homogeneous and temporally constant. The surface parameters are provided through a look-up table indexed by the vegetation type. Both cases do not consider water balance at the land surface.

This representation of the surface characteristics in MM5V2 is very simple, and, it may not work well in some simulations. For example, Zhang(1985) found that the soil moisture availability parameter had to be modified to represent the wetting of the surface during

the precipitation and the drying afterwards in order to get a reasonable feedback from the surface to the PBL. Oncley and Dudhia(1995) compared the direct observations of surface fluxes of momentum, sensible and latent heat and the results from MM5V2 and concluded that the the surface fluxes are very sensitive to the parameters such as roughness length and moisture availability. If they are not specified appropriately, the simulation results of the surface fluxes from MM5V2 do not correspond well with the observations.

The above calls the need for a more complete and sophisticated surface parameterization in the mesoscale atmospheric model MM5V2. A good choice is the Biosphere-Atmosphere Transfer Scheme(BATS) which is developed by Dickinson(1984, 1986). BATS is a complicated soil-vegetation-atmosphere transfer scheme which emphasizes the role of vegetation in the modifying the surface moisture and energy budgets. It allows for heterogeneity in each grid cell and time-dependent surface parameters. A combination of the NCAR/Penn State model version 1 and BATS, which is much simpler than the version MM5V2, has already been utilized in studies of the regional climate of the western United States by Dickinson et al.(1989) and Giorgi and Bates(1989). Lakhtakia(1993) coupled BATS within the one-dimensiona NCAR/Penn State mesoscale model to improve the description of the land surface processes. Their studies showed that the simulation results improve after using BATS as the surface parameterization.

This study seeks to understand the water and energy balance over the Amazon and to investigate the impact of Amazonia deforestation on the regional climate and hydrological processes. Recent field observations from the Amazon confirm that conversion of the land surface cover from tropical rain forest to savannah increases sensible heat flux and surface temperature, while it decreases evaporation and rainfall. These results lead to modify the land surface energy balance and therefore impact the structure of the overlying atmospheric boundary layer. Several numerical experiments have been carried out by Dickinson and Henderson-Sellers(1988), Lean and Warrilow(1989), Dickinson and Kennedy(1992) and Dirmeyer and Shukla(1994). They used General Circulation Models(GCMs) to study the impact of the Amazonia deforestation. They concluded that larger-scale(the Amazon basin wide) deforestation will result in: higher surface temperature, less evaporation and less rainfall. Eltahir and Bras(1994) performed several numerical experiment using a regional climate

model (MM4) with BATS in it. In the experiments, they assumed that the rain forest is replaced by short grass over an area 250km x 250km. The results indicated that the change of rainfall is of the same sign, but of much smaller magnitude, compared to the results from GCMs. However, Bastable et al.(1993) found that there is no significant difference between the observed rainfall over a rain forest area and that over the nearby deforested area of 1 to 100 squared kilometers.

The magnitude of predicted changes in climate seems to become smaller as the atmospheric numerical models become more refined and the land surface parameterization improves. Does scale influence the impact of deforestation? MM5V2 is a good atmospheric model to address this problem since MM5V2 can represent processes from global scale down to cloud scale. From the previous description, we know that the surface parameterization in MM5V2 is quite simple. The simulation of surface fluxes will improve if BATS is coupled into MM5V2. The high-resolution Blackadar PBL scheme is chosen to be used in the coupled model. More realistic and accurate simulation results are expected from MM5V2-BATS coupled model.

## 2.3 Overall approach

In coupling the Biosphere-Atmosphere Transfer Scheme (BATS) to the mesoscale atmospheric model MM5V2, the simple surface module in the high-resolution Blackadar PBL scheme is replaced by BATS. This requires a complete comparison and matching of variables and parameters in BATS and MM5V2. Additional initializations are required according to more parameters required by BATS. An interface is built to transfer the atmospheric and surface hydrological data between the atmospheric model MM5V2 and BATS. Some physical modifications are performed such as the calculation of Richardson number and the instantaneous precipitation rate.

After testing, debugging and choosing the appropriate physics options, two validation experiments are performed using the coupled model in the Amazon basin. A deforestation experiment and a control experiment are also carried out in order to study the impact of the Amazonia deforestation.

# Chapter 3

## Description of Mesoscale

### Meteorological Model MM5V2

The PSU/NCAR mesoscale model is a limited-area, hydrostatic/non-hydrostatic, sigma-coordinate model designed to simulate or predict mesoscale and regional scale atmospheric circulation. It is a three-dimensional primitive equation solver. It was developed at Penn state and NCAR (National Center for Atmospheric Research) as a community mesoscale model and is continuously being improved. It can be used as a framework to test the parameterizations of the turbulent fluxes in the planetary boundary layer since model results can be compared to detailed and localized observations.

The fifth-Generation NCAR/Penn State Mesoscale Model (MM5) is the latest in a series that was developed from the mesoscale model used by Anthes at Penn State in the early 70's and was later documented by Anthes and Warner(1978). Since that time, it has undergone many changes designed to broaden its usage. These include: (i) a multiple-nesting capability, (ii) nonhydrostatic dynamics, and (iii) a four-dimensional data-assimilation capability. MM5 Version 1 was released early in 1994, but it assumed that most users use the NCAR Cray for running MM5 and all the pre-processors. In order to meet the need to use MM5 both on Cray and most workstations, MM5V2 was developed and also released in 1994. As a growing number of atmospheric physics options becomes available, MM5V2 has undergone many changes and still need more tests and improvement.

## 3.1 Structure of the MM5V2 Model System

MM5V2 is supported by several auxiliary programs which are collectively called the MM5V2 modeling system. A schematic diagram Figure 3-1 is provided to show the complete MM5V2 modeling system. The MM5V2 modeling system includes TERRAIN, DATAGRID, RAWINS, INTERP and MM5V2. The primary functions of these programs are described below. Terrestrial and isobaric meteorological data are horizontally interpolated ( programs TERRAIN and DATAGRID ) from a latitude-longitude mesh to a variable high-resolution domain on either a Mercator, Lambert conformal, or polar stereographical projection. The horizontally interpolated data can be enhanced by the program RAWINS which handles the observations from the standard network of surface and rawinsonde stations. Program INTERP performs the vertical interpolation pressure-level data from either RAWINS or DATAGRID to the sigma coordinate system of MM5V2. Sigma levels near the surface closely follow the terrain while the higher levels tend to approximate the isobaric surfaces.

## 3.2 Features of MM5V2 Model

MM5V2 was developed on the workstation version of MM5 and was first released in 1994. MM5V2 has been changed dramatically to meet a growing demand of scientific needs. Some of its features are listed below.

### 3.2.1 Terrain-following Coordinate

One of the features of MM5V2 is the terrain-following vertical coordinate which is essential to a mesoscale atmospheric model. The terrain following coordinate means that the lower levels are following the terrain while the top levels are very flat. A dimensionless variable  $\sigma$  is used to represent the model levels and is defined by

$$\sigma = \frac{p - p_t}{p_s - p_t} \quad (3.1)$$

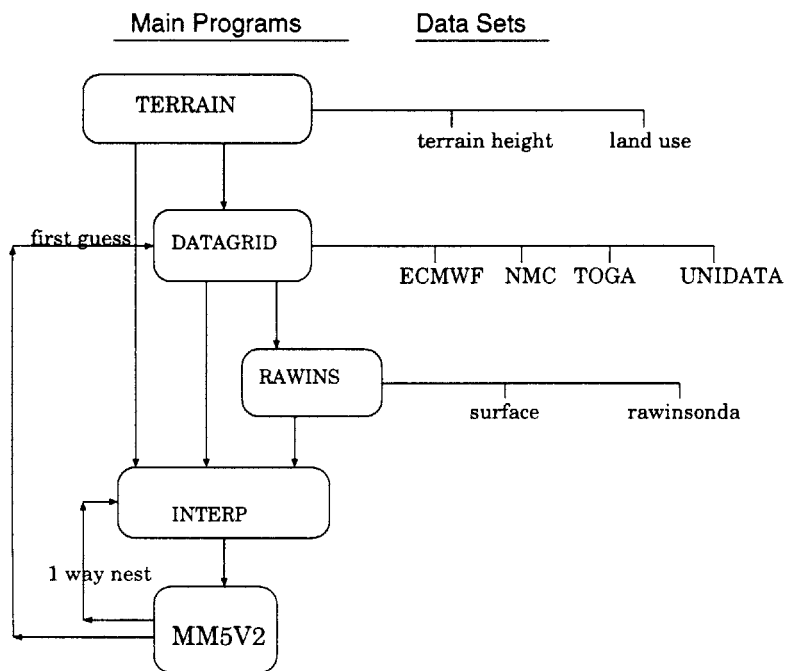


Figure 3-1: Diagram of MM5V2 Modeling System

where  $p$  is the pressure,  $p_t$  is the top pressure while  $p_s$  is the surface pressure. From the formulation, we can see that  $\sigma$  is zero at the top and one at the surface.

### 3.2.2 Directory Tree Structure

The NCAR/Penn State mesoscale atmospheric model MM5V2 has more than 200 subroutines and these are grouped according to functions or atmospheric physics options. A single directory may contain routines that are relevant to one parameterization. This allows easy and efficient compilation and modifications. The directory structure of MM5V2 is illustrated in Figure 3-2.

## 3.3 Input Data for MM5V2

MM5V2 allows real time data inputs. It can use routine observations, for example, upper air and surface observations, including wind, temperature, relative humidity, sea-level pressure, and sea surface temperature.

The results of other models, GCMs or the regional models, can be used as first guess for objective analysis or as lateral boundary conditions to drive MM5V2. Examples of these accessory models are the NCEP and ECMWF global analysis, NCEP/NCAR and ECMWF reanalysis, NCEP ETA model. Before incorporating into the MM5V2 model, the GCM data normally has to be interpolated from large grid resolution to mesoscale grid resolution.

Data required by MM5V2 include lateral boundary conditions and initial conditions. Required three-dimensional input variables are temperature, U-wind, V-wind and relative humidity. Needed two dimensional variables include terrain elevation, land use, snow cover, sea-level pressure and surface temperature.

The input data of temperature, U-wind, V-wind and relative humidity, snow cover, sea-level pressure and temperature are obtained and processed using program DATAGRID which accesses the archived low-resolution meteorological analysis stored in NCAR's mass storage system. These include: NMC(global analysis; grid size of  $2.5^\circ \times 2.5^\circ$ ), ECMWF(global analysis; grid size of  $2.5^\circ \times 2.5^\circ$ ; 1980-1989 only), TOGA(global analysis; grid size of  $2.5^\circ \times$



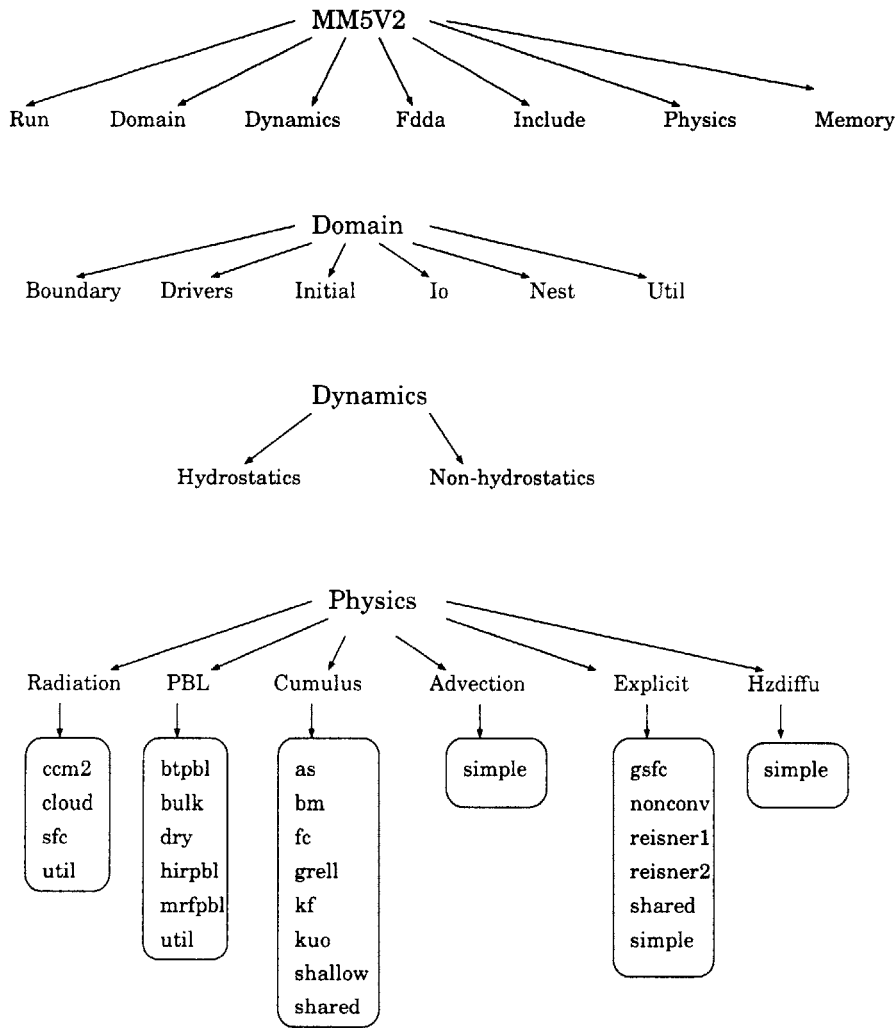


Figure 3-2: MM5V2 multi-level directory structure

Resolution	Data source	Coverage	Size
1 deg.(111.0 km)	PSU/NCAR	Global	180x360
30 min.(55.0 km)	PSU/NCAR	Global	360x720
10 min.(18.5 km)	Geophysical Data Center	Global	1080x2160
5 min.(9.25 km)	Geophysical Data Center	Global	2161x4320
30 sec.(0.925 km)	Defense Mapping Agency	51-23N,130-60W	3361x8401

Table 3.1: Terrain Heights Data Sources

Resolution	Data source	Coverage	Size
1 deg.(111.0 km)	PSU/NCAR	Global	180x360x13
30 min.(55.0 km)	PSU/NCAR	Global	360x720x13
10 min.(18.5 km)	PSU/NCAR	Global	1080x2160x13

Table 3.2: Land Use Data Sources

2.5°), Unidata(NMC MRF forecasts, grid size of 2.5° x 5.0°).

The input data of terrain height and land use are obtained and processed using program TERRAIN. There are five types of elevation data sources: 1-degree, 30-, 10-, 5-minute and 30-second, and three types of land-use data: 1-degree, 30- and 10-minute, available. Table 3.1 shows the information of terrain elevation data sources. Table 3.2 gives the information of land use data sources. There are 13 vegetation types in each land use data source. Data sources are selected to be compatible with the mesoscale grid resolution desired.

The output data from MM5V2 in each time period includes three-dimensional atmospheric variables and two-dimensional surface variables. Three-dimensional variables are U-wind, V-wind, temperature, water vapor mixing ratio, cloud water mixing ratio, rain water mixing ratio, cloud ice mixing ratio, snow mixing ratio, graupel, number concentration of ice, turbulent kinetics, atmospheric radiation tendency, vertical velocity and perturbation pressure. Two-dimensional forecast variables are ground temperature, accumulated convective and nonconvective rainfall, PBL height, surface sensible heat flux, surface latent heat flux, frictional velocity, surface downward shortwave and longwave radiation.

### 3.4 Uses and Capabilities of MM5V2

The Mesoscale model MM5V2 can be used for a broad spectrum of theoretical and real-time studies, including simulation and four-dimensional data assimilation of monsoons, hurricanes and cyclones. The model is very flexible. The horizontal resolution can be set from the global scale down to cloud scale ( for example less than 5km). With high resolution of 2-200km, this mesoscale model can be used for studying mesoscale convective systems, mountain-valley circulations, land-sea breeze and urban heat islands. It can also be used as a framework to test parameterizations of the turbulent fluxes in the planetary boundary layer since results can be compared to detailed and localized observations.

MM5V2 can be used globally. The modeling system provides three kinds of projections to support the different latitudes. Polar projections are used for the latitude ranging from  $60^\circ$  to the pole in the southern or northern hemisphere. Lambert conformal projection serves the area between  $30^\circ$  and  $60^\circ$  latitude, while in the tropical range, Mercator is mostly used.

One aspect of MM5V2 is its nesting capability which allows up to nine domains to run at the same time and to interact completely. It can be run in both 2-way and 1-way nesting mode. The 1 way nesting means that the fine-mesh model is driven by the coarse-mesh model. The 2-way nesting means fine-mesh model and coarse-mesh model interact with each other. The nest can be started, moved and ended at any time.

Another attractive feature of MM5V2 is that the model is free and widely available. It can run on various platforms, such as DEC, SUN, IBM, HP, SGI, Cray and some PCs which can run Linux.

MM5V2 has a wide range of applications for theoretical or real-time studies. It has various advanced physical parameterizations covering many different aspects of atmospheric processes. New physics options available include three cumulus parameterizations (Kain-Fritsch, Fritsch-Chappell and Betts-Miller), a new planetary boundary layer scheme(Burk-Thompson), radiation scheme(CCM2) and two microphysics schemes with graupel(Reisner-2 and Goddard).

MM5V2 is commonly used to simulate the atmosphere-land surface interactions. In studying this issue, a complete and realistic description of the land surface processes is

necessary. If a land surface scheme is to be coupled with MM5V2, it is very clear that the planetary boundary layer is a critical element. The PBL structure is determined by the spatial and temporal variations of sensible heat flux, latent heat flux and momentum flux from the land surface. In turn, the PBL conditions will directly affect land surface variables such as the temperatures of vegetation and soil. The PBL scheme is the key connection if we want to couple a model like the Biosphere-Atmosphere Transfer Scheme(BATS) with MM5V2. The following section is the detailed description of the PBL schemes used in MM5V2.

### **3.5 PBL schemes in MM5V2**

The computation of the sensible heat flux and the latent heat flux depends on what PBL parameterization is used in MM5V2. There are five PBL options available in MM5V2: None, Bulk-aerodynamic PBL, High-resolution Blackadar PBL, Burk-Thompson PBL and MRF PBL. In None PBL scheme, there is no surface layer and is unrealistic in real-time solutions. The bulk-aerodynamic PBL parameterization calculates the surface fluxes using exchange coefficients and the characteristics of the land surface and the meteorological conditions of the atmosphere near the land surface. The bulk PBL parameterization is suitable for a coarse vertical resolution in the boundary layer, for example, more than 250m in the vertical grid. The high-resolution Blackadar PBL parameterization provides more vertical levels in the lower atmosphere. It is suitable for high resolution representation of the PBL, for example 5 layers in the lowest km and a surface layer less than 100m thick. Four stability conditions, stable, mechanically driven turbulence, forced convection and unstable(free convection) are considered in this scheme. The Burk-Thompson PBL scheme is good for both coarse and high-resolution PBLs. It can predict turbulent kinetic energy for use in vertical mixing, based on Mellor-Yamada formulas(see Burk-Thompson(1989) for details). The MRF PBL (or Hong-Pan PBL) is suitable for high-resolution in the PBL(as the Blackadar scheme). It is based on a Troen-Mahrt representation of the profiles in the well mixed PBL, as implemented in the NCEP MRF model(see Hong and Pan(1996) for details). The MRF PBL and Burk-Thompson PBL schemes are newly available. The high-resolution Blackadar scheme is chosen

in this study to be the PBL scheme when the Biosphere-Atmosphere Transfer Scheme is coupled to MM5V2.

The high-resolution Blackadar PBL scheme follows Blackadar (1976)'s pioneering work. It was further developed by Zhang and Anthes(1982). The scheme is designed to simulate the characteristics of the planetary boundary layer, the land surface and their interactions. The scheme includes three atmosphere layers and two soil layers. The atmosphere layers are: free atmosphere layer, mixed layer of the PBL and atmosphere surface layer. The soil layers are a soil surface slab layer and a soil substrate layer.

The surface fluxes in the high resolution PBL scheme are calculated on the basis of similarity theory. The friction velocity is defined as

$$u_{\star} = MAX\left(\frac{kV}{\ln\left(\frac{z_a}{z_0}\right) - \psi_m}, u_{\star 0}\right) \quad (3.2)$$

where  $k$  is the von Karman constant.  $u_{\star 0}$  is the background value (usually 0.1 m/s over land and zero over water). The local velocity  $V$  is given by

$$V = (V_a^2 + V_c^2)^{\frac{1}{2}} \quad (3.3)$$

where  $V_a$  is the local velocity at the lowest atmospheric layer while  $V_c$  is the local convective velocity, which is defined under unstable and neutral conditions as

$$V_c = 2(\theta_g - \theta_a)^{\frac{1}{2}} \quad (3.4)$$

while it is zero under stable condition.

Based on the similarity theory, the surface sensible heat flux is computed as

$$H_s = -C_{pm}\rho_a k u_{\star} T_{\star} \quad (3.5)$$

where

$$T_{\star} = \frac{\theta_a - \theta_g}{\ln\frac{z_a}{z_0} - \psi_h} \quad (3.6)$$

where  $T_*$  is the temperature scaling parameter,  $C_{pm}$  is the specific heat at constant pressure for moist air,  $z_0$  is the roughness parameter,  $z_a$  is the height of the lowest  $\sigma$  level.  $\theta_a$  and  $\theta_g$  are the atmosphere potential temperature at the lowest atmosphere level and ground level, respectively.  $\psi_h$  is a nondimensional stability parameter for sensible heat flux.

The surface moisture flux is calculated from

$$E_s = -M\rho_a h u_* q_* \quad (3.7)$$

where  $M$  is the surface moisture availability which is a given constant based on the vegetation type. The approach to define  $q_*$  is similar to the way to define  $T_*$ .  $q_*$  is given by

$$q_* = \frac{q_a - q_s(T_g)}{\ln \frac{z_a}{z_0} - \psi_m} \quad (3.8)$$

where  $q_*$  is the specific humidity scaling parameter,  $q_a$  is the atmosphere specific humidity at the lowest atmosphere level,  $q_s(T_g)$  is the saturated specific humidity at the ground temperature.  $\psi_m$  is the nondimensional stability parameter for moisture heat flux.

Both  $\psi_h$  and  $\psi_m$  are the nondimensional stability parameters which are functions of the bulk Richardson number  $R_{iB}$  which is defined as

$$R_{iB} = \frac{gz_a}{\theta_a} \frac{\theta_{va} - \theta_{vg}}{V^2} \quad (3.9)$$

where the subscript  $v$  represents the virtual potential temperature. The definition of the virtual potential temperature is

$$\theta_{va} = \theta_a \left[ 1 - \frac{E \times (1 - 0.622)}{P} \right] \quad (3.10)$$

where  $\theta_a$  is the potential temperature,  $E$  is the actual vapor pressure and  $P$  is the pressure.

There are four stability cases in this scheme: the stable case, mechanically driven turbulence, the unstable(forced convection) case and the unstable(free convection) case.

A) Stable case

For the stable case,  $R_{iB} > R_{ic}$ , where the critical Richardson number  $R_{ic}$  is defined as

$$R_{ic} = .2 \quad (3.11)$$

In this case,

$$\psi_m = \psi_h = -10 \ln \frac{z_a}{z_0} \quad (3.12)$$

and

$$H_s = \text{Max}(-250 \text{wm}^{-2}, -C_{pm} \rho_a k u_* T_*) \quad (3.13)$$

B) Mechanically driven turbulence

For this case  $0 \leq R_{iB} \leq R_{ic}$ ,

$$\psi_m = \psi_h = -5 \left( \frac{R_{iB}}{1.1 - 5R_{iB}} \right) \ln \frac{z_a}{z_0} \quad (3.14)$$

C) Unstable(forced convection) Here  $R_{iB} < 0$  and  $|h/L| \leq 1.5$ , where the Monin-Obukhov

length(L) defined as

$$L = - \frac{c_{pm} \rho_m \theta_a u_*^3}{kg H_s} \quad (3.15)$$

where  $h$  is the height of the PBL. In this case,  $\psi_m = \psi_h = 0$ .

D) Unstable(free convection)

For this case  $R_{iB} < 0$  and  $|h/L| > 1.5$ , and we get

$$\psi_h = -3.23 \left( \frac{z_a}{L} \right) - 1.99 \left( \frac{z_a}{L} \right)^2 - 0.474 \left( \frac{z_a}{L} \right)^3 \quad (3.16)$$

and

$$\psi_m = -1.86\left(\frac{z_a}{L}\right) - 1.07\left(\frac{z_a}{L}\right)^2 - 0.249\left(\frac{z_a}{L}\right)^3 \quad (3.17)$$

where  $z_a/L$  is restricted to be no less than -2.0 in this approximation. For  $z_a/L$  equal to -2.0,  $\psi_h = 2.29$  and  $\psi_m = 1.43$ .

In the general case,  $z_a/L$  is a function of  $\psi_m$ . We can approximate  $z_a/L$  as an explicit function of  $R_{iB}$  as

$$\frac{z_a}{L} = R_{iB} \ln \frac{z_a}{z_0} \quad (3.18)$$

The high-resolution Blackadar scheme emphasizes the energy transfer between the land surface and the overlying atmosphere and ignores the water transfer. A slab model is used to calculate the surface temperature through an energy budget equation. The energy budget equation is based on the 'force-restore' method developed by Blackadar (Zhang and Anthes 1982). The budget equation is

$$C_g \frac{\partial T_g}{\partial t} = R_n - H_m - H_s - L_v E_s \quad (3.19)$$

where  $C_g$  is the thermal capacity of the slab per unit area,  $R_n$  is the net radiation,  $H_m$  is the heat flow into the substrate,  $H_s$  is the sensible heat flux into the atmosphere,  $L_v$  is the latent heat of vaporization, and  $E_s$  is the surface moisture flux. Blackadar (1979) defines that

$$C_g = 3.293 \times 10^6 \chi \quad (3.20)$$

where  $\chi$  ( $\text{cal cm}^{-2} \text{K}^{-1} \text{s}^{-\frac{1}{2}}$ ;  $1 \text{ cal} = 4.18 \text{ J}$ ) is the thermal inertia, specified in the model as a function of vegetation/land-use characteristics (See in Table 3.4).

In Chapter 5, the differences in calculations of the surface fluxes between MM5V2 and BATS will be discussed.



Landuse Index	MM5V2
1	Urban land
2	Agriculture
3	Range-grassland
4	Deciduous forest
5	Coniferous forest
6	Mixed forest and wet land
7	Water
8	Marsh or wet land
9	Desert
10	Tundra
11	Permanent ice
12	Tropical or sub tropical forest
13	Savannah

Table 3.3: Vegetation/land cover types in MM5V2

### 3.6 Vegetation

There are 13 vegetation types in MM5V2, shown in Table 3.3. Three types of land-use source data are available: 1-degree, 30-, 10-minute. The information about the land use dataset sources was presented in section 3.3. At each grid point of the dataset, there are 13 numbers of percentages for the 13 categories. The overlapping parabolic interpolation method is applied to obtain the percentages for each land-use category at the mesoscale grid point. If the water coverage is more than 50 percent at the mesoscale grid point, the category of water will be assigned to the mesoscale grid point. If the water coverage is less than 50 percent, the category with the maximum percentage excluding water will be assigned to the mesoscale grid point.

MM5V2 translates the vegetation type into the land surface characteristics, such as albedo, moisture availability, emissivity, roughness length, and thermal inertia, all of which are shown in Table 3.4.

The unit for albedo, moisture availability and emissivity is percentage, and the unit for thermal inertia is  $\text{cal cm}^{-2}\text{k}^{-1}\text{s}^{-1/2}$ . All the parameters of land surface characteristics in MM5V2 are temporally constant and seasonally dependent, according to summer or winter

Veg.Index	Albedo		Moi.Avail.		Emissivity		Roughness(cm)		Thermal Inertia	
	S	W	S	W	S	W	S	W	S	W
1	18	18	5	10	88	88	50	50	0.03	0.03
2	17	23	30	60	92	92	15	5	0.04	0.04
3	19	23	15	30	92	92	12	10	0.03	0.04
4	16	17	30	60	93	93	50	50	0.04	0.05
5	12	12	30	60	95	95	40	40	0.05	0.06
6	14	14	35	70	95	95	40	40	0.05	0.06
7	8	8	100	100	98	98	0.01	0.01	0.06	0.06
8	14	14	50	75	95	95	20	20	0.06	0.06
9	25	25	2	5	85	85	10	10	0.02	0.02
10	15	70	50	90	92	92	10	10	0.05	0.06
11	55	70	95	95	95	95	5	5	0.05	0.06
12	12	12	50	50	95	95	50	50	0.05	0.05
13	20	20	15	15	92	92	15	15	0.03	0.03

Table 3.4: Descriptions of vegetation categories and physical parameters for summer(15 April - 15 October) and winter(15 October - 15 April).

season(for northern hemisphere). All these values for the variables are climatological and may not be optimal for a particular case, especially moisture availability.

# Chapter 4

## Description of the Biosphere-Atmosphere Transfer Scheme

The Biosphere-Atmosphere Transfer Scheme(BATS) was introduced by Dickinson and Kennedy (1984). This scheme represents a comprehensive model of land-surface processes. Special emphasis has been given to properly describing the role of vegetation in modifying the surface moisture and energy fluxes. This model is suitable for use in "coupled mode" (interactively coupled to an atmospheric model) or in "stand-alone mode" (forced with observed atmospheric data). Several versions described by Dickinson(1984), Dickinson et al(1986), Wilson et al.(1989) and Dickinson(1993) were later developed with contributions from Klaus Bluemel, Filippo Giorgi, and Ann Henderson-Sellers. Initially BATS was developed for a multilevel GCM which had a very detailed description of the boundary layer and the soil layer. The present version, BATS1e, is used as the land surface parameterization for the NCAR Community Climate Model(CCM). We modify the BATS1e version and couple it within the mesoscale atmospheric model(MM5V2) in order to study the role of the land surface in the mesoscale atmospheric circulation. The summary of the features of BATS, as well as our modifications, are described below. Next several sections are mostly based on the document of BATS Version 1e described by Dickinson et al. (1993).

The purposes of BATS are

1. to determine the fraction of incident solar radiation that is absorbed by different surfaces and their net exchange of thermal infrared radiation with the atmosphere;
2. to calculate the transfers of momentum, sensible heat, and moisture between the earth's surface and the atmospheric layers;
3. to determine values for wind, moisture, and temperature in the atmosphere, within vegetation canopies, and at the level of surface observations;
4. to determine values of temperature and moisture quantities at the earth's surface.

Included in point 4 are the determination of the moisture content of soil, the excess rainfall that goes into runoff, and the state of the moisture content of soil at the surface, i.e., whether it is snow or water. In order to carry out these calculations, it is important to prescribe a dominating land use type in each mesoscale grid point since the coverage of the vegetation has a significant impact on the exchanges of the energy and water between the atmosphere, vegetation and soil. BATS allows for heterogeneity over each grid cell. Bare-soil and vegetation-covered sub-areas can coexist in each grid cell. The vegetation coverage is seasonally varied.

BATS considers four layers: a vegetation layer, a surface soil layer, a root-zone soil layer and a deep soil layer. The schematic of the most important processes in BATS is presented in the Figure 4-1.

## 4.1 Parameters in BATS

Many parameters are involved in the simulations of different processes at the land surface in BATS. These parameters are grouped into three categories: the type of vegetation cover, the soil texture and the color of the soil. BATS defines 18 vegetation types, 12 soil texture classes and 8 soil color types. Table 4.1 shows the vegetation types in BATS and their corresponding soil-texture classes and soil-color classes. Twelve soil-texture classes range from sand(class 1) to heavy clay(class 12) through loam(class 6). Eight soil-color classes range from light(class 1) to dark(class 8). Table 4.2 shows the parameters that are dependent on vegetation types, as well as their values. Those parameters which are dependent on the soil textures and soil

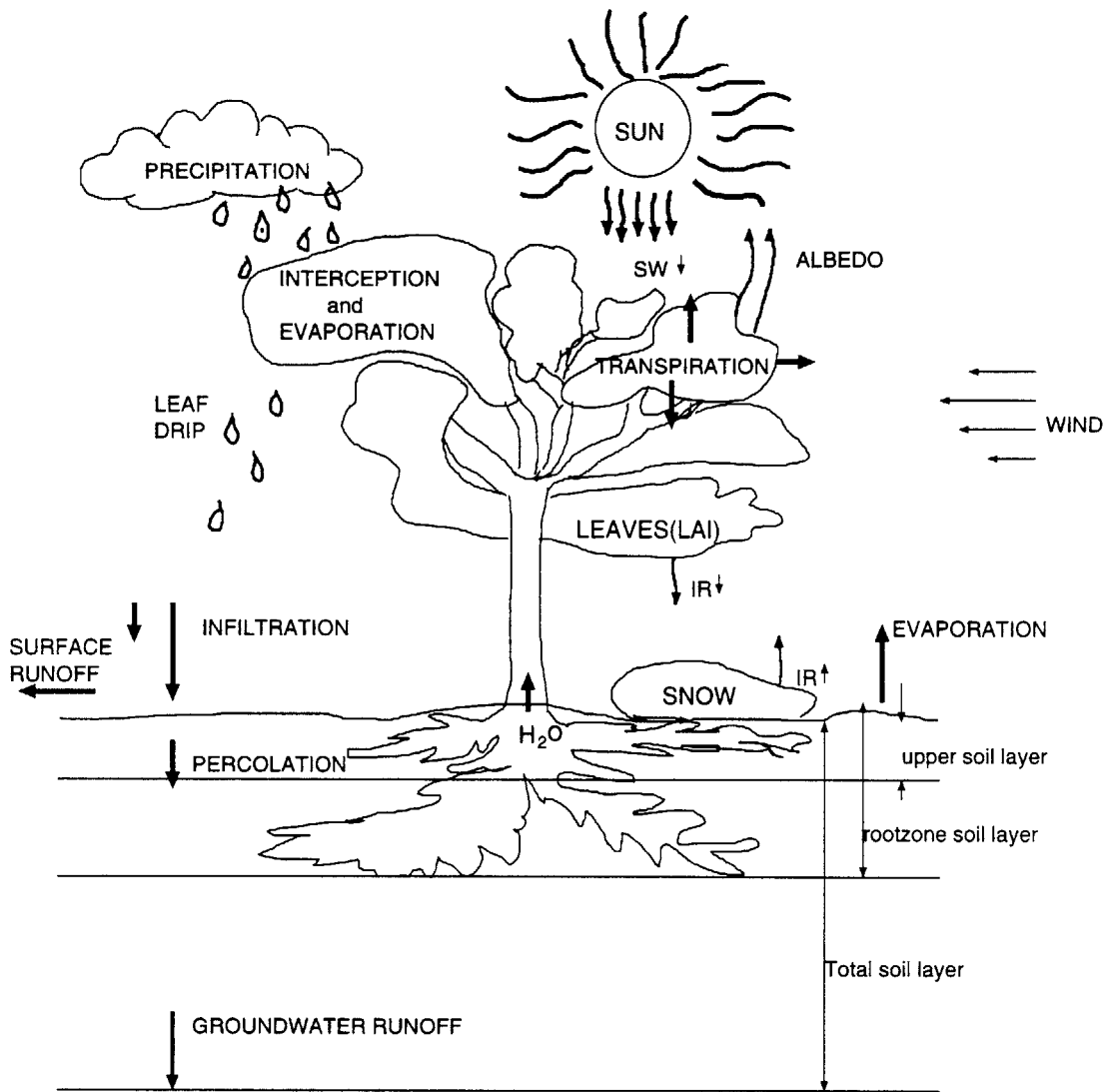


Figure 4-1: Schematic diagram of the processes in BATS(modified from Dickinson et al.1993.)

Veg. Index	Veg. Description	Soil-texture type	Soil-color type
1	Crop/mixed farming	6	5
2	Short grass	6	3
3	Evergreen needleleaf tree	6	4
4	Deciduous needleleaf tree	6	4
5	Deciduous broadleaf tree	7	4
6	Evergreen broadleaf tree	8	4
7	Tall grass	6	4
8	Desert	3	1
9	Tundra	6	3
10	Irrigated crop	6	3
11	Semi-desert	4	1
12	Ice cap/glacier	-	-
13	Bog/marsh	6	5
14	Inland water	-	-
15	Ocean	-	-
16	Evergreen shrub	6	4
17	Deciduous shrub	5	3
18	Mixed woodland	6	4

Table 4.1: Vegetation/land cover types and their soil-texture classes and soil-color classes in BATS

colors are listed in Table 4.3.

The major parameters of vegetation in BATS include fractional vegetation coverage, leaf area index, vegetation albedo, roughness length, and emissivity. Among these, the leaf area index and the fractional vegetation coverage are seasonally dependent. Other parameters, such as minimum stomatal resistance, heat storage capacity and root depth must be specified.

## 4.2 Time-Dependent Parameters

Some parameters which describe surface characteristics in BATS are time-dependent. For example, BATS allows for varying albedos for the vegetation and the bare soil. There are three albedo variables for each grid cell in BATS. The albedo variables in BATS are visible solar albedo of vegetation ( $\lambda < 0.7\mu\text{m}$ ), near-infrared albedo of vegetation ( $\lambda > 0.7\mu\text{m}$ ), and soil albedo. The values for albedo are determined from several sources: the work of

Table 4.2: Vegetation parameterization in BATS (from Dickinson et al. 1993)

		<u>VEGETATION/LAND COVER PARAMETERS</u>																	
	<u>Parameter</u>	<u>Land Cover/Vegetation Type</u>																	
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
a)	Maximum fractional vegetation cover	0.85	0.80	0.80	0.80	0.80	0.90	0.80	0.0	0.60	0.80	0.10	0.0	0.80	0.0	0.0	0.80	0.80	0.80
b)	Difference between maximum fractional vegetation cover and cover at temperature of 269 K	0.6	0.1	0.1	0.3	0.3	0.5	0.3	0.0	0.2	0.6	0.1	0.0	0.4	0.0	0.0	0.2	0.3	0.2
c)	Roughness length (m)	0.06	0.02	1.9	1.0	0.8	2.0	0.1	0.05	0.04	0.06	0.1	0.01	0.03	0.0024	0.0024	0.1	0.1	0.8
d)	Depth of the rooting zone soil layer (m)**	1.0	1.0	1.5	1.5	2.0	1.5	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	2.0
e)	Depth of the upper soil layer (m)**	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
f)	Fraction of water extracted by upper layer roots (saturated)	0.3	0.8	0.67	0.67	0.5	0.8	0.8	0.9	0.9	0.3	0.8	0.5	0.5	0.5	0.5	0.5	0.5	0.5
g)	Vegetation albedo for wavelengths <0.7 $\mu\text{m}$	0.10	0.10	0.05	0.05	0.08	0.04	0.08	0.20	0.10	0.08	0.17	0.80	0.06	0.07	0.07	0.05	0.08	0.06
h)	Vegetation albedo for wavelengths >0.7 $\mu\text{m}$	0.30	0.30	0.23	0.23	0.28	0.20	0.30	0.40	0.30	0.28	0.34	0.60	0.18	0.20	0.20	0.23	0.28	0.24
i)	Minimum stomatal resistance ( $\text{s m}^{-1}$ )	120	200	200	200	200	150	200	200	200	200	200	200	200	200	200	200	200	200
j)	Maximum LAI	6	2	6	6	6	6	6	0	6	6	6	0	6	0	0	6	6	6
k)	Minimum LAI	0.5	0.5	5.0	1.0	1.0	5.0	0.5	0.0	0.5	0.5	0.5	0.0	0.5	0.0	0.0	5.0	1.0	3.0
l)	Stem (& dead matter area index	0.5	4.0	2.0	2.0	2.0	2.0	2.0	0.5	0.5	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
m)	Inverse square root of leaf dimension ( $\text{m}^{-1/2}$ )	10	.5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
n)	Light sensitivity factor ( $\text{m}^2 \text{W}^{-1}$ )	0.02	0.02	0.06	0.06	0.06	0.06	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.06

\*\*Soil depths in code are in mm as are water storages to make the conversion factor 1.0 between water amounts and SI energy fluxes. All types have a total soil depth of 10 m to represent ground water storage.

**SOIL PARAMETERS**

**I/FUNCTIONS OF TEXTURE**

Parameter	Texture Class (from sand (1) to clay (12))											
	1	2	3	4	5	6	7	8	9	10	11	12
a) Porosity (volume of voids to volume of soil)	0.33	0.36	0.39	0.42	0.45	0.48	0.51	0.54	0.57	0.60	0.63	0.66
b) Minimum soil suction (mm)	30	30	30	200	200	200	200	200	200	200	200	200
c) Saturated hydraulic conductivity ( $\text{mm s}^{-1}$ )	0.2	0.08	0.032	0.013	$8.9 \times 10^{-3}$	$6.3 \times 10^{-3}$	$4.5 \times 10^{-3}$	$3.2 \times 10^{-3}$	$2.2 \times 10^{-3}$	$1.6 \times 10^{-3}$	$1.1 \times 10^{-3}$	$0.8 \times 10^{-3}$
d) Ratio of saturated thermal conductivity to that of loam	1.7	1.5	1.3	1.2	1.1	1.0	0.95	0.90	0.85	0.80	0.75	0.70
e) Exponent "B" defined in Clapp & Hornberger (1978)	3.5	4.0	4.5	5.0	5.5	6.0	6.8	7.6	8.4	9.2	10.0	10.8
f) Moisture content relative to saturation at which transpiration ceases	0.088	0.119	0.151	0.266	0.300	0.332	0.378	0.419	0.455	0.487	0.516	0.542

**II/FUNCTIONS OF COLOR**

Parameter	Color (from light (1) to dark (8))							
	1	2	3	4	5	6	7	8
a) Dry soil albedo								
< $0.7 \mu\text{m}$	0.23	0.22	0.20	0.18	0.16	0.14	0.12	0.10
$\geq 0.7 \mu\text{m}$	0.46	0.44	0.40	0.36	0.32	0.28	0.24	0.20
b) Saturated Soil Albedo								
< $0.7 \mu\text{m}$	0.12	0.11	0.10	0.09	0.08	0.07	0.06	0.05
$\geq 0.7 \mu\text{m}$	0.24	0.22	0.20	0.18	0.16	0.14	0.12	0.10

Table 4.3: Soil parameterization in BATS (from Dickinson et al. 1993)



Monteith(1975, 1976), Barry and Chambers(1966), Tucker and Miller(1977), and Kukla and Robinson(1980).

The division into visible and near-infrared fluxes albedos in BATS is based on the the data of Tucker and Miller(1977), Kriebel(1979), and Fuller and Rouse(1979). The values for visible and near-infrared albedos of vegetation are presented in Table 4.2. These values are based on the assumption that vegetation is green, whether or not branches and brown leaves may be present.

The vegetation albedo is determined by the vegetation type and the solar zenith angle as

$$ALBS_{veg} = ALBS * ALBZN \quad (4.1)$$

$$ALBL_{veg} = ALBL * ALBZN \quad (4.2)$$

$$ALB_{veg} = 0.5 * (ALBS_{veg} + ALBL_{veg}) \quad (4.3)$$

where  $ALB_{veg}$  is the effective vegetation albedo, and  $ALBS_{veg}$  and  $ALBL_{veg}$  are the vegetation albedos for wavelength  $\lambda$  is less than  $0.7 \mu\text{m}$  and  $\lambda$  greater than  $0.7 \mu\text{m}$ , respectively. The vegetation albedos, ALBS and ALBL, are functions of vegetation types and are provided in Table 4.2. The zenith angle dependence for albedo is

$$ALBZN = 0.85 + \frac{1.0}{1.0 + \cos \zeta} \quad (4.4)$$

where  $\zeta$  is the zenith angle.

The albedo of the soil surface is determined by the soil type and soil wetness. The albedo of bare soil(ALBGS) is given by

$$ALBGS = ALBGO + \delta\alpha_g(S_{sw}) \quad (4.5)$$

where ALBGO is the albedo for a saturated soil, and the increase of albedo due to dryness of surface soil for wavelength  $\lambda$  less than  $0.7 \mu\text{m}$  is given as a function of the ratio of surface

water content  $S_{sw}$  in millimeters to the upper soil layer depth  $Dep_{sw}$  in millimeters

$$\delta\alpha_g(S_{sw}) = 0.01(11 - \frac{40S_{sw}}{Dep_{sw}}) \quad (4.6)$$

if  $\delta\alpha_g(S_{sw})$  is less than zero, then

$$\delta\alpha_g(S_{sw}) = 0 \quad (4.7)$$

The soil albedos for wavelength  $\lambda$  greater than  $0.7 \mu\text{m}$  are twice those for  $\lambda$  less than  $0.7 \mu\text{m}$ .

Another time-dependent parameter is fractional vegetation cover  $\sigma_f$ . Two related parameters and their values are provided in Table 4.2. These parameters are maximum fractional vegetation cover ( $\sigma_{fMAX}$ ) and difference between maximum fractional vegetation cover and cover at temperature of 269K ( $\sigma_{fDIFF}$ ). The fractional vegetation cover varies with the ground temperature ( $T_g$ ). The fractional vegetation cover is defined as

$$\sigma_f = \sigma_{fMAX} - \sigma_{fDIFF} \times F_{SEAS}(T_g) \quad (4.8)$$

where  $F_{SEAS}(T_g)$  is

$$F_{SEAS}(T_g) = MAX[0.0, 1. - 0.0016 \times (298.0 - T_g)^2] \quad (4.9)$$

### 4.3 Energy transfer in BATS

Various types of energy are received or emitted by the surface. Net solar radiation received by the surface is partly determined by the land surface albedo. The land surface albedo is significantly affected by vegetation/land-use type, wavelength and the solar zenith angle. Infrared radiation is the out-going long wave radiation emitted by the earth's surface according to the formula  $\epsilon\sigma_s T^4$ , where  $\epsilon$  is the thermal emissivity,  $\sigma_s$  is the Stefan-Boltzmann constant, and T is the temperature of the bare soil or vegetation. The calculations of the sensible heat flux, latent heat flux and the momentum are based on similarity theory, which

assumes that the flux is proportional to the difference of the variables such as temperature or specific humidity between the surface and the overlying atmosphere. The sensible and latent heat fluxes are dependent on drag coefficients. The turbulent fluxes are dependent on the roughness and the other characteristics of the vegetation. The drag coefficients  $C_D$  are quite variable (e.g. Garratt 1977). In BATS, the drag coefficients are calculated as a function of the atmospheric boundary layer stability and the drag coefficient for the neutral condition ( $C_{DN}$ ) which is obtained from mixed-layer theory as

$$C_{DN} = \left[ \frac{k}{\ln(z_1/z_0)} \right]^2 \quad (4.10)$$

where  $k$  is the von Karman constant (we assign  $k = 0.40$ ),  $z_0$  is the roughness length. For unstable conditions, the drag coefficients are determined by the surface bulk Richardson number

$$R_{iB} = \frac{gz_1(1 - \frac{T_g}{T_a})}{(V_a)^2} \quad (4.11)$$

where  $T_g$  is the surface temperature with the absence of vegetation. In the presence of vegetation in the grid cell,  $T_g = \sigma_f T_f + (1 - \sigma_f) T_s$ .  $\sigma_f$  is the fractional vegetation cover,  $T_f$  is the canopy temperature and  $T_s$  is the bare soil temperature.  $T_a$  is the atmospheric temperature on the lowest model level.

$$(V_a)^2 = (u_1)^2 + (v_1)^2 + (U_c)^2 \quad (4.12)$$

where  $u_1$  and  $v_1$  are the wind components at  $z_1$  and  $U_c$  is the convective wind at  $z_1$  which is the lowest level in the atmospheric model. The definition for  $U_c$  is

$$U_c = 0.1 \text{ms}^{-1} \quad (4.13)$$

when  $T_g/T_a < 1$ , otherwise

$$U_c = 1.0 \text{ms}^{-1} \quad (4.14)$$

For  $R_{iB} < 0$ , the drag coefficient  $C_D$  is calculated as

$$C_D = C_{DN}(1 + 24.5(-C_{DN}R_{iB})^2) \quad (4.15)$$

and for  $R_{iB} > 0$

$$C_D = C_{DN}(1 + 11.5R_{iB}) \quad (4.16)$$

The sensible heat flux and latent heat flux over the bare soil surface are estimated using the momentum drag coefficients defined above. For sensible heat flux

$$H_s = \rho_a C_p C_D V_a (T_g - T_a) \quad (4.17)$$

Where  $\rho_a$  is the surface air density and  $C_p$  is the specific heat for air. Similarly the latent heat flux is formulated as:

$$E_q = \rho_a C_D V_a f_g (q_g - q_a) \quad (4.18)$$

Where  $f_g$  is wetness factor which has a value of 1.0 except for diffusion limited soil.  $f_g$  is defined as ratio of the actual evaporation to potential evaporation.  $q_g$  is the saturated specific humidity at the ground temperature while  $q_a$  is the specific humidity of the near surface air.

In processing the energy transfer, BATS allows each grid cell to be heterogeneous which means that vegetation and bare soil can co-exist in the grid cell. The fraction of the vegetated area is parameterized according to the vegetation type and the season. The vegetation part of the grid cell is only taken into account when the vegetation coverage is greater than 0.001. The average surface fluxes are a combination of the weighted fluxes over the two different sub-areas.

The sensible heat flux from the vegetation is

$$H_f = \sigma_f L_{SAI} r_{la}^{-1} \rho_a C_p (T_f - T_{af}) \quad (4.19)$$

where  $\sigma_f$  is the fractional vegetation coverage for each grid cell.  $L_{SAI}$  is the leaf-stem area

index.  $r_{la}$  represents the aerodynamic resistance to heat and vapor flux from the vegetation. The definition of  $r_{la}$  is:

$$r_{la}^{-1} = C_f \times \left(\frac{U_{af}}{D_f}\right)^{\frac{1}{2}} \quad (4.20)$$

here  $C_f$  equals  $0.01ms^{-1/2}$ ,  $D_f$  is the characteristic dimension of the vegetation leaves in the direction of the wind.  $U_{af}$  is the wind speed incident on the leaves.

The latent heat flux or evapotranspiration over the vegetation includes two parts: one is evaporation from the wet area of the leaves, the other is the transpiration from the dry area of the leaves. The formulation for evaporation per unit wetted area is

$$E_f^{WET} = \rho_a \sigma_f r_{la}^{-1} (q_f^{SAT} - q_{af}) \quad (4.21)$$

where  $q_f^{SAT}$  is the saturated water vapor specific humidity at the temperature of the leaves  $T_f$  while  $q_{af}$  is the water-vapor specific humidity of the air in the canopy. The canopy surfaces are partly wet, and evaporation  $E_f$  from the wetted fraction of the canopy surfaces is

$$E_f = L_w E_f^{WET} \quad (4.22)$$

where  $L_w$  is the wetted fraction of leaf-stem area that is free to evaporate. It is defined as

$$L_w = \left(\frac{C}{C_{max}}\right)^{\frac{2}{3}} \quad (4.23)$$

where  $C$  is canopy storage and  $C_{max}$  is the maximum allowed storage.

Transpiration,  $E_{tr}$ , is determined by evaporation, the aerodynamic resistance and the stomatal resistance. Transpiration  $E_{tr}$  occurs only from dry leaf surfaces and is only outward. It is defined as

$$E_{tr} = \delta(E_f^{WET}) L_d \left(\frac{r_{la}}{r_{la} + r_s}\right) E_f^{WET} \quad (4.24)$$

where  $E_f^{WET}$  is evaporation per unit wetted area,  $\delta$  is a step function which is one for positive

argument and zero for negative argument.  $L_d$  is the unwetted fraction of leaf-stem area that is free to transpire.  $L_d = 1 - L_w$ .  $r_{la}$  is the aerodynamic resistance and  $r_s$  is the stomatal resistance. The transpiration must be consistent with the maximum transpiration that the vegetation can sustain. The root resistance is important in determining the maximum transpiration. In the section of the role of vegetation, the stomatal resistance and the root resistance will be described in detail.

The sensible heat flux( $H_a$ ) and the latent heat flux( $E_a$ ) from the canopy and the soil to the overlying atmosphere are

$$H_a = H_s + H_f \quad (4.25)$$

and

$$E_a = E_q + E_f + E_{tr} \quad (4.26)$$

The energy balance of the canopy assumes that the net radiation absorbed by the canopy is balanced by the sensible heat flux and latent heat flux from the canopy to the overlying atmosphere. The temperature of the canopy and that of the air within the canopy are calculated by diagnostic equations which describe the conservation of energy and water mass over and within the canopy. The soil temperatures are calculated by prognostic equations generated from the force restore method of Deardorff(1978).

## 4.4 Water Transfer in BATS

Precipitation and soil moisture are important variables in the land surface scheme. Precipitation not only affects the water supply to the vegetation and the soil, but also determines the surface runoff and infiltration. Soil moisture has a major effect on the characteristics of the surface fluxes and, therefore, affects the characteristics of the planetary boundary layer. The components of the water balance includes rainfall, interception, infiltration, evapotranspiration, surface runoff, ground water runoff and the diffusion between two soil layers. Since we have discussed the evaporation in the energy transfer Section 4.1, we will focus on soil moisture budget, surface runoff and interception.

Moisture which has arrived at the surface either infiltrates the soil or is lost to surface runoff. In BATS, there are three soil layers. The top layer is the surface air interface which is about 10cm deep. The second soil layer goes from the surface down to 1m which is usually called the rootzone layer. The total soil layer is from the surface down to 10m.  $S_{sw}$ ,  $S_{rw}$  and  $S_{tw}$  represent the soil moisture in millimeters at the surface layer, rootzone layer and total soil layer, respectively.  $S_{tw}$  contains  $S_{rw}$  which contains  $S_{sw}$ . Since the three soil layers all have the same top surface at the soil-air interface, we assume that the three soil layers get the same amount of water from rainfall and lose the same quantity of evapotranspiration and surface runoff based on the fact that all these fluxes happen on the surface. The water budgets in these three soil layers in the absence of vegetation are formulated as

$$\frac{\partial S_{sw}}{\partial t} = G - R_s + \Upsilon_{w1} \quad (4.27)$$

$$\frac{\partial S_{rw}}{\partial t} = G - R_s + \Upsilon_{w2} \quad (4.28)$$

$$\frac{\partial S_{tw}}{\partial t} = G - R_s - R_g \quad (4.29)$$

where

$$G = P_r + S_m - E_q \quad (4.30)$$

$G$  is the net water mass incident on the surface,  $P_r$  represents rainfall,  $S_m$  is snowmelt and  $E_q$  equals evaporation. The terms evaporation( $E_q$ ), surface runoff( $R_s$ ), ground runoff( $R_g$ ), movement of water from the rootzone to the surface( $\Upsilon_{w1}$ ), movement of water from the total soil layer to the rootzone( $\Upsilon_{w2}$ ) are parameterized based on a multi-layer soil model(Dickinson, 1984).

In the presence of vegetation , the soil moisture formulations become

$$\frac{\partial S_{sw}}{\partial t} = P_r(1 - \sigma_f) - R_s + \Upsilon_{w1} - \beta E_{tr} + S_m + D_w \quad (4.31)$$

$$\frac{\partial S_{rw}}{\partial t} = P_r(1 - \sigma_f) - R_s + \Upsilon_{w2} - E_{tr} + S_m + D_w \quad (4.32)$$

$$\frac{\partial S_{tw}}{\partial t} = P_r(1 - \sigma_f) - R_w - E_{tr} - E_q + S_m + D_w \quad (4.33)$$

where  $\sigma_f$  is the fractional vegetation cover,  $\beta$  defines the fraction of transpiration from the top soil layer, which is calculated as

$$\beta = \frac{Dep_{sw}}{Dep_{rw}} \quad (4.34)$$

where  $Dep_{sw}$  is the depth of the top soil layer, and  $Dep_{rw}$  is the depth of the rootzone soil layer.

$D_w$  is the rate of excess water dripping from the leaves,  $S_m$  is snowmelt,  $E_q$  is moisture flux from the soil to atmosphere,  $R_w$  is the total runoff

$$R_w = R_s + R_g \quad (4.35)$$

where  $R_s$  and  $R_g$  are surface runoff and ground runoff, respectively.

The treatment of the surface runoff in BATS is based on the criterion that a small amount of runoff occurs when the soil moisture is at field capacity or less while all rainfall runs off when the soil is at saturation. If  $T_g \geq 0^\circ C$ , the surface runoff is calculated as

$$R_s = \left(\frac{\rho_w}{\rho_{wsat}}\right)^4 G \quad (4.36)$$

if  $T_g < 0^\circ C$ , then the surface runoff is calculated as

$$R_s = \frac{\rho_w}{\rho_{wsat}} G \quad (4.37)$$

where  $\rho_{wsat}$  is the ‘‘saturated soil water density’’, that is the maximum mass of water per volume of soil possible, and  $\rho_w$  is the soil water density at the top soil layer, which is defined as



$$\rho_w = \rho_{wsat} \frac{s_1 + s_2}{2} \quad (4.38)$$

$s_1$  is the ratio of rootzone soil moisture in millimeters to its maximum allowed (degree of saturation), and  $s_2$  is the ratio of upper soil moisture to its maximum allowed.

The ground runoff is computed as

$$R_g = K_{wo} s^{2B+3} \quad (4.39)$$

where  $K_{wo}$  represents the flow rate for saturated soil due to gravity. Its value is listed in Table 4.3.  $B$  is the parameter which depends on the soil type and its value is provided in Table 4.3. The variable  $s$  is the ratio of total soil moisture to maximum allowed. Analogously to  $s_1$  and  $s_2$ , it is the percent of volumetric soil content.

Due to the presence of vegetation, the partition of rainfall into interception loss and throughfall which is divided into infiltration and surface runoff will definitely affect the water budget in the soil layers. The treatment of interception in BATS is very simple: whenever canopy storage ( $C$ ) exceeds the maximum allowed storage ( $C_{max}$ ), canopy drainage occurs to restore the canopy storage back to  $C_{max}$ . The canopy drainage is defined as

$$D_w = \frac{C - C_{max}}{\delta t} \quad (4.40)$$

where  $\delta t$  is the time step in the simulation.

## 4.5 The role of vegetation

Vegetation plays a significant role in controlling the diurnal cycle of energy and water over the land. The vegetation influences the

- (1) absorption of solar radiation and shading of the ground
- (2) exchanges of the sensible heat flux and latent heat flux with the atmosphere (see Equations 4.19, 4.21 and 4.24).
- (3) interception of rainfall and the presence of vegetation surface moisture affecting the

water transfer between the atmosphere and the soil (see Equations 4.31, 4.32,4.33).

The previous sections have described how BATS accounts for many of the vegetation impacts. The resistances:  $r_{la}$ (aerodynamic resistance), and  $r_s$ (stomatal resistance) are very important vegetation parameters which affect heat flux and evaporation from the canopy to the overlying atmosphere.

The aerodynamic resistance  $r_{la}$  is described in Equation 4.20. It plays an essential role in calculating evaporation and transpiration. The stomatal resistance,  $r_s$ , is a very important factor in calculating transpiration. It is the total mechanical resistance encountered by diffusion from inside leaf to the outside which is largely dependent on the size, distribution and the opening degree of the stomatal. The stomatal resistance is also determined by incoming solar radiation and vapor pressure deficit. The formulation is complicated and is developed based on several scientists' previous studies, such as the works of Hinckley et al.(1978), Watts(1977) and Denmead and Millar(1976). The stomatal resistance is given by

$$r_s = r_{smin} \times R_f \times S_f \times M_f \times V_f \quad (4.41)$$

where  $r_{smin}$  is the minimum stomatal resistance. The factor  $R_f$  gives the dependence of the stomatal resistance on solar radiation. The factor  $S_f$  means the dependence of the stomatal resistance on seasonal temperature,  $M_f$  depends on the soil moisture and the ability of plant roots to take water from the soil. The factor  $V_f$  is the dependence of stomatal resistance on vapor pressure deficit which can be described as

$$V_f = \frac{1}{\max(0.1, 1 - 0.025v_{pd})} \quad (4.42)$$

where  $v_{pd}$  is the departure from the saturation vapor pressure inside the leaf boundary layer.

The factor  $R_f$  varies from 1 for overhead sun to  $r_{smax}/r_{smin}$  for nighttime. It is defined as

$$R_f = \frac{1 + f}{f + r_{smin}/r_{smax}} \quad (4.43)$$

where  $r_{smax}$  is the maximum stomatal resistance.  $r_{smax} = 20000s/m$ .  $r_{smin}$  is the minimum

stomatal resistance, and its value is provided in Table 4.2.  $f = F_v \times f_c$ .  $F_v$  is the visible solar radiation received by the canopy and  $f_c$  is the light dependence of the stomatal resistance. In the coupled model,  $f_c = 0.06m^2/W$  for trees and  $0.02m^2/W$  for crops and grass.

The seasonal temperature factor  $S_f$  is defined as

$$S_f = \frac{1}{F_{SEAS}(T_f)} \quad (4.44)$$

where  $F_{SEAS}(T_f)$  is given by Equation 4.9, except that  $T_g$  is replaced by the leaf temperature  $T_f$ .

$M_f$  is initially assigned to 1. If transpiration exceeds the maximum value,  $M_f$  is increased so that the transpiration is maintained as the maximum value.

If the stomatal resistance  $r_s$  exceeds the maximum value  $r_{smax}$ , it is set to  $r_{smax}$ .

The transpiration  $E_{tr}$  calculated from Equation 4.24 must be consistent with the maximum transpiration available from the plants ( $E_{trmx}$ ). If  $E_{tr}$  is found to exceed  $E_{trmx}$ , then the stomatal resistance,  $r_s$ , is redetermined so that  $E_{tr}$  equals  $E_{trmx}$ . The determination of the maximum transpiration available from the plants ( $E_{trmx}$ ) is based on the Soil Plant Atmosphere Continuum model of Federer (1979). The plant water uptake in each soil layer is restricted by the difference between soil and the leaf potential divided by an effective root resistance. The effective root resistance depends on the length of the root and the internal plant resistance per unit root length. If the soil is very dry, the diffusion of water from the soil to the roots also accounts for the effective root resistance. All these factors yield the formula

$$E_{trmx} = \Upsilon_{r0} \sum_i R_{ii}(1 - W_{LT}^i) \quad (4.45)$$

where  $\Upsilon_{r0}$  is the maximum transpiration that can be sustained. We can take  $\Upsilon_{r0} = 2 \times 10^{-4}mms^{-1} \times \sigma_f \times S_{SEAS}$ , where  $S_{SEAS}$  is a factor that is 1 during the growing season and drops to zero when the soil is frozen. The sum is over the soil layers, each designated by the subscript  $i$ ,  $R_{ii}$  presents the fraction of the root in the  $i$ th soil layer. The fraction of the root in the upper soil layer to the rootzone layer  $R_{i1}$  is given in Table 4.2.  $W_{LT}^i$  means the soil dryness, which is defined as

$$W_{LT}^i = \frac{S_i^{-B} - 1}{S_w^{-B} - 1} \quad (4.46)$$

where  $S_i$  is the water of the  $i$ th layer and  $S_w$  is the soil water for which transpiration essentially goes to zero, defined here as the soil water at which suction reaches 15 bars. Soil of clay-like texture would have larger values and sandy-textured soils lower values. The factor  $W_{LT}^i$  ranges from 0 at saturation to 1 at the 'permanent wilting point'.  $B$  is a parameter which is dependent on soil-texture. Its value is provided in Table 4.3.

The above three resistances of vegetation play significant roles in the energy and water transfers between the atmosphere and the land surface, which are shown in Equations 4.19, 4.21, 4.24 and 4.45. The more realistic their descriptions, the more correct the simulation of the heat fluxes and evaporation from the land surface to the overlying atmosphere.

# Chapter 5

## Coupling BATS to MM5

### 5.1 Introduction

A realistic and accurate description of the land surface process is necessary in order to adequately simulate atmospheric circulation. Surface conditions directly affect the characteristics of the planetary boundary layer in the lower atmosphere. The land surface scheme used in the mesoscale atmospheric model MM5V2, discussed in Chapter 3, is very simple and far from accurate in representing the actual land surface processes. BATS is a biophysically based, vegetation-soil hydrology parameterization scheme, which allows for a realistic representation of the diurnal cycle of the surface forcings, especially evaporation (Chapter 4). The reasons to couple BATS to MM5V2 are:

- \* BATS includes water balance between atmosphere, vegetation and soil, which is ignored in the current MM5V2 surface schemes.

- \* BATS has a complete description of vegetation influences in energy and water transfer between land surface and the lower atmosphere layers.

- \* The time-dependent surface parameters in BATS provide a dynamic feedback between the surface and the atmosphere, while the surface parameters in the surface schemes in MM5V2 are constant during the whole simulation.

- \* BATS provides a realistic diurnal cycle of surface temperature and evaporation, which is very important in model simulations for mesoscale weather and global climate change.

\* Linking BATS to the mesoscale atmospheric model MM5V2 allows for the long-term simulations at high spatial resolution, thereby filling a gap in the spatial-temporal scale in current climate modeling.

The planetary boundary layer is the bridge which links the land surface and the atmosphere. Its structure is determined by the temporal and spatial variations in the intensities of the surface fluxes, such as the sensible heat flux and the latent heat flux and momentum. In turn, soil and vegetation temperatures and the soil moisture are affected by the temperature and turbulent profile of the atmosphere close to the land surface. Through the high-resolution Blackadar PBL scheme, BATS can be coupled to the mesoscale atmospheric model MM5V2.

The details of coupling BATS to the mesoscale atmospheric model MM5V2 are described in the next several sections.

## 5.2 Structure of the Coupled Model

MM5V2 has more than 200 subroutines which are grouped according to function or physics option. The structure of MM5V2 is shown in figure 3.2. This multi-level directory structure allows us to incorporate new physical schemes into MM5V2 easily and efficiently. Because the planetary boundary layer is the bridge of the atmosphere and the land surface, it is possible to put BATS in the high-resolution Blackadar planetary boundary scheme under the PBL directory . BATS is used as a stand-alone module in each grid cell of the atmospheric model MM5V2. BATS contains over 20 subroutines which follow the BATS computation flow. The functions of the subroutines are described in Appendix B. A new subroutine INTERF was built, which implements the data interface between BATS and MM5V2 (see Appendix E). The coupled BATS computation flow is shown in Figure 5-1.

The structure of the coupled model is almost same as that of the original MM5V2, except the original hirpbl scheme ( the high-resolution Blackadar PBL scheme) under directory Physics/PBL is replaced by hirpbl-BATS. The simple surface module in the high-resolution Blackadar PBL scheme is replaced by BATS. Figure 5-2 illustrates the new structure of the hirpbl-BATS scheme, as well as that of the original hirpbl scheme.

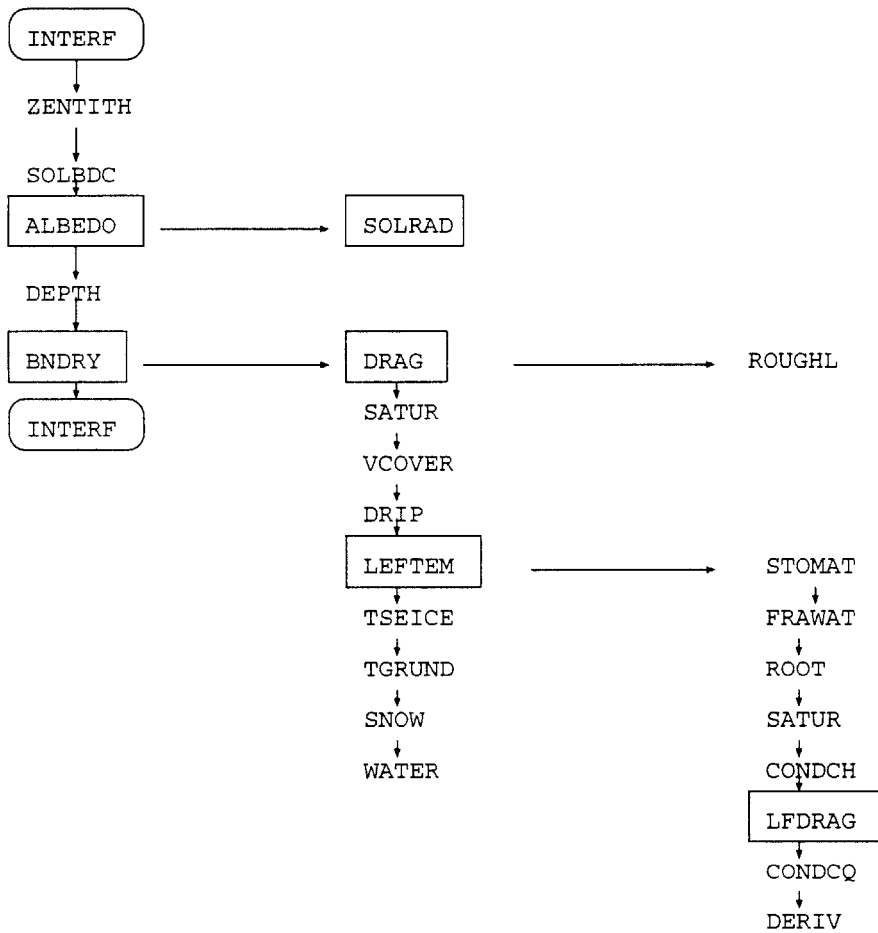


Figure 5-1: Coupled BATS computation flow chart

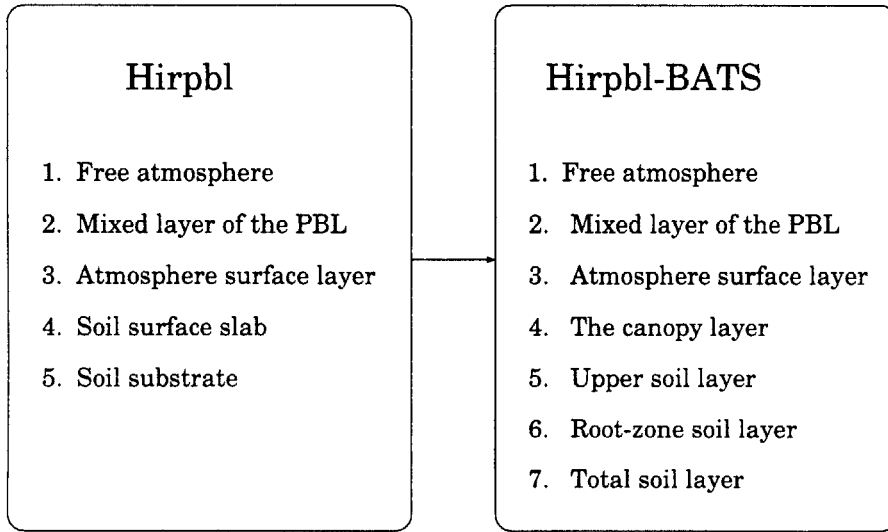


Figure 5-2: The Structures of the original Hirpbl scheme and the New Hirpbl-BATS scheme

### 5.3 Variables and Parameters

BATS needs more variables and parameters to describe the characteristics and the hydrological processes of the land surface than MM5V2. All the necessary variables and parameters used in BATS should be included in the coupled model. This section focuses on establishing a complete and correct set of variables and parameters for the coupled model. Since BATS and MM5V2 are developed by different groups, there are many differences in definition of the variables and parameters.

#### 5.3.1 Variable: Vegetation Type

There are 18 vegetation types in BATS while 13 vegetation types are included in MM5V2 (See Chapters 3 and 4).

In MM5V2, the vegetation type in each grid cell is represented by the vegetation type index. All the physical parameters to describe the characteristics of the vegetation are directly related to the corresponding vegetation type index. BATS has a different way of assigning the vegetation type index. The transformation of the vegetation types from MM5V2 to BATS was made, which is shown in Table 5.1.



MM5 Land Cover	MM5 index	To BATS index	BATS Land Cover
Urban land	1	5	Deciduous broadleaf tree
Agriculture	2	1	Crop farming
Range-Grassland	3	2	Short grass
Deciduous forest	4	5	Deciduous broadleaf tree
Coniferous forest	5	3	Evergreen needle-leaf tree
Mixed forest	6	18	Mixed woodland
Water	7	15	Ocean
Marsh	8	13	Bog or marsh
Desert	9	11	Semi-desert
Tundra	10	9	tundra
Permanent ice	11	12	Glacier
Tropical forest	12	6	Evergreen broadleaf tree
Savannah	13	7	Tall grass

Table 5.1: Vegetation/land cover types transformations from MM5V2 to BATS

### 5.3.2 Variables of Soil

Soil characteristics in BATS have been divided into twelve texture classes and eight color classes. The twelve texture classes range from sand (very coarse) to heavy clay(very fine). The details of the parameterizations of the soil textures are provided in Table 4.3 in Chapter 4. In MM5V2, there are no specific descriptions about soil.

There are three soil layers in BATS, each of which has a different depth. The upper two layers are thermally active. Hydrological processes occur in all of the three soil layers. The upper soil layer ( with a depth of 10cm) and the rootzone soil layer ( with a depth of 1 meter) are influenced by the diurnal heating cycle, while the third soil layer ( about 10 meters in total depth) is allowed to have a seasonal cycle.

Prognostic equations based on energy balance are used to predict the temperatures of the three soil layers, the equations are similar to the scheme used in calculating soil temperatures in MM5V2. However, there are two slabs and a substrate layer in BATS while there is only one slab and a substrate layer in MM5V2.

Another important difference is that MM5V2 does not include calculations of soil moisture. The equations to calculate the soil moistures in BATS and the coupled model are based

on water budgets, which include rainfall, interception, drainage, surface runoff, groundwater runoff, evaporation, transpiration and snowmelt.

The coupled model uses all the soil variables defined in BATS.

### 5.3.3 Parameters of Vegetation

BATS allows for the heterogeneity in one grid cell, which means that the vegetation coexists with the bare soil. In BATS, there are many more physical parameters for each land-use type. From Table 4.2 in Chapter 4, we can see that besides roughness and albedo necessary in MM5V2. BATS requires a fractional vegetation,  $\sigma_f$ , and leaf and stem area indexes LAI and SAI in order to describe the heterogeneity in each grid cell. LAI and SAI range between the minimum and maximum values according to a parameter  $F_{SEAS}(T_g)$  which is calculated by Equation 4.9. The leaf area index LAI is

$$LAI = LAI_{max} - (LAI_{max} - LAI_{min})F_{SEAS}(T_g) \quad (5.1)$$

where  $LAI_{max}$  and  $LAI_{min}$  are the maximum and minimum leaf area indexes, respectively. Both are dependent on the vegetation type and their values are given in Table 4.2.

The fractional vegetation  $\sigma_f$  is calculated as

$$\sigma_f = \sigma_{fmax} - \delta\sigma_f F_{SEAS}(T_g) \quad (5.2)$$

where  $\sigma_{fmax}$  is the maximum fractional vegetation cover, while  $\delta\sigma_f$  represents the difference between the maximum fractional vegetation cover and that when the canopy temperature is 273 K. Both of the two parameters are dependent on the vegetation type and their values are provided in Table 4.2.

### 5.3.4 Parameter: Albedo

One important characteristics of the land surface is albedo. The albedo has proven to be critical to land surface-atmosphere interactions; for example, Amazon deforestation may cause a large fraction of solar radiation to be reflected back into the space, resulting in

changing land surface properties.

In MM5, albedo is temporally constant while seasonally varied. In BATS, albedo is time-dependent. There is only one albedo in each grid cell in MM5 while there are three albedo variables for each grid cell in BATS. The albedo variables in BATS are visible solar albedo of vegetation ( $\lambda < 0.7\mu\text{m}$ ), near-infrared albedo of vegetation ( $\lambda > 0.7\mu\text{m}$ ), and soil albedo. The values for albedo are determined from several sources: the work of Monteith(1975, 1976), Barry and Chambers(1966), Tucker and Miller(1977), and Kukla and Robinson(1980).

The division into visible and near-infrared fluxes albedos in BATS is based on the the data of Tucker and Miller(1977), Kriebel(1979), and Fuller and Rouse(1979). Their calculations are described in section 4.2 in Chapter 4. In the MM5V2-BATS coupled model, the three time-dependent albedos are used.

### **5.3.5 Variable: Instantaneous Precipitation Rate**

The input of BATS requires the instantaneous precipitation rate at each grid cell. MM5V2 deals with accumulated rainfall. A new variable, instantaneous precipitation rate (PRECIP), is created. It is obtained by dividing the accumulated rainfall over one time step by the time step. The formula to calculate the instantaneous precipitation rate is added in the cumulus schemes.

### **5.3.6 BATS Variables**

After resolving the conflicts, BATS variables used in MM5V2 are listed in an include file “bats.incl” ( see Appendix D). The include file “bats.incl” must be used anytime a MM5V2 subroutine uses any of the variables in “bats.incl”. The variables in “bats.incl” are grouped into several common blocks according to function. The descriptions of the variables are provided in Appendix A.

## 5.4 Initialization of Variables

One of the most complicated things in coupling is the data initialization. With respect to the atmospheric module and radiative transfer scheme, the initializations in BATS and MM5V2 are the same. Concerning the surface processes, BATS requires the initialization of the time-dependent variables such as 1) soil moistures for the three soil layers, 2) the ground temperature, 3) the subground temperature, 4) the temperature of the air in the canopy and 5) the foliage temperature.

The coupled model initializes the temperature of the foliage and the air in the canopy by using the temperature of the atmosphere at the lowest atmospheric model level.

For soil, the coupled model needs to specify the soil texture and the soil class and to initialize the temperatures and the soil moistures of the three soil layers. The surface soil temperature is obtained from the the lowest atmospheric layer while the other variables such as soil moisture are determined by

$$S_{sw} = Dep_{sw} \times S_{void} \times (MS_{wilting} + (1. - MS_{wilting}) \times MS_{avail}) \quad (5.3)$$

$$S_{rw} = Dep_{rw} \times S_{void} \times (MS_{wilting} + (1. - MS_{wilting}) \times MS_{avail}) \quad (5.4)$$

$$S_{tw} = Dep_{tw} \times S_{void} \times (MS_{wilting} + (1. - MS_{wilting}) \times MS_{avail}) \quad (5.5)$$

where  $S_{sw}$  is the soil moisture of the upper soil layer, and  $S_{rw}$  and  $S_{tw}$  are the soil moistures of the rooting zone soil layer and total soil layer, respectively. The variables  $Dep_{sw}$ ,  $Dep_{rw}$  and  $Dep_{tw}$  are the depths(mm) of upper soil layer, rooting zone soil layer and total soil layer, respectively. The variable  $S_{void}$  is the fraction of soil that is voids, and  $MS_{wilting}$  represents the fraction of water content at which permanent wilting occurs. The variable  $MS_{avail}$  means moisture availability and its value is specified in Table 3.4.

An additional initialization file “initb.f” is created. All the initializations for BATS variables are provided in this file.

## 5.5 Data Interface

An data interface between MM5V2 and BATS is created. This interface includes hundreds of variables which are involved in BATS and MM5V2 lower atmospheric processes. The interface contains two parts. One is the atmospheric input to the Atmosphere-Biosphere Transfer Scheme(BATS). The other is the hydrological input to the atmospheric model MM5V2. Figure 5-3 illustrates the data transfers between MM5V2 and BATS.

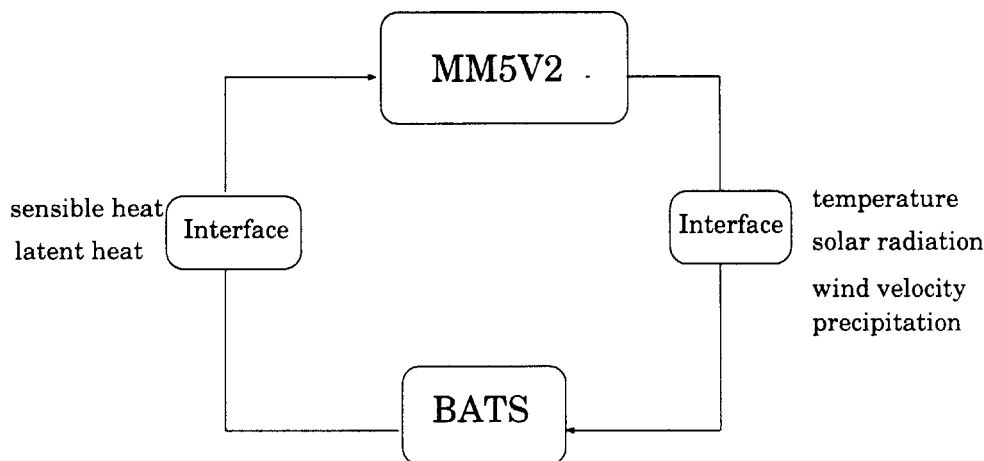


Figure 5-3: The DATA Transfer Diagram between BATS and MM5V2

From the atmosphere to BATS, the major variables transferred are: temperature, humidity, velocity at the lowest atmosphere layer, precipitation. Precipitation(including the total amount, rate and coverage) is clearly the most important atmospheric input to land surface hydrological processes. Temperature and total radiation are two additional atmospheric inputs that are important with respect to long-term hydrological processes such as soil-moisture depletion and vegetation growth. Atmospheric input such as wind is also an important variable in the land surface processes.

The major BATS output to MM5V2 includes sensible heat flux, latent heat flux, ground temperature and plus variables necessary for hydrological processes analysis, such as soil moisture of the three soil layers, surface runoff and ground water runoff. The partitioning

of energy fluxes into sensible and latent heat fluxes in the land surface processes exerts a major effect on the atmosphere.

Since the feedback between the atmospheric and hydrological processes is nonlinear and MM5V2 and BATS are developed by different research groups each driven by different objectives, this makes the coupling complicated, and leads to many conflicts of how to define each variable. Significant effort has been spent in matching the variables and building the data interface. The data interface is presented in Appendix E. There is an index in the data interface to denote the direction of the data flow. If the index equals one, the data from the overlying atmospheric layer are transferred to BATS, otherwise the results from BATS simulation are transferred into MM5V2.

## 5.6 Modifications of Physical Scheme

The surface fluxes calculated in BATS are based on the bulk aerodynamic formulas in which the drag coefficients are computed from the bulk Richardson number. As previously stated, the coupled model uses the high-resolution Blackadar PBL scheme. In the Blackadar PBL scheme, the surface heat and moisture fluxes are computed from similarity theory. Their calculations are based on the friction velocity  $u_*$  and nondimensional stability parameters  $\psi_h$  and  $\psi_m$  (see Section 3.5 in Chapter 3). In the MM5V2-BATS coupled model, the surface module to calculate the surface fluxes in the high-resolution Blackadar PBL scheme is replaced by BATS. Because of incompatibility with the rest of the Blackadar PBL scheme, some modifications were made in the original BATS and the Blackadar PBL scheme.

The drag coefficients used to calculate the surface fluxes in BATS are related to the bulk Richardson number. Equation 4.11 indicates that the calculation of the bulk Richardson number in BATS is different from that in the Blackadar PBL scheme (see Equation 3.9). The Blackadar PBL scheme uses the virtual potential temperature while BATS uses the temperature. In order to be compatible with the rest of the high-resolution Blackadar PBL scheme, the bulk-Richardson number in BATS is substituted by the bulk Richardson number calculated in the high-resolution Blackadar PBL scheme in MM5V2. However, the original way to calculate the bulk Richardson number does not consider the role of vegetation in

the high-resolution Blackadar PBL scheme. The formula to calculate the bulk Richardson number needs to include the effect of canopy temperature.

The bulk Richardson number in the MM5V2-BATS coupled model is then computed as

$$R_{iB} = \frac{gz_a(\Delta\theta)}{\theta_a V^2} \quad (5.6)$$

here  $R_{iB}$  is the bulk Richardson number,  $g$  is the gravity,  $z_a$  is the height of the lowest atmosphere layer,  $\theta_a$  is the atmosphere potential temperature near surface.  $V$  is the velocity which includes the large scale wind speed and the convective wind caused by the difference of temperature at the grid point with those of the adjacent points.  $\Delta\theta$  is the difference of the virtual potential temperature between the atmosphere and the underlying land surface. Considering the coexistence of vegetation and bare soil in each grid cell, the definition of  $\Delta\theta$  is

$$\Delta\theta = \theta_{va} - \sigma_f \theta_{vc} - (1. - \sigma_f) \theta_{vg} \quad (5.7)$$

where  $\theta_{va}$  is the virtual potential temperature of the atmosphere near surface,  $\sigma_f$  is the fractional vegetation cover,  $\theta_{vc}$  represents the virtual potential temperature of the vegetation and  $\theta_{vg}$  is the virtual potential temperature of bare soil.

However, the modifications result in abnormally high canopy temperature during noon time. The bulk Richardson number seems to fluctuate easily and sometimes leads to an unusually stable atmosphere at noon time. The stability strongly inhibits the turbulence transfer between the surface and the lower atmosphere. The energy received over the foliage is then stored in the canopy, which leads to an unreasonable and abrupt rise in the canopy temperature.

To control the behavior of the bulk Richardson number and solve the above problem, the code was modified to only allow gradual change of the bulk Richardson number. If the local Richardson number is greater than the average value over the last half an hour, it is re-set to the average value. Such a modification adequately improves the simulations of the canopy temperatures and therefore the sensible heat fluxes.

## 5.7 Final Version

After matching the variables and parameters between MM5V2 and BATS, building the data interface and modifying some physical parameterizations, the MM5V2-BATS coupled model is created. Some simulation experiments are to be carried out to assess the the coupled model in the next chapter. The overview of the MM5V2-BATS coupled model and the information of how to run the coupled model are provided in the user manual (see Appendix C).



# Chapter 6

## Numerical Simulations Using the Coupled Model

Two pairs of intensely deforested areas in Amazonia were chosen to perform the numerical simulations using the coupled model which incorporates the Biosphere-Atmosphere Transfer Scheme in the NCAR/Penn State mesoscale atmospheric model MM5 version 2. One of the sites is located in eastern Amazonia near Maraba. It lies on the edge of the zone which is naturally forest. It has a seasonal dry period between June and August. The wettest months are between December and April. The other site is in the southern Amazonia. This site includes Rondonia which is close to the south-western edge of the forest zone. This area has a significant dry season between June and August, with periods of several weeks without rain. The wettest period is from December to April.

Following the two experiments, a deforestation experiment and a control experiment are performed in order to investigate the impact of Amazon deforestation on the regional climate and the hydrological processes.

### 6.1 Experiment Design 1

This experiment is designed to simulate the atmospheric and hydrological processes in eastern Amazonia. The date and time of the experiment are from 1200 UTC Jan. 1, 1986 to 1200

Jan. 6, 1986 in the eastern Amazon basin. The model domain set up for the case is shown in the attached figure 6-1. The domain is centered at  $8^{\circ}S$  and  $54^{\circ}W$ . The grid size is 60.0 km and the domain IX(north-south), JX(east-west) dimensions are 25 x 28. The scale of the region is 1500km x 1680km which encompasses the area which is roughly from  $1.2^{\circ}S$  to  $14.82^{\circ}S$  in latitude and from  $61.64^{\circ}W$  to  $46.38^{\circ}W$  in longitude.

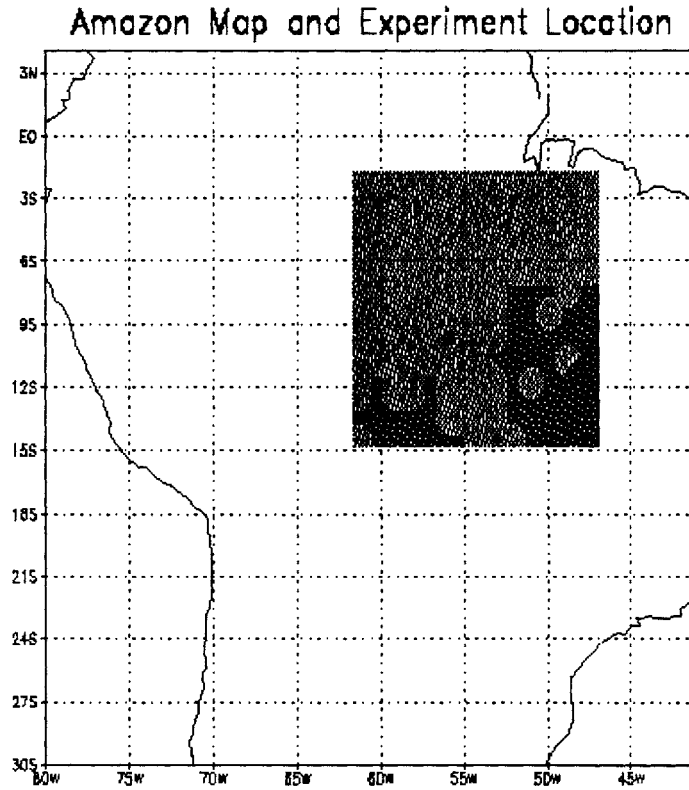


Figure 6-1: Location of the numerical experiment.

Before running numerical simulations of each site, several interpolations must be carried out in programs TERRAIN, DATAGRID and INTERP.

### 6.1.1 Terrain and Land-Use Data

Program TERRAIN was executed over the defined domain to obtain the terrain and land-use data for DATAGRID. The datasets are from NCAR. Five types of terrain height data are available: 1-degree, 30-, 10-, 5-minute and 30 second. Three types of land use data are provided: 1-degree, 30- and 10-minute. In this simulation, the 30-minute terrain height

data and 30-minute land use data are used. Program TERRAIN horizontally interpolates the latitude-longitude interval terrain elevation and land use categories onto the chosen mesoscale domains.

### 6.1.2 Boundary and Initial Conditions

The atmospheric model MM5V2 is driven by solar radiation and boundary conditions from the ECMWF TOGA global data set. It consists of temperature, relative humidity, U wind, V wind and Vertical wind on 10 pressure levels such as 1000, 850, 700, 500, 400, 300,250, 200, 150, 100mb. The top level in the atmosphere model is defined as 100mb. The data are provided every 12 hours. We get the data from 1200Z Jan. 1,1986 to 1200Z Jan. 8,1986. The horizontal(lat-lon) grid spacing of the data is  $2.5^\circ \times 2.5^\circ$ . Program DATAGRID horizontally interpolates the first guess analysis from the latitude-longitude interval atmospheric variables onto the chosen mesoscale grid point.

The method of horizontal interpolation in DATAGRID is a two dimensional and 16-point overlapping parabolic fit. Figure 6-2 and Figure 6-3 give clear descriptions. The values for the intermediate points are obtained by lineally interpolating the values of the two adjacent latitude or longitude grid points.

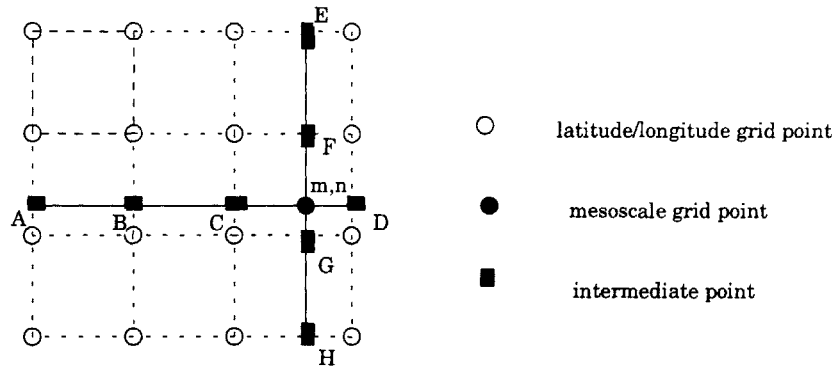


Figure 6-2: Diagram of the two-dimensional interpolation in DATAGRID.

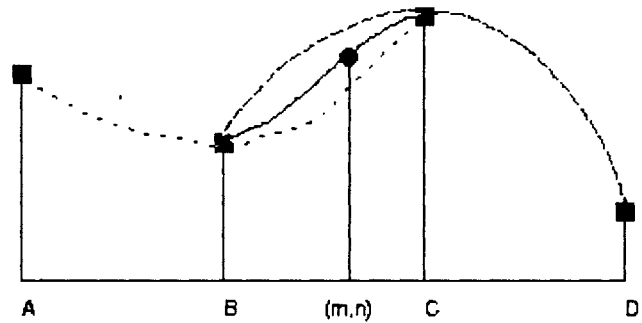


Figure 6-3: Diagram of the one-dimensional interpolation in DATAGRID.

### 6.1.3 Vertical Interpolation

The atmospheric mesoscale model MM5V2 is based on the  $\sigma$  coordinate while the data obtained from the other global model analysis are stored by pressure levels. In order to solve this conflict, program INTERP is used here to vertically interpolate the global analysis from the original pressure levels to the model sigma level. The total number of model vertical half sigma levels is 23. The full sigma levels are therefore 24, and are defined as 1., .99, .98, .96, .93, .89, .95, .8, .75, .7, .65, .6, .55, .5, .45, .4, .35, .3, .25, .2, .15, .1, .0.05 and 0.0. We use INTERP to obtain the boundary file and initial file for the model domain to run MM5V2 with BATS in it.

### 6.1.4 Initialization of the coupled model

The coupled model requires more initializations given that BATS has more variables to describe the surface processes. The additional initialization relates to the vegetation and soil.

For vegetation, the model converts the original MM5 landuse type to one of the 18 separate vegetation types in BATS. The vegetation type in a particular grid cell is assigned by the value of the most predominant vegetation class. BATS requires the specifications of the fractional vegetation cover and the leaf area index. The values of the surface albedo, roughness length, moisture availability, thermal inertia are calculated by weighting those

values of the bare soil and the vegetation with the fractional vegetation cover as the weighting factor. It also needs to initialize the temperature of the foliage and the air in the canopy by using the temperature of the atmosphere at the lowest atmospheric model level.

For soil, the coupled model needs to specify the soil texture and the soil class and to initialize the temperatures and the soil moistures of the three soil layers. The surface soil temperature is obtained from the the lowest atmospheric layer while the other variables such as soil moisture are determined by Equations 5.4, 5.5 and 5.6.

## 6.2 Results of Experiment 1

The simulation begins at 12UTC Jan.1, 1986 and ends at 12 UTC Jan.6, 1986. The land cover distribution is shown in Figure 6-1. The dark color area in the simulation domain is covered by savannah, and the light color area is covered by tropical rain forest. From the figure, we can see that most of the north part in the domain is covered by forest while in the south part savannah is dominant, with some small forest patches in it.

Our goal is to evaluate the coupled model with emphasis on the role of vegetation on the atmosphere-land surface interaction, especially the partitioning of surface heat flux, evaporation and impact on rainfall. The presence of vegetation controls the diurnal cycles of sensible heat fluxes, which is one important feature of the Biosphere-Atmosphere Transfer Scheme(BATS). Figure 6-4 shows the time series of the simulated ground temperature, canopy temperature, sensible heat flux and latent heat flux in this 5-day simulation at the point ( $52^{\circ}$  W,  $10^{\circ}$  S). This grid cell is covered by savannah. The results suggest that the diurnal cycles are very important for each of the variables. The range of the ground temperature for this particular savannah point is from about  $21.5^{\circ}\text{C}$  to  $29^{\circ}\text{C}$  with the maximum value of  $29^{\circ}\text{C}$  at the noon of the second simulation day. Day to day variation is clear. The ground temperature at noon of the second day is  $25^{\circ}\text{C}$  which is  $4^{\circ}\text{C}$  less than the maximum. The average ground temperature is around  $24^{\circ}\text{C}$ . Compared to the profile of the ground temperature, the canopy temperatures are about 3-4 degree higher. The range of the canopy temperature (around 10 degree) is a little larger than that of the ground temperature(about 7 degree). The time series of the surface heat fluxes suggest that in the savannah region, the

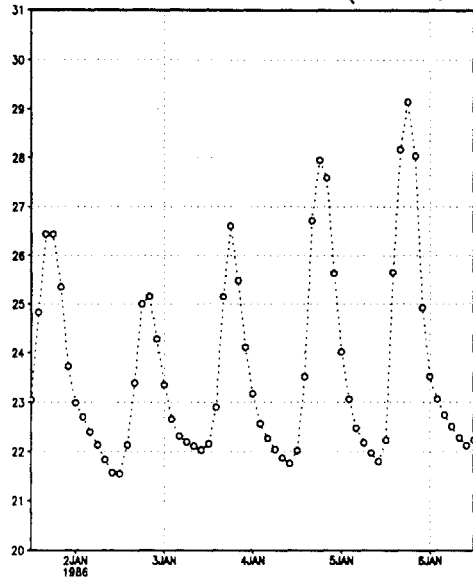
net radiation at the surface is balanced to large degree by the latent heat flux. The average bowen ratio(the ratio of sensible heat flux to latent heat flux) is about 0.7. The sensible heat flux is very high at noon due to the fact that the temperature of the savannah is much higher than the temperature of the overlying atmosphere. The negative value at night means that cooling over the savannah at night is very strong and the outgoing longwave radiation is very large over the savannah area during nighttime. The daily variations of all the four variables reflect that there is some amount of rainfall throughout the simulation period with a large amount precipitation at the night of the first simulation day. Under the effect of the rainfall, the values for all the four variables are smaller compared to those on the later days. Only a small amount of rainfall occurs during the last three days, which causes the ground temperature, canopy temperature at noon to increase with the time. The accumulated rainfall time series is illustrated in Figure 6-6.

Figure 6-5 exhibits the time series of the ground temperature, canopy temperature, sensible heat flux and latent heat flux over a tropical forest grid point. Comparing the two figures 6-5 and 6-4, we can find that the range of the canopy temperature over the forest area is smaller than that over the savannah area. The reason is that the heat capacity of the forest is much larger than that of the savannah, so the during the daytime, the temperature will increase slowly while decrease slowly at night.

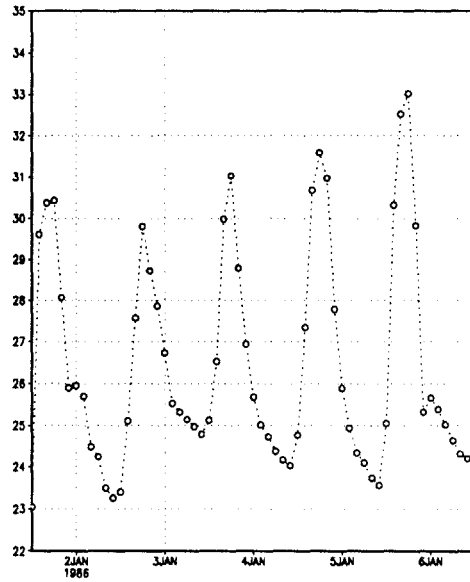
From Figure 6-6, Figure 6-4 and 6-5, we can see that the canopy temperature decreases as the rainfall increases. The net surface radiation will be smaller due to the reflection and absorption of the solar radiation by cloud water. The sensible heat flux and latent heat flux are decreasing correspondingly.

The five-day averaged fields of the ground temperature and canopy temperature are illustrated in Figure 6-7. Of greatest interest to us is the obvious influence of the vegetation type over the spatial distributions of the ground temperature, canopy temperature, sensible heat flux and latent heat flux. The distribution of the ground temperature shows that the averaged value over the savannah area is a little higher than that over the tropical forest area. The canopy temperature is also somewhat higher over the savannah area. The canopy temperature is 3°C to 4°C higher than the ground temperature. Figure 6-9 shows that the averaged latent heat flux exhibits a strong dependence on the vegetation type. The averaged

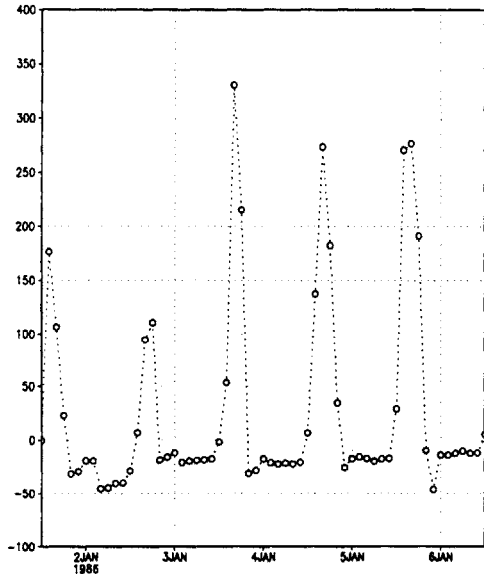
GROUND TEMP TIME SERIES (at 52w,10s)



CANOPY TEMP TIME SERIES



SENSIBLE HEAT FLUX TIME SERIES



LATENT HEAT FLUX TIME SERIES

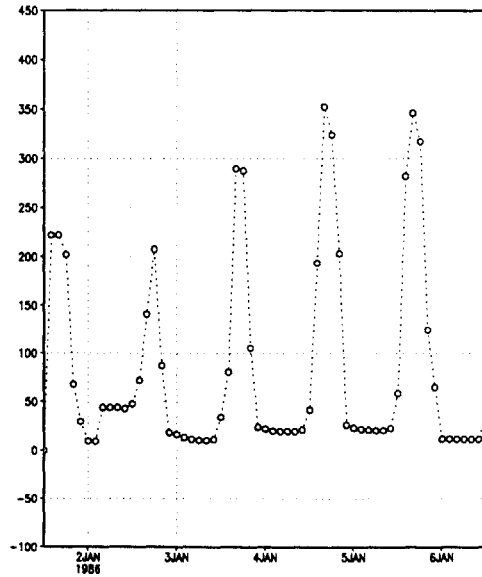


Figure 6-4: Time series of ground temperature, canopy temperature, sensible heat flux and latent heat flux at a savannah grid point

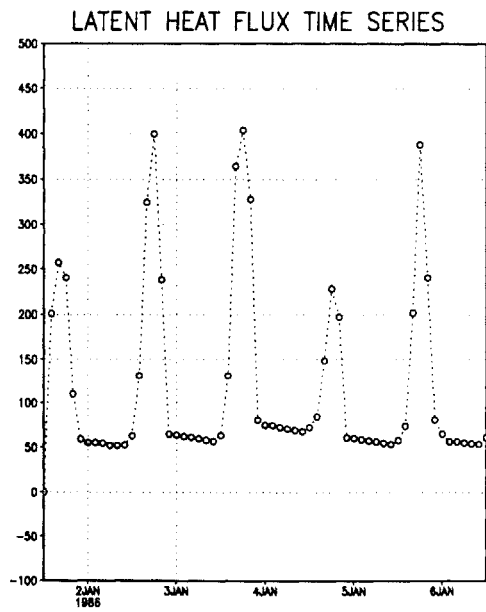
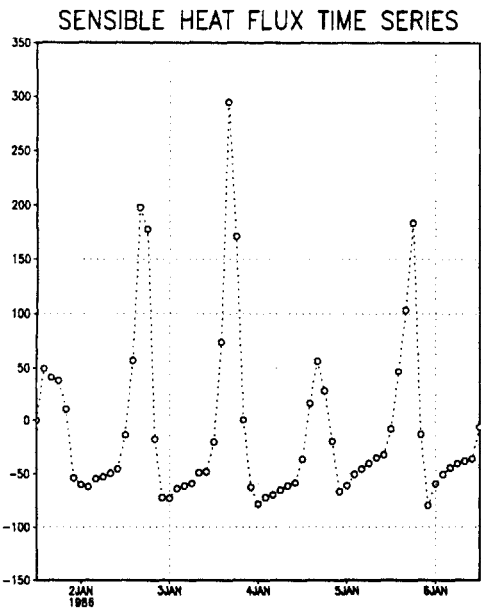
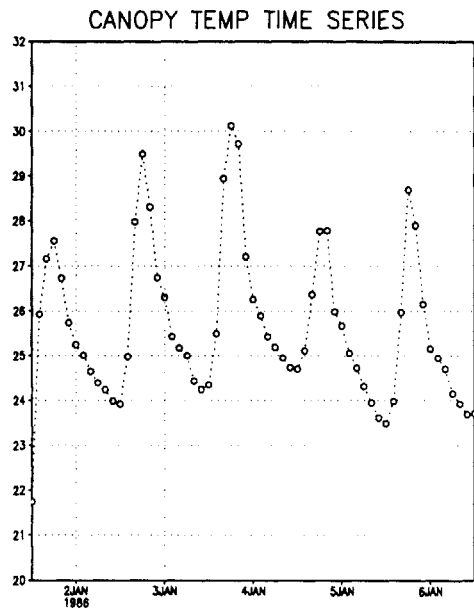
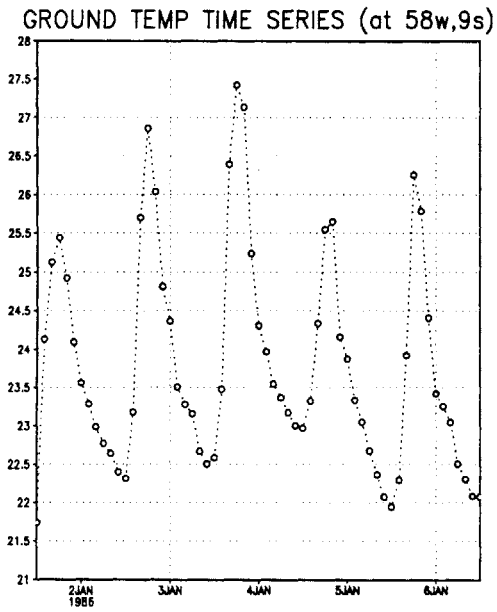


Figure 6-5: Time series of ground temperature, canopy temperature, sensible heat flux and latent heat flux at a forest grid point



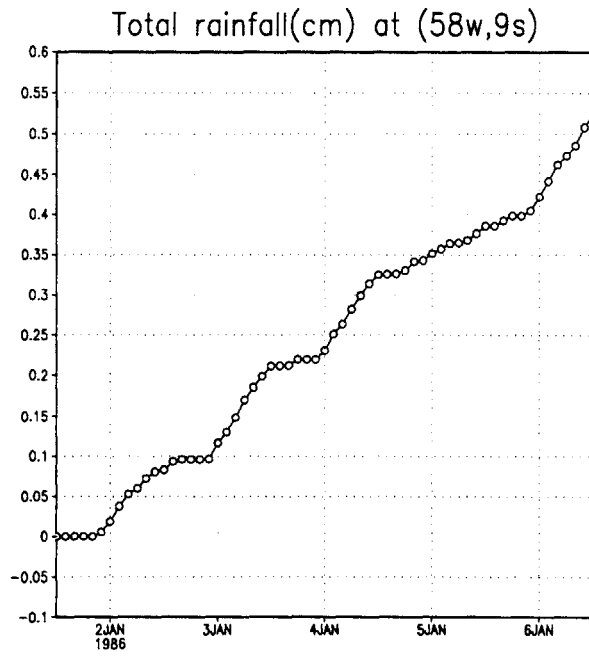
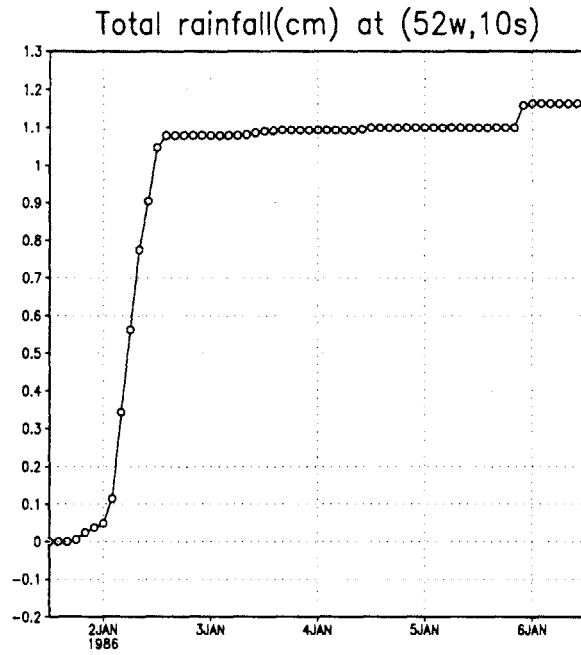


Figure 6-6: The time series of the total accumulated rainfall at grid points (52w,10s) savannah and (58w, 9s) forest

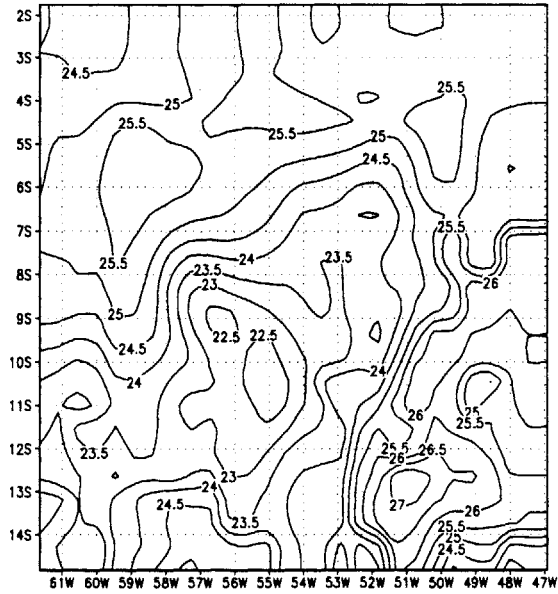
latent heat flux over savannah is about  $110 W/m^2$ . It is  $130 W/m^2$  over the tropical forest area. The results correspond well to the simulation results of J. Lean and C.B. Bunton(1997) based on the ABRACOS field experiment. The sensible heat flux over the forest is about  $20 W/m^2$  with some patches of negative values. The reason is that over those patches, there is extensive rainfall which causes less net surface radiation with corresponding large latent heat flux due to evaporation. The combined effect results in negative value for the sensible heat flux. Figure 6-8 shows the distributions of the net surface radiation and accumulated rainfall. The averaged value for the sensible heat flux over savannah is about  $70 W/m^2$ , which is a little higher than that ( $42W/m^2$ ) measured by J. Lean's (1997) in the ABRACOS field experiment.

In summary, the simulation results correspond well with the result in ABRACOS experiment, particularly in the latent heat flux. However, there is still some problems in the simulation. One big issue is along the boundaries of the simulation domain, there is a huge gradient in the variables such as net surface radiation, sensible heat flux, latent heat flux and rainfall. All these variables definitely control the whole atmospheric and hydrological processes and their interaction. In the next experiment, some modifications are made in order to solve this issue.

### 6.3 Design of Experiment 2

Another simulation experiment was performed over the southwestern Amazon Basin. The domain includes Rondonia where during the last two decades a large scale deforestation effort has taken place in order to build a road network. The area is therefore a mixture of cleared savannah interspersed with strips of forest. Its impact of the deforestation on the climate and regional hydrological processes has received the worldwide attention. It is valuable to assess the coupled model in this specific region.

### AVERAGED SURFACE TEMPERATURE(C)



### AVERAGED CANOPY TEMPERATURE(C)

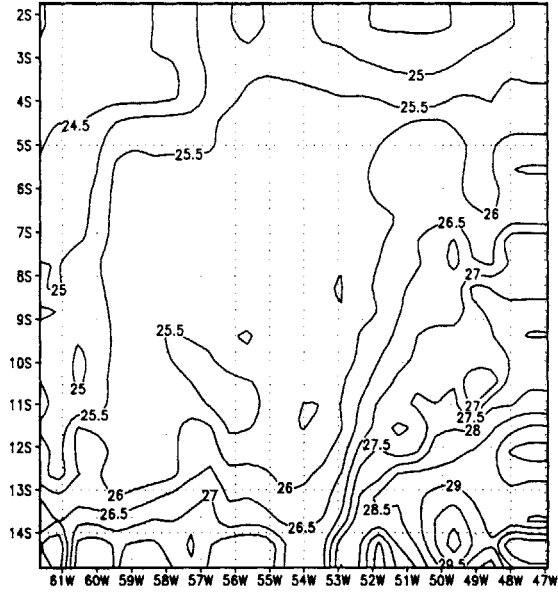
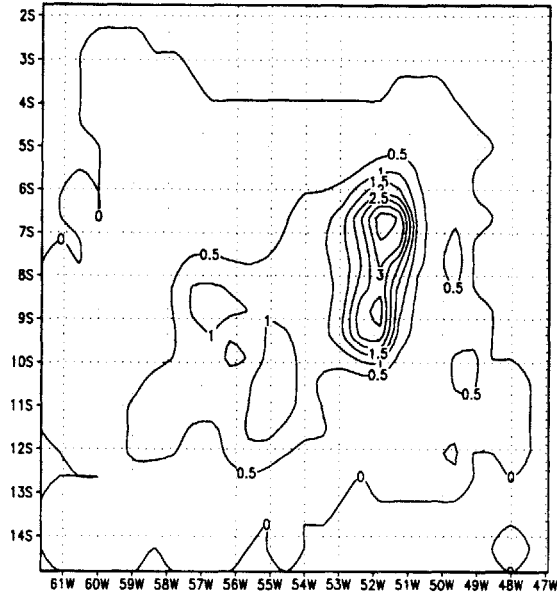


Figure 6-7: The averaged fields of the ground temperature and canopy temperature over the simulation domain

Accumulated total rainfall(cm)



Accumulated net surface radiation( $w/m^2$ )

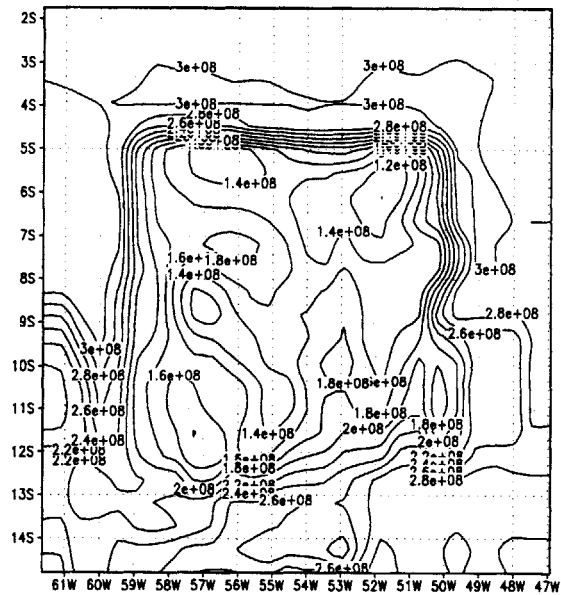
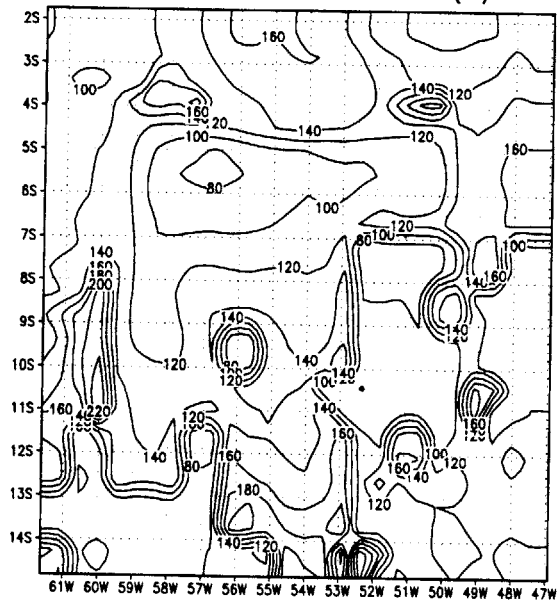


Figure 6-8: The averaged fields of the net surface radiation and accumulated rainfall over the simulation domain

AVERAGED LATENT HEAT FLUX( $w/m^2$ )



AVERAGED SENSIBLE HEAT FLUX( $w/m^2$ )

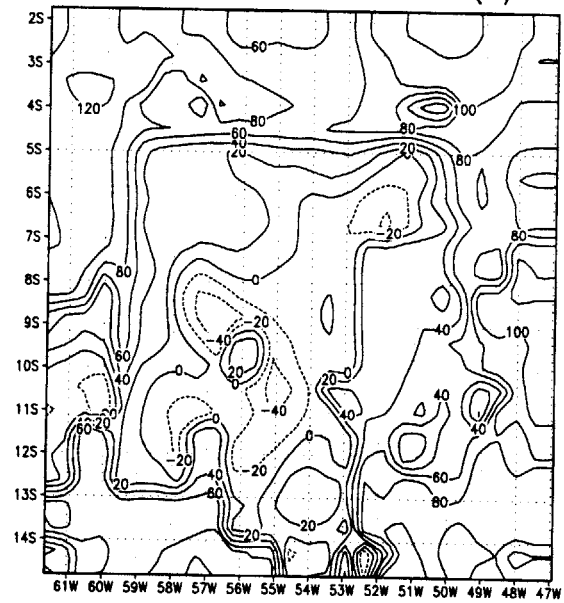


Figure 6-9: The averaged fields of the sensible heat flux and latent heat flux over the simulation domain

### 6.3.1 Correction of Boundary Condition

Before designing the experiment, it is necessary to solve the lateral boundary conditions problem noticed in experiment 1. This issue was solved by removing 5 or more grid points from each boundary. In order to understand why this was done, it is useful to study the two methods combining the mesoscale model predicted values with the value on the lateral boundary from the larger scale analysis. The first approach is called sponge boundary conditions which is given by

$$\left(\frac{\partial\alpha}{\partial t}\right)_n = w(n)\left(\frac{\partial\alpha_{MC}}{\partial t}\right) + (1 - w(n))\left(\frac{\partial\alpha_{LS}}{\partial t}\right) \quad (6.1)$$

where  $n$  is the point away from the lateral boundary,  $n$  equals 1,2,3,4 for cross-point variables and 1,2,3,4,5 for dot-point variables. Dot-point variables are defined at the grid intersection points while cross-point variables are defined in the middle of the grid cell. Figure 6-10 illustrates the definitions for dot-point and cross-point variables.  $\alpha_{MC}$  stands for any of the time dependent variables whose values are calculated by the coupled model.  $\alpha_{LS}$  stands for the variables from the large-scale analysis such as ECMWF-TOGA used in the simulation.  $w(n)$  are the weighting coefficients: 0.0, 0.4, 0.7, 0.9 for cross-point variable and 0.0, 0.2, 0.55, 0.8 and 0.95 for dot-point variables. If  $n$  is greater than 5,  $w(n)$  equals 1 which means there is no effect from the value on the lateral boundary from the larger scale analysis.

The other method is a relaxation boundary condition which relaxes the model-predicted value toward a large-scale analysis. Newtonian and diffusion terms are included in the method defined as

$$\left(\frac{\partial\alpha}{\partial t}\right)_n = F_n F_1 (\alpha_{LS} - \alpha_{MC}) - F_n F_2 (\alpha_{LS} - \alpha_{MC}) \quad (6.2)$$

where  $F$  are the weighting coefficients which decrease linearly from the lateral boundary such as

$$F_n = \frac{5 - n}{3} \quad (6.3)$$

if  $n$  is greater than 5,  $F_n$  equals zero which means there is no effect of the lateral boundary

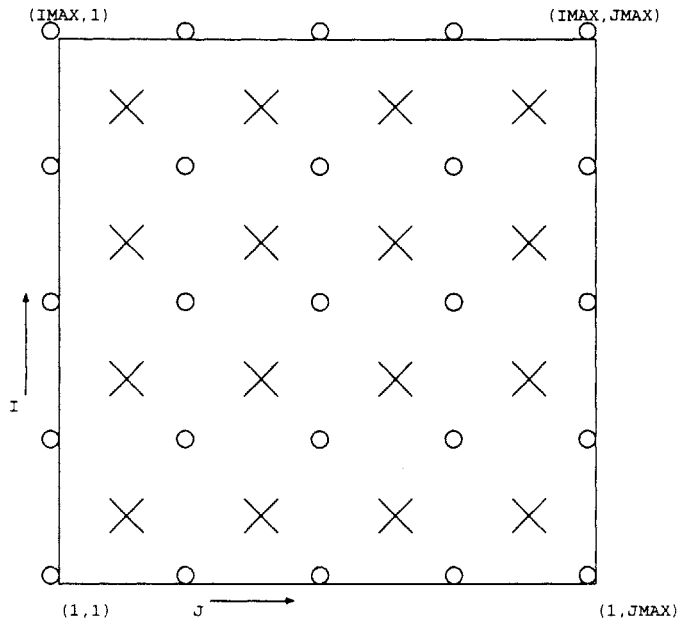


Figure 6-10: Schematic representation of the dot (O) and cross (X) grid points

values from the larger scales analysis.

When  $n$  is less than 5.  $F_1$  is given by

$$F_1 = \frac{1}{10\Delta t} \quad (6.4)$$

While  $F_2$  is defined by

$$F_2 = \frac{(\Delta s)^2}{50\Delta t} \quad (6.5)$$

where  $\Delta s$  means the grid spatial resolution and  $\Delta t$  is the temporal resolution.

In both methods, the larger scale analysis affects the mesoscale model's variables at least five grid points away from the lateral boundaries. In most of the physical processes in MM5V2, variables not available from the large-scale analysis are defined to be zero at the boundary, this practice often creates a very large artificial gradient along the boundary. This gradient often causes the mesoscale model to produce erroneous results. Because the

larger scale analysis only affects the mesoscale model in the first five grid points away from a boundary, by ignoring these data grid points for the purpose of data analysis, the artificial gradient is eliminated.

### 6.3.2 Simulation Design

The domain is centered at 10°S and 60°W with the spatial resolution of 50.km. The simulation domain encompasses an area of 1600km x 2000km. Initialization, interpolation and boundary and initial conditions are set in a way similar to experiment 1. The 10-minute terrain height data and 10-minute land use data are used. Program TERRAIN horizontally interpolates the latitude-longitude interval terrain elevation and land use categories onto the chosen mesoscale domain whose grid resolution is 50km.

Program DATAGRID gets the atmospheric data such as geopotential height, temperature, wind and humidity on each pressure levels over the simulation domain from the ECMWF TOGA global analysis dataset. DATAGRID then interpolates all the atmospheric variables from the latitude-longitude interval onto the chosen mesoscale grid point. Program INTERP interpolates the global analysis from the original pressure levels to the model MM5V2 sigma level and then get the initial data and boundary data to run MM5V2 with BATS in it.

The simulation begins from 12 UTC January 2, 1986 and ends at 12 UTC January 27, 1986. The simulation results are stored every 2 simulation hours. The vegetation cover is described in Figure 6-11. The dark area marks savannah area while the light area denotes tropical rain forest. From the figure, it can be seen that most of the northern area in the simulation domain is covered by tropical rain forest. There are two separate patches of savannah near the center of the domain. The savannah patch in the west is the region of Rondonia. In this simulation, Rondonia is largely deforested. In the southeastern part of the simulation domain savannah is dominant.



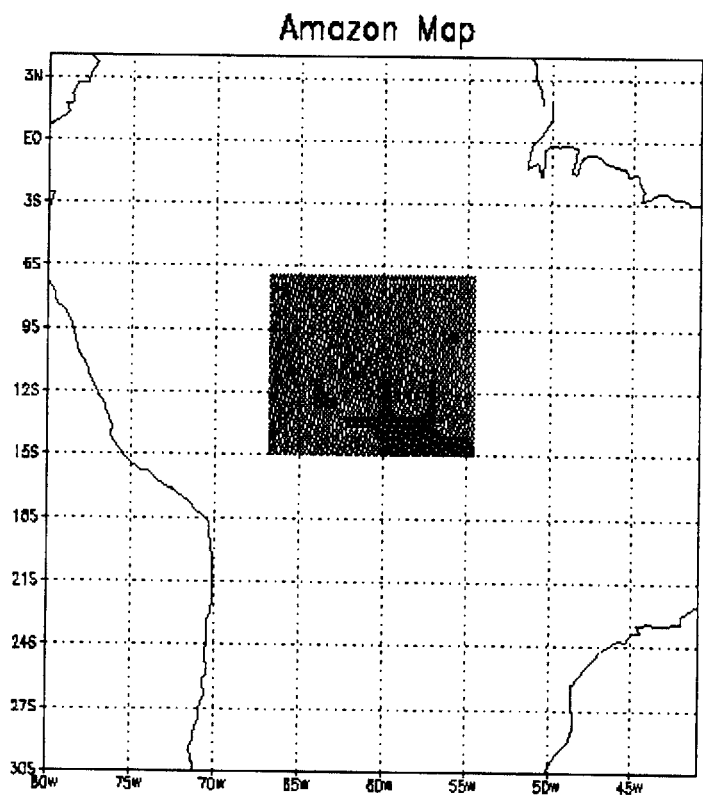


Figure 6-11: The Land cover distribution in Experiment 2.

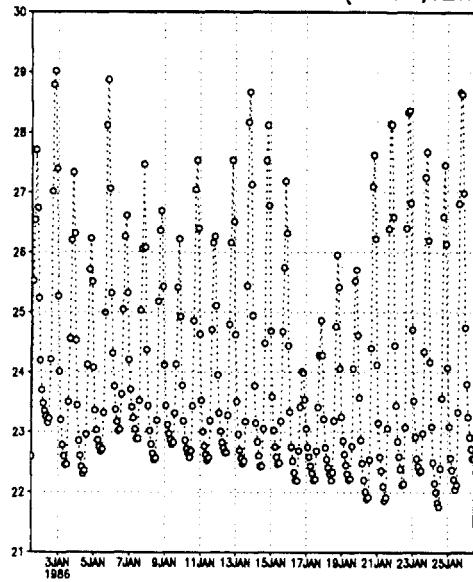
### 6.3.3 Simulation Results

The goal of this simulation is to assess the performance of the coupled model in Rondonia. The simulation has a 25-day period. The long time simulation can help us test the stability of the coupled model and understand the mechanisms of the land surface-atmosphere interactions. The results are analyzed in terms of the surface temperatures and fluxes that affect the overlying atmosphere.

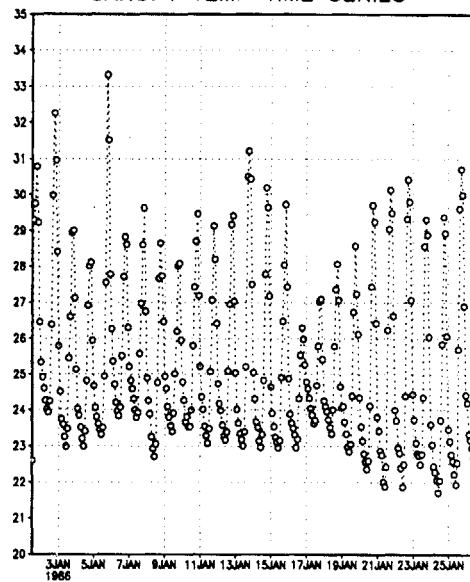
Figure 6-12 shows the time series of the ground temperature, canopy temperature, sensible heat flux and latent heat flux at a savannah point (63.6°W, 12.7°S). This point is inside the Rondonia region. The results indicate that there is a strong diurnal cycle in each of the variables. From the time series of the ground temperature at this specific savannah point, we can see that day to day variation exists. The maximum value for the ground temperature is 29°C at noon and the minimum is 21.8°C at night. The average value for the ground temperature is about 24°C. The variation corresponds well with the time series of the rainfall at this savannah point. Figure 6-14 and 6-15 show the total rain in every two hours at this savannah point and the accumulated total rainfall during the whole simulation period, respectively. The time series of the canopy temperature indicates that the maximum value reaches 33.5°C and the minimum value is 21.7°C. In each day the canopy temperature at noon is 3 – 5°C higher than the ground temperature. The day to day variation in the canopy temperature is influenced by precipitation. From the figures 6-14 and 6-15, we can see that during January 17th to 19th, there is a lot of precipitation at this savannah grid point (63.6°W, 12.7°S). Under this impact, the canopy temperature and ground temperature are very much lower when compared to the other time periods. The time series of the sensible heat flux shows that the values are very high at this savannah point, with the maximum value of 380  $W/m^2$ . The latent heat flux at this point is at the same magnitude as that of the sensible heat flux. The bowen ratio (the ratio of sensible heat flux to latent heat flux) is around 0.9. Both of the sensible and latent heat fluxes are strongly affected by the simulated rainfall.

Figure 6-13 shows the time series of the ground temperature, canopy temperature, sensible heat fluxes and latent heat fluxes during the 25-day simulation at the grid point

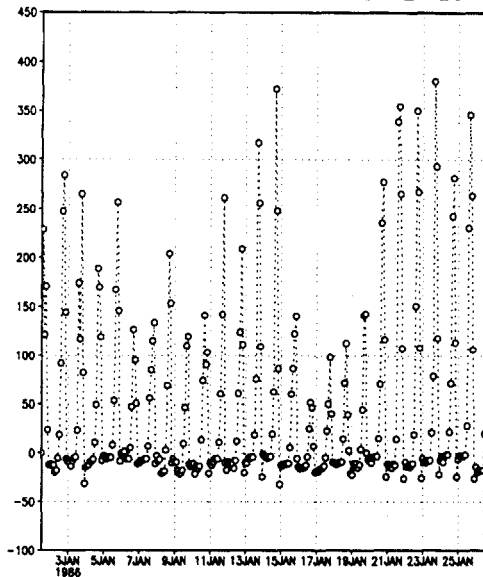
GROUND TEMP TIME SERIES (63.6w,12.7s)



CANOPY TEMP TIME SERIES



SENSIBLE HEAT FLUX TIME SERIES



LATENT HEAT FLUX TIME SERIES

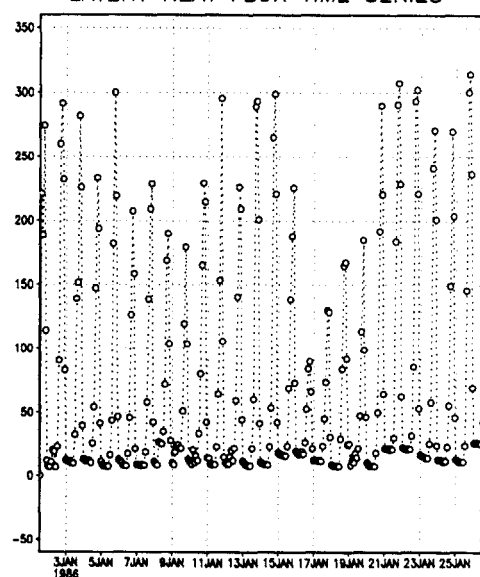
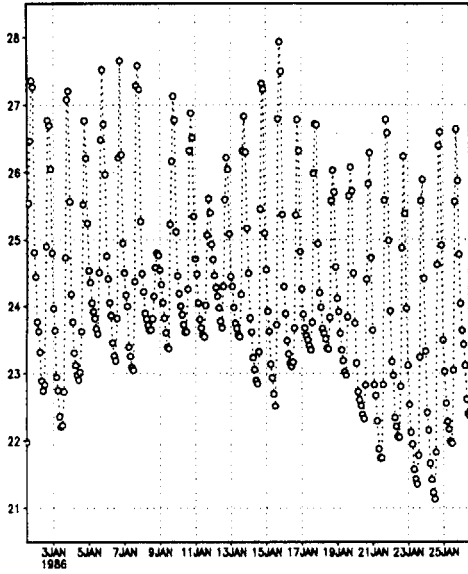
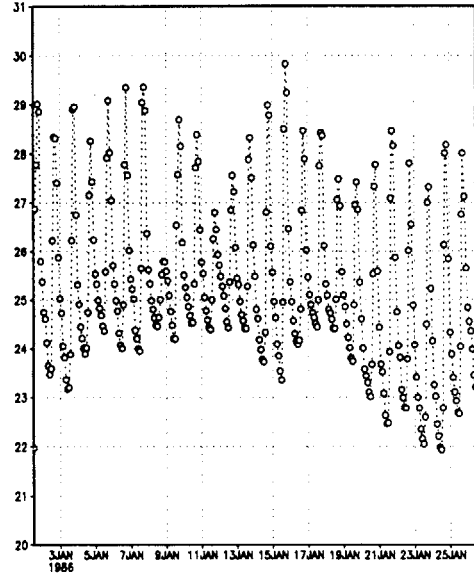


Figure 6-12: Time series of ground temperature, canopy temperature, sensible heat flux and latent heat flux at a savannah grid point

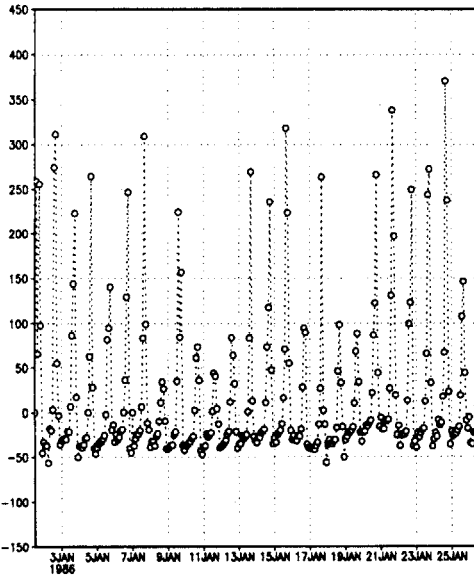
GROUND TEMP TIME SERIES (63w,10s)



CANOPY TEMP TIME SERIES



SENSIBLE HEAT FLUX TIME SERIES



LATENT HEAT FLUX TIME SERIES

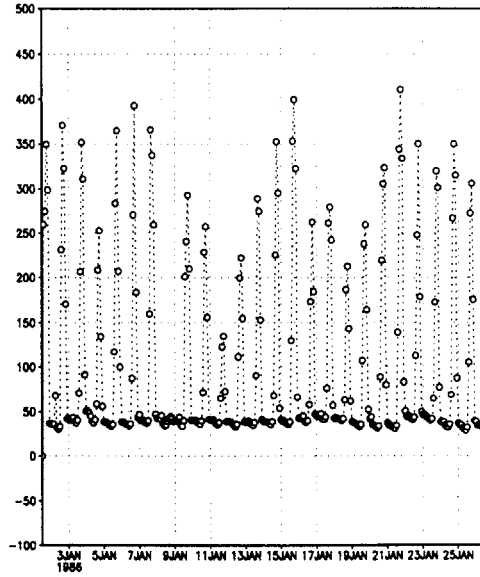


Figure 6-13: Time series of ground temperature, canopy temperature, sensible heat flux and latent heat flux at a forest grid point

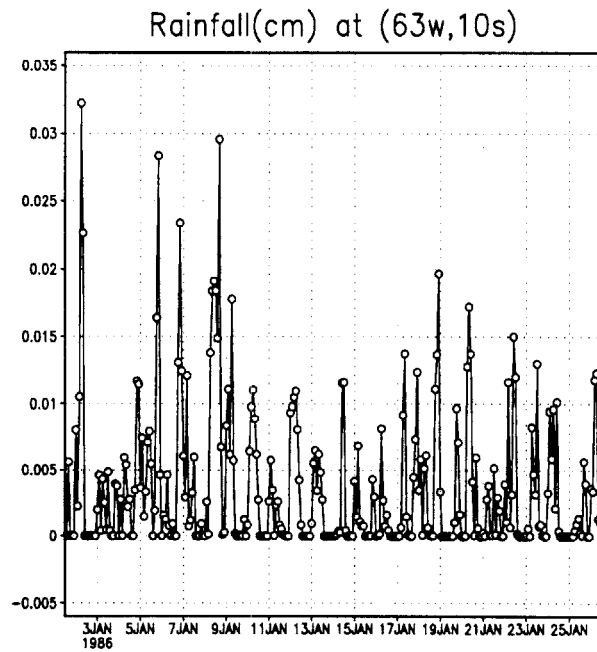
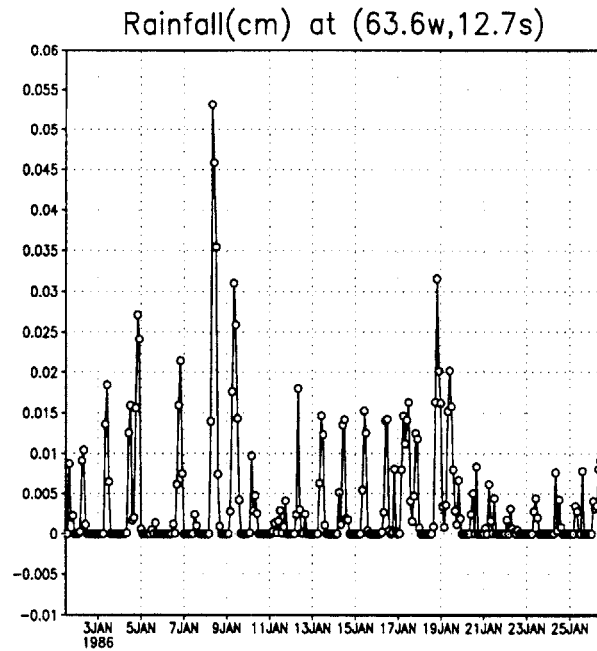


Figure 6-14: Time series of total rainfall in every 2 hours at grid points (63.6w,12.7s) savannah and (63w,10s) forest

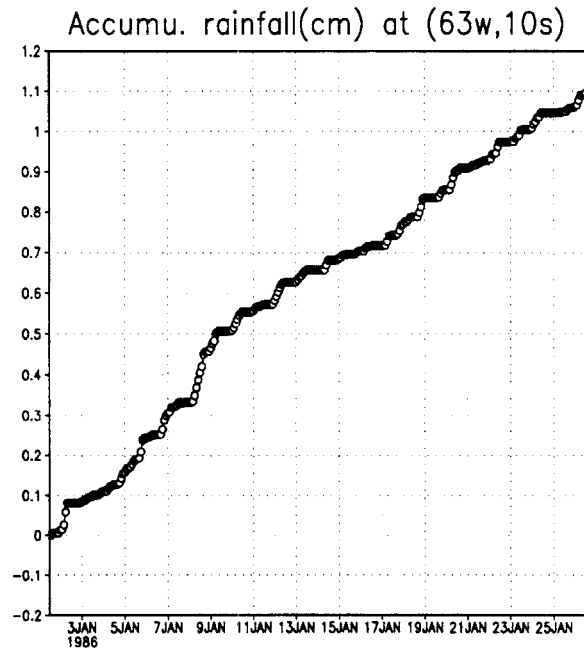
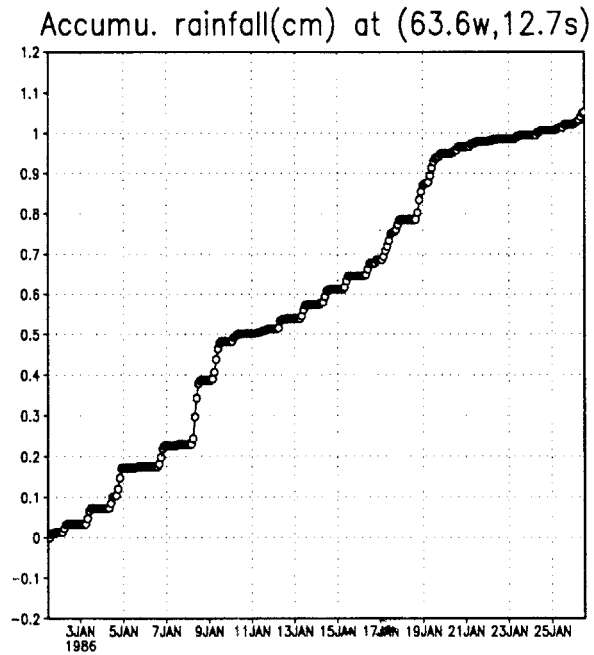


Figure 6-15: Time series of accumulated total rainfall during the simulation period at grid points (63.3w,12.7s) savannah and (63w,10s) forest

(63°W, 10°S). This grid point is covered by tropical rain forest. The time series of the ground temperature shows that the maximum value is 28°C and the minimum value is about 21°C at this specific forest site. The averaged value for the ground temperature is about 24.5°C. The maximum value for the canopy temperature is 30°C and the averaged value is about 26°C. Compared to the figures at the savannah site, the difference between the ground temperature and the canopy temperature is smaller at this forest site. The reason may be that the heat capacity for the forest is higher. The Figure 6-13 also shows that the latent heat flux is higher than the sensible heat flux. The averaged bowen ratio is about 0.6. The maximum latent heat flux is  $430W/m^2$  and the maximum sensible heat flux is  $370W/m^2$ . From the figure, we can see that there is a strong diurnal cycle and day to day variation in each of the four variables. Figure 6-13, figure 6-14 and figure 6-15 indicate that the day to day variation is affected by the amount of the total rainfall. From January 7 to 13th, rainfall is 0.4cm resulting in very much lower ground temperature, canopy temperature, sensible heat flux and latent heat flux.

The spatial distribution of the averaged fields for ground temperature and canopy temperature are illustrated in Figure 6-16. The distributions of the ground temperature and canopy temperature reveal the signal of the vegetation type. The signal is not very strong because the impact of the overlying atmosphere. In general, over the savannah area, the averaged ground temperature is about 23.5°C and the averaged canopy temperature is 25.5°C. However, the ground temperature and canopy temperature in the forest area about the savannah area is on average 0.5 to 1 degree lower than those in the savannah area. In the upper left corner, the temperatures are very much higher in the forest area due to the impact of the large scale overlying atmospheric circulation.

The spatial distribution of the averaged fields for sensible heat flux and canopy latent heat flux are illustrated in Figure 6-18. This figure shows a very strong signal of the vegetation cover in the distributions of the latent and sensible heat fluxes. The latent heat flux is about  $90W/m^2$  over the savannah area and  $120W/m^2$  over the forest area. The results correspond very well to the results of J. Leans and C.B. Bunton(1997) in the ABRACOS field experiment. In the distribution of the sensible heat flux, we can see that there is a very strong signal of the vegetation cover, except that there is several regions of negative sensible heat flux. The

averaged sensible heat flux is about  $40W/m^2$  over the savannah area and  $25W/m^2$  over the forest area. The results corresponds very well to those of J. Leans and C.B. Bunton(1997) based on the ABRACOS field experiment. In their simulation, the monthly mean value of the sensible heat flux is  $41.6W/m^2$  over the savannah area and  $31.9W/m^2$  over the forest area. The negative regions can be explained by the distribution of the accumulated rainfall and the net surface radiation shown in Figure 6-17. The regions of negative sensible heat flux exactly correspond to the regions of a large amount of rainfall, low net surface radiation and large latent heat flux.

The results of the second experiment do not exhibit the effects of boundary conditions. The 25-day simulation gives more valuable and correct information and sheds more insight on the impact of vegetation cover on the atmosphere-land surface interaction.

## 6.4 Deforestation Experiment in the Amazon Basin

The deforestation simulation site is located in southern Amazonia which is the same domain as in the experiment 2. but the whole domain is artificially covered by savannah. The grid resolution is 50km, and the simulation domain encompasses an area of 1600km x 2000km. The meteorological initial and boundary conditions are the same as those in the experiment 2. The simulation begins from 12 UTC January 2, 1986 and ends at 12 UTC January 8, 1986. Another experiment (control experiment) is carried out at the same time with all the same initial and boundary conditions and physical schemes except that the vegetation data used in the experiment is obtained from the NCAR dataset archive. The distribution of vegetation cover and simulation domain in the control experiment is the same as that in Experiment 2.

The difference between the results from the control and deforestation experiments are discussed.



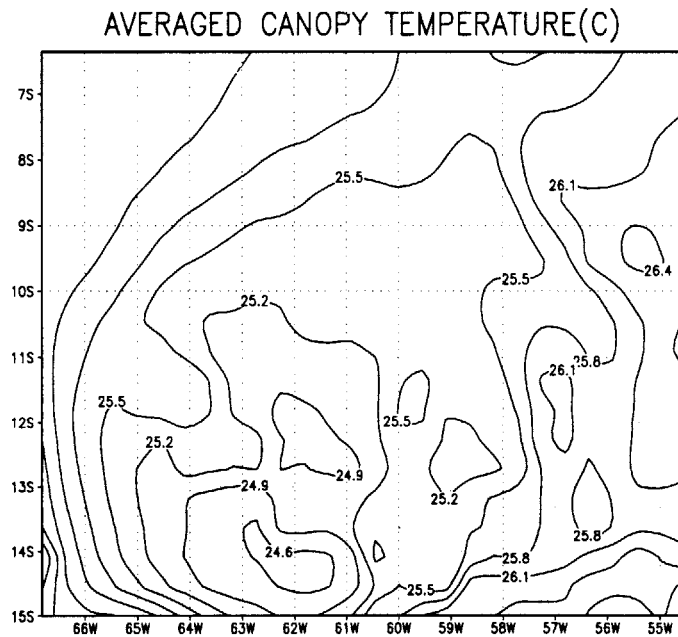
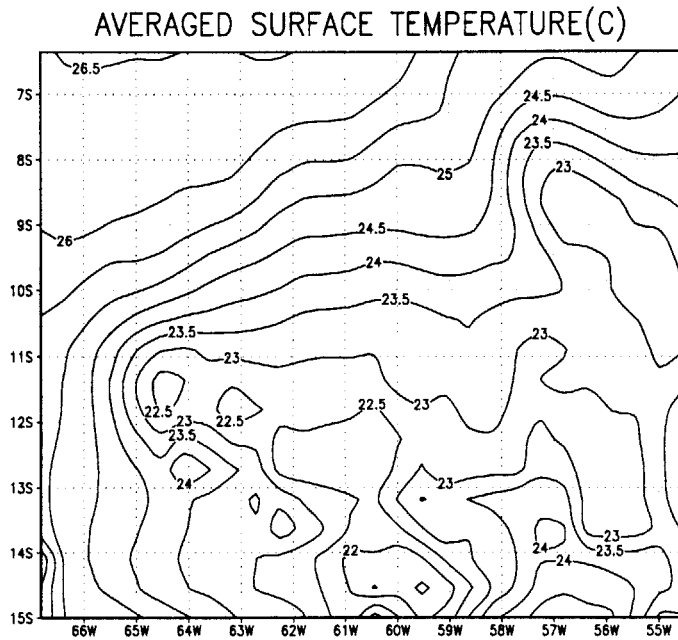


Figure 6-16: The spatial distribution of the averaged ground temperature and canopy temperature in exp.2

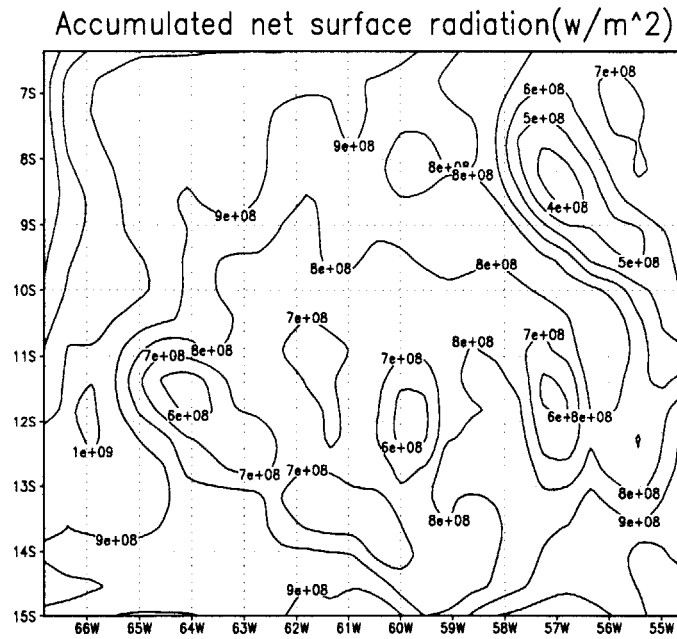
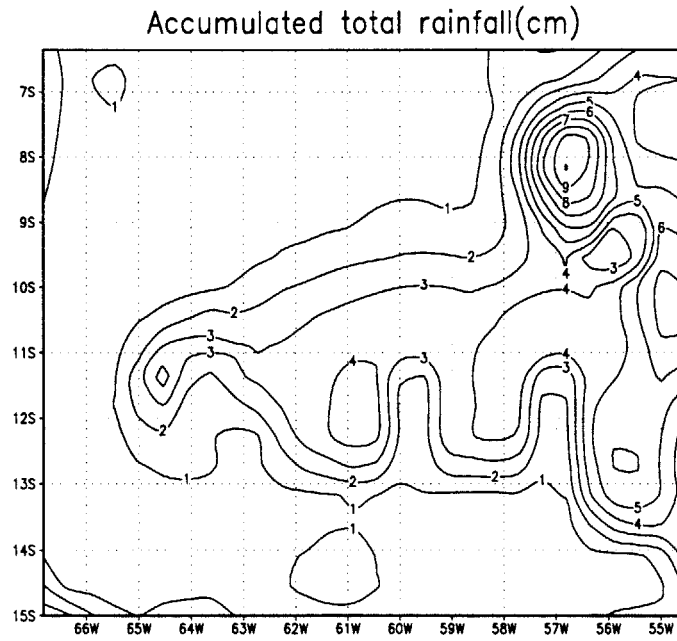


Figure 6-17: The spatial distribution of the accumulated total rainfall and net surface radiation in exp.2

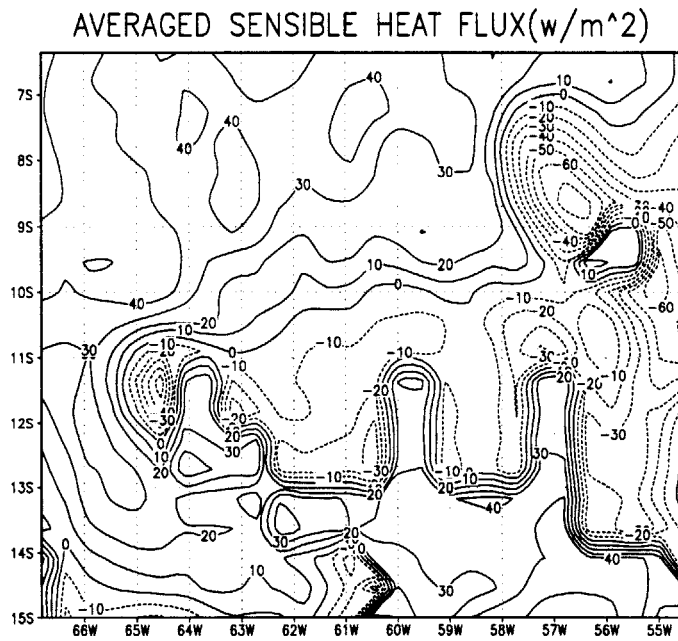
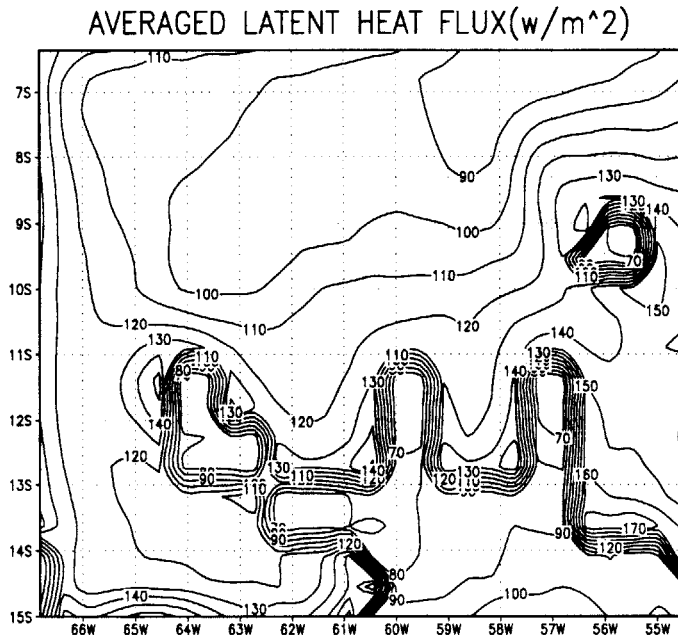


Figure 6-18: The spatial distribution of the averaged sensible heat flux and latent heat flux in exp.2

### 6.4.1 Time Series of the Surface Variables

Figure 6-19 shows the time series of the ground temperature, canopy temperature, sensible heat flux and latent heat flux at the grid point ( $63^{\circ}W$ ,  $10^{\circ}S$ ) in the control experiment. This grid point is characterized as tropical forest. Figure 6-20 illustrates the time series at the same grid point in the deforestation experiment. In the deforestation experiment, this grid point is covered by savannah and the maximum ground temperature is above  $30.5^{\circ}C$ , 2-3 degrees above the control experiment. The maximum temperature of the canopy temperature is over  $32.5^{\circ}C$ , an increase of 3 degrees over the control experiment. On average, the ground temperature increases around 2-3 degrees and the canopy temperature increases 2-3 degrees. The time series of the surface fluxes in the deforestation experiment (see Figure 6-20) indicates that the sensible heat flux increases and the latent heat flux decreases relative to the results in the control experiment (see Figure 6-19).

Figure 6-21 shows the time series of the accumulated rainfall at the grid point ( $63^{\circ}W$ ,  $10^{\circ}S$ ) from the deforestation experiment and the control experiment. There is significant decrease in the accumulated rainfall with deforestation at this specific point.

### 6.4.2 Spatial Distributions of the Surface Variables

The spatial distribution of the time averaged fields of ground temperature and canopy temperature in the deforestation and control experiments are illustrated in Figures 6-23 and 6-22. The averaged ground temperature increases around 3 degrees, and the averaged canopy temperature increases about 2-3 degrees after deforestation.

The time averaged spatial distribution of the sensible heat and latent heat fluxes in the deforestation experiment are illustrated in Figure 6-25. The pattern of the latent heat flux does not exhibit the level of spatial variability that is evident in the control experiment shown in Figure 6-24. The averaged latent heat flux in the deforestation experiment is about  $105 W/m^2$ . From the figure 6-26, we can see that there is a significant amount of rainfall in that left part of the simulation domain which does affect the latent heat flux. The averaged sensible heat flux in the deforestation experiment is about  $50 W/m^2$  for the whole domain, which indicates that that the sensible heat flux increases around  $10-20 W/m^2$  compared to

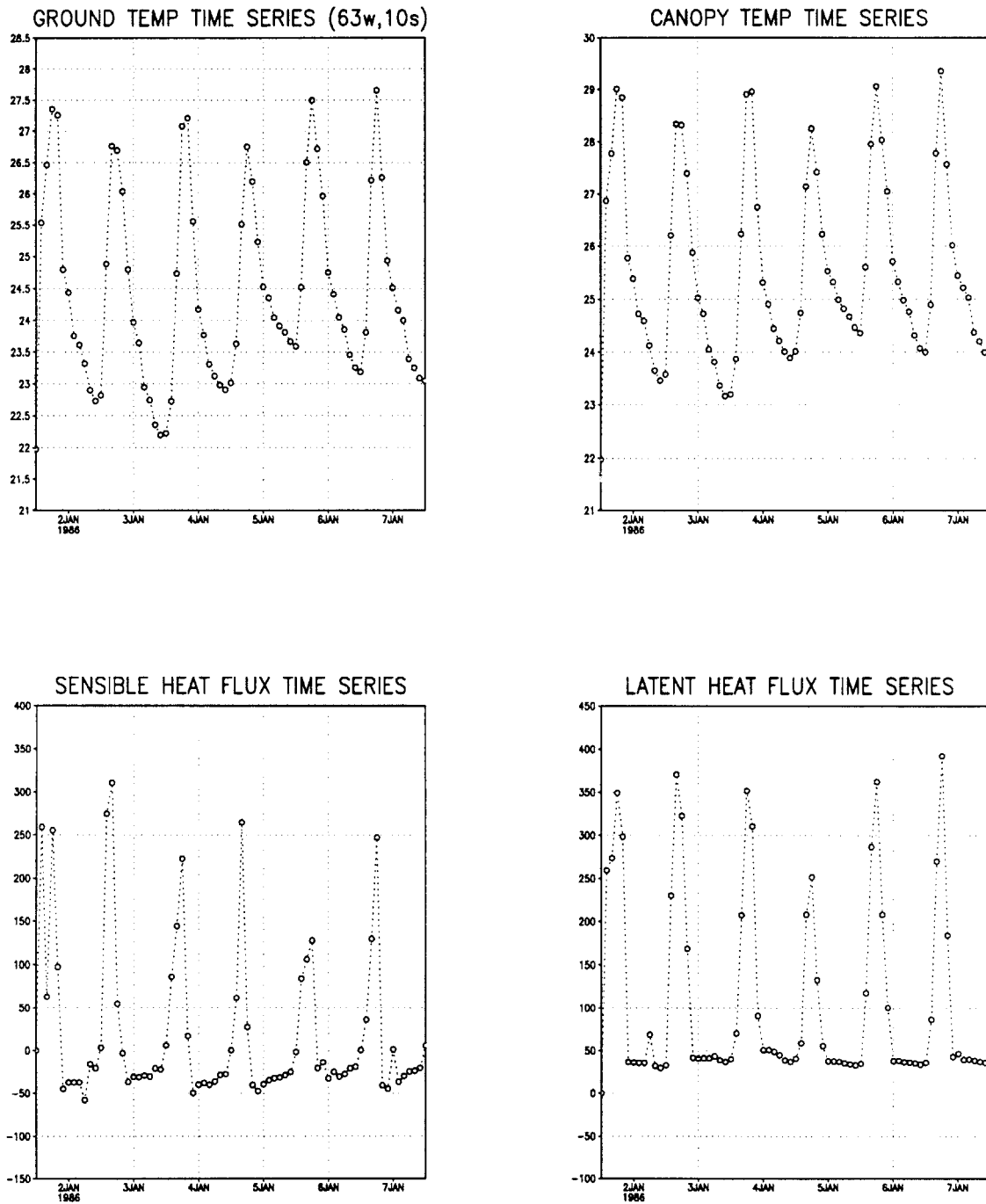


Figure 6-19: Time series of ground temperature, canopy temperature, sensible heat flux and latent heat flux at a forest grid point in the control experiment

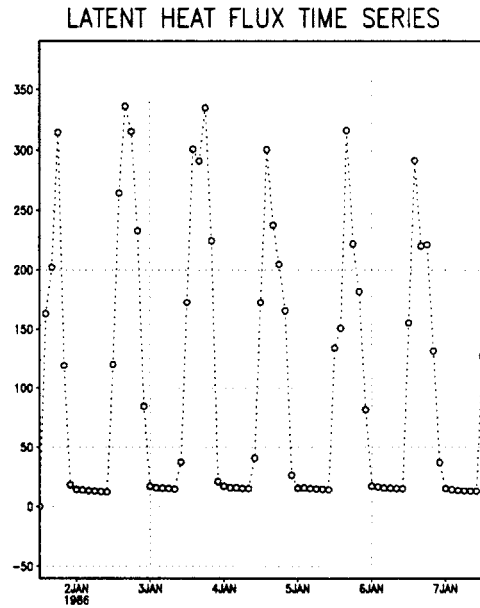
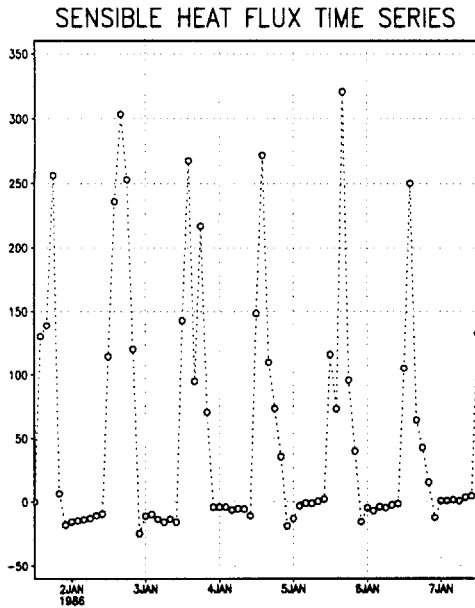
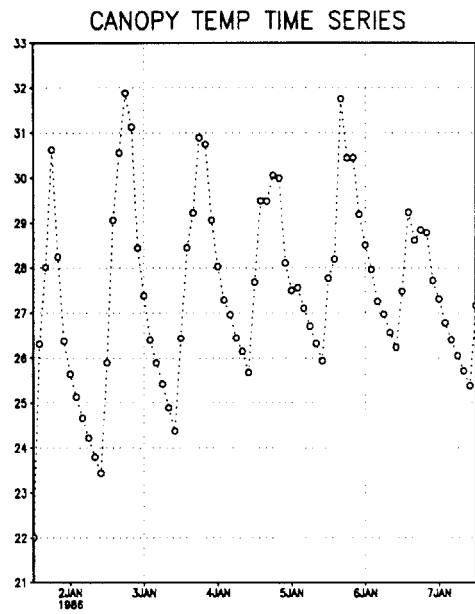
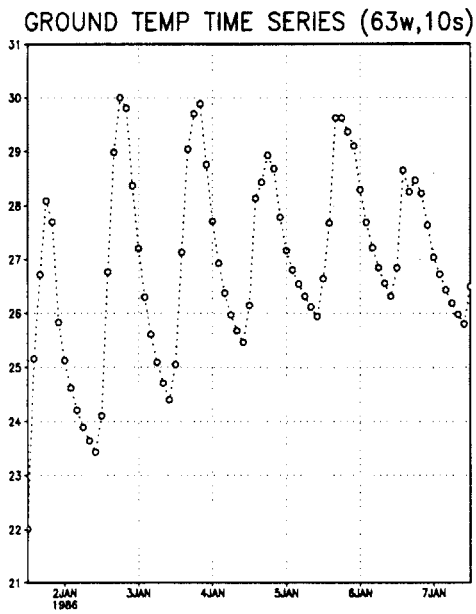
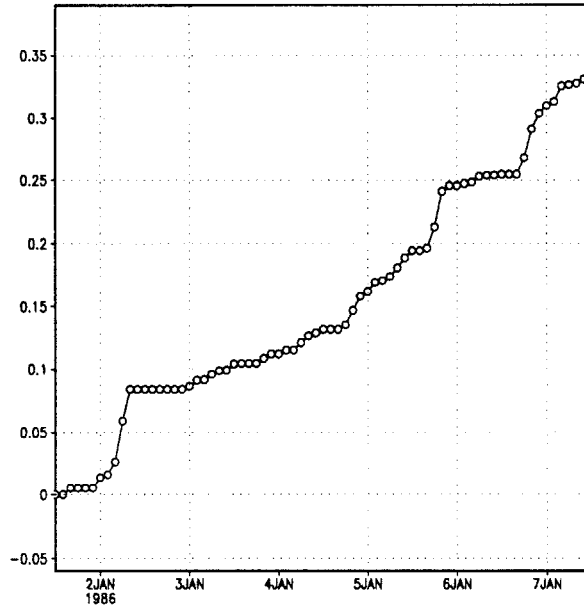


Figure 6-20: Time series of ground temperature, canopy temperature, sensible heat flux and latent heat flux at the same grid point in the deforestation experiment

Accumu. rainfall(cm) at (63w,10s) in Control E



Accumu. rainfall(cm) at (63w,10s) in Defor. E

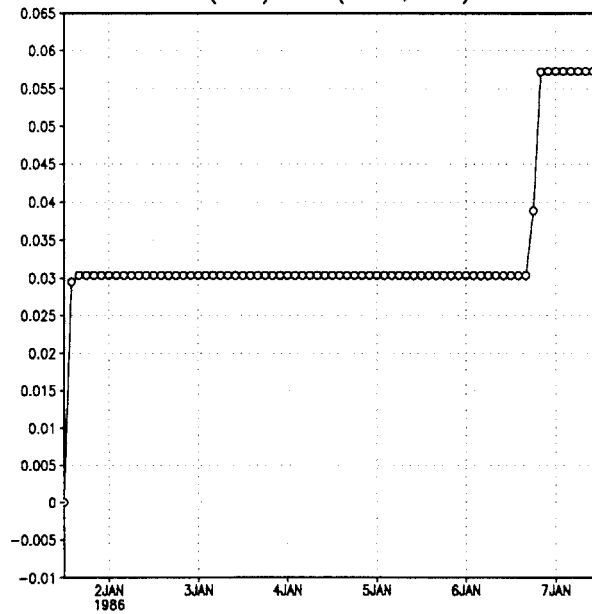


Figure 6-21: Time series of accumulated rainfall at the grid point (60w, 10s) in the control experiment and the deforestation experiment

the control experiment.

Figure 6-26 shows the distribution of the accumulated total rainfall in the deforestation experiment and the control experiment. The results indicate that the rainfall in the deforestation experiment is significantly less than that in the control experiment.

The results from the deforestation experiment indicate that the ground temperature increases by about 1-2 degrees, and the canopy temperature increases by about 2-3 degrees. There is a significant decrease in the rainfall and latent heat flux. The sensible heat flux increases.

The results of the deforestation experiment and the control experiment are consistent with previous studies. The previous studies on the sensitivity of the Amazon climate to the change from forest to savannah have been published by Lean and Warrilow (1989), Lean and Rowntree (1993), Lean et al.(1997), Dickinson and Kennedy (1992)and Henderson-Sellers et al. (1993b). Dickinson and Kennedy (1992) concluded that due to deforestation, maximum daily temperature increased by about 3 degrees, sensible heat flux increased, evapotranspiration decreased and precipitation decreased significantly. The results of this study also agree with those of Manzi and Planton (1997) in which following deforestation the temperature of air near the surface increased by an average of  $1.3^{\circ}C$  and the maximum daily temperature increased by about  $3^{\circ}C$ . The average latent heat flux decreased by about  $9 Wm^{-2}$  and the average sensible heat flux increased by the same amount.



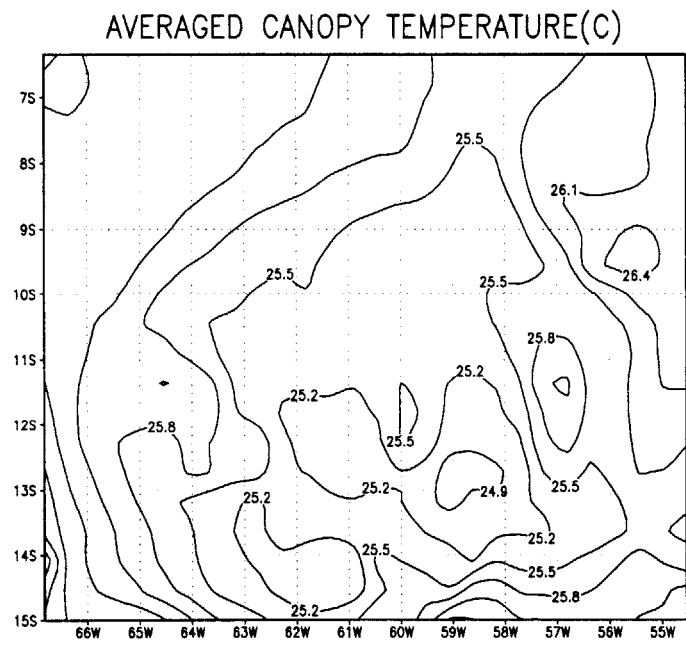
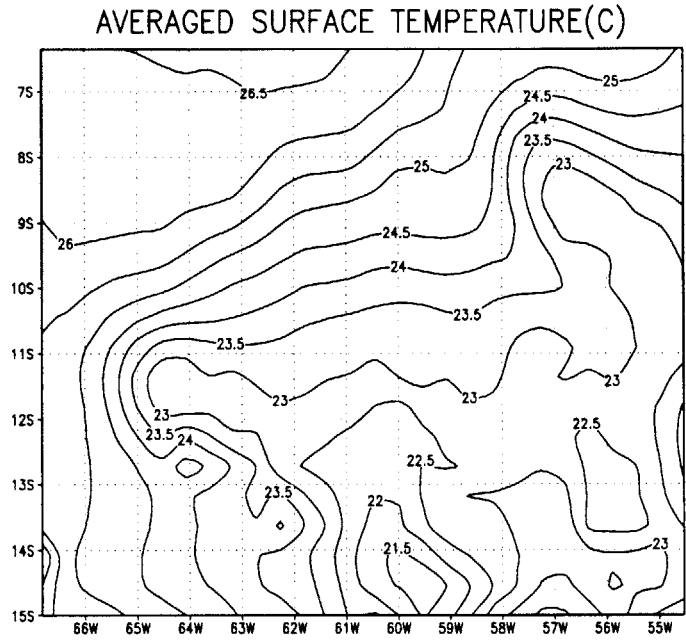


Figure 6-22: The spatial distribution of the averaged ground temperature and canopy temperature in the control experiment

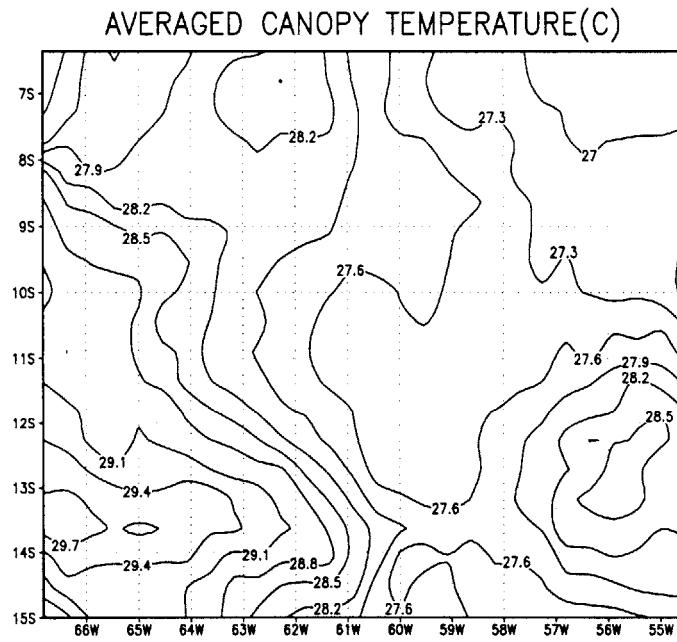
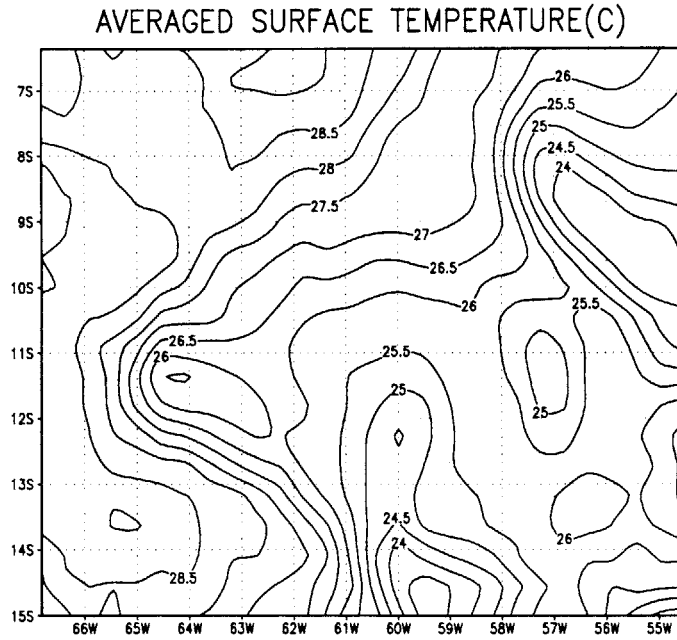


Figure 6-23: The spatial distribution of the averaged ground temperature and canopy temperature in the deforestation experiment

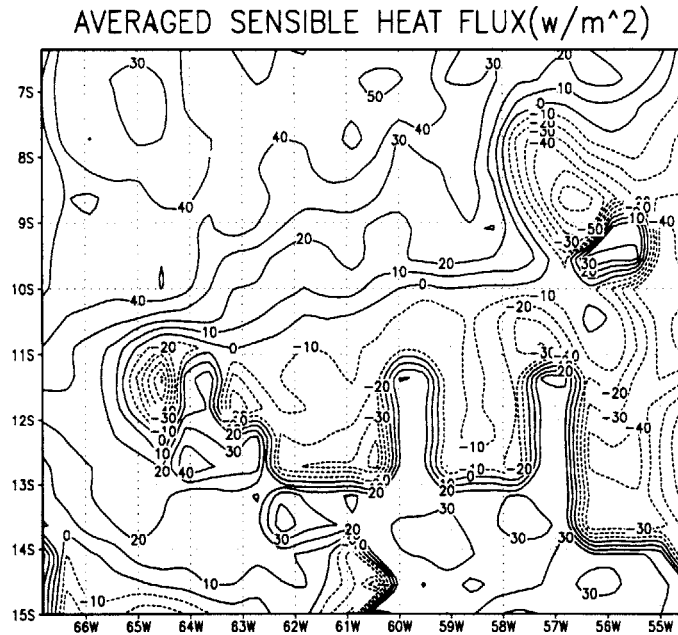
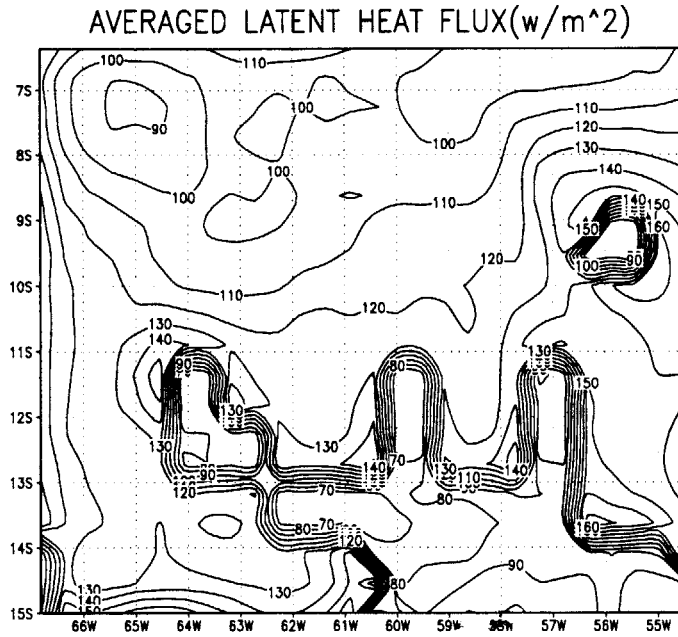


Figure 6-24: The spatial distribution of the averaged sensible and latent heat fluxes in the control experiment

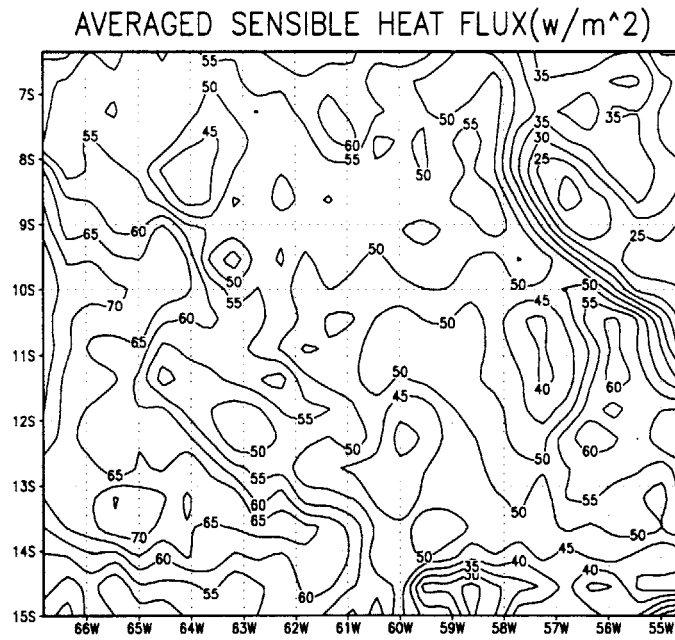
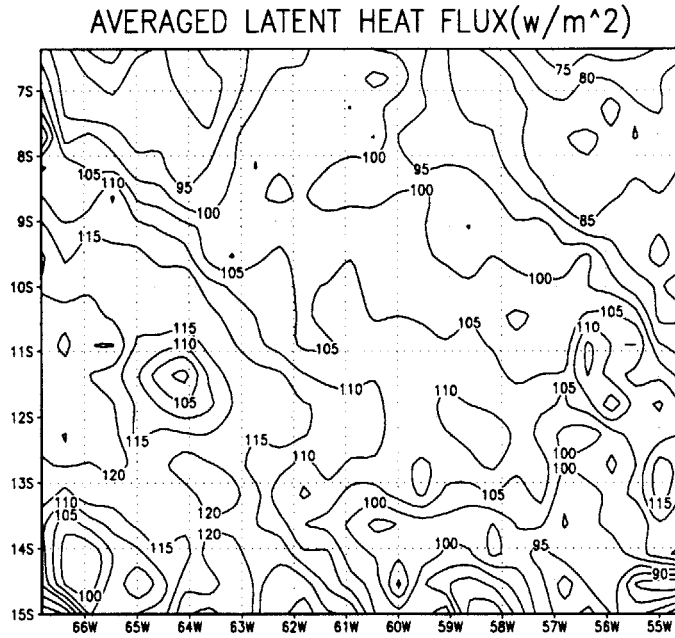


Figure 6-25: The spatial distribution of the averaged sensible and latent heat fluxes in the deforestation experiment

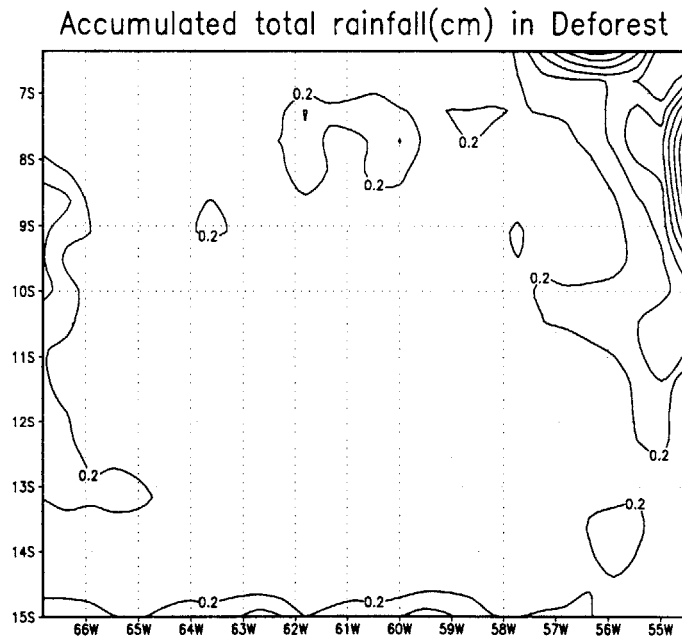
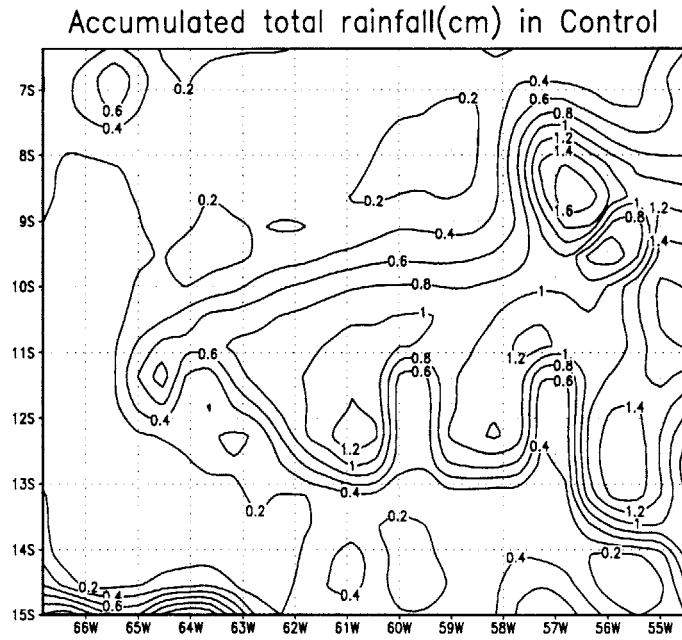


Figure 6-26: The spatial distribution of the accumulated total rainfall in the control experiment and the deforestation experiment

# Chapter 7

## Discussion and Conclusions

### 7.1 Summary

In this thesis, the Biosphere-Atmosphere Transfer Scheme was coupled to the NCAR/Penn State mesoscale atmospheric model MM5V2. The Biosphere-Atmosphere Transfer Scheme (BATS) contains a complete description of the role of vegetation in the energy and water transfer between the atmosphere and the land surface. BATS also includes representation of the surface water balance and allows heterogeneity in one grid cell which means one type of vegetation and bare soil can coexist. Another important feature of BATS is the time-dependent variables such as the fractional vegetation cover, leaf area index, surface albedo, water availability and etc. These features make the numerical simulation more realistic.

Chapter 3 and 4 describe the NCAR/Penn State mesoscale atmospheric model MM5V2 and the Biosphere-Atmosphere Transfer Scheme(BATS) in detail. In Chapter 3, MM5V2 is described as a mesoscale atmospheric model with focus on its features, uses, and capabilities. The high-resolution Blackadar planetary boundary layer scheme is discussed because the planetary boundary layer is the bridge which links the land surface with the overlying atmosphere. A simple land surface scheme is also included in this planetary boundary layer scheme. Compared to the surface scheme used in MM5V2, the Biosphere-Atmosphere Transfer Scheme(BATS) is more complete. Chapter 4 gives a detailed description of BATS by focusing on two important processes: energy transfer and water transfer. The role of

vegetation in these two processes is discussed.

Chapter 5 presents the differences between BATS and the original surface scheme in MM5V2 and then describes the modifications made to BATS and MM5V2. A description of the coupling processes is included.

Chapter 6 describes the design and results of the numerical simulations performed with the coupled model. Two numerical experiments are carried out to simulate processes over two different sites. Both sites includes significantly deforested areas in the Amazon basin. One is in the eastern Amazon basin. The other one is in the south-western Amazon which includes the Rondonia region. The first experiment is a 5-day simulation from January 1 to January 6, 1986, carried out in eastern Amazon basin. The second experiment is a 25-day simulation from January 2 to January 27, 1986, carried out in south-western Amazon. From the results of these experiments, we concluded that the coupled model behaves well and produces a fairly complete description of the land surface processes.

After the two preliminary experiments, a deforestation experiment is performed with the same initial and boundary conditions as those of the second experiment described above. The deforestation simulation assumes that the whole domain is covered by savannah. A control experiment is carried out at the same time whose land cover data is specified based on the NCAR dataset archive. The distribution of the vegetation cover in the simulation domain is the same as that of the second experiment . Both of the deforestation experiment and the control experiment begin on January 1 and extend to January 7, 1986. Deforestation leads to an increase of ground temperature of 1-2 degrees. The canopy temperature increases by about 2-3 degrees. The sensible heat flux increases and latent heat flux decreases. Rainfall decreases significantly with deforestation. It seems that deforestation in Amazon can have a significant impact on the regional climate and the hydrological processes.

## 7.2 Discussions

The goal of this study was to link a mesoscale atmospheric model (MM5V2) to a Biosphere-Atmosphere Transfer Scheme (BATS) and to use the coupled model to simulate deforestation over the Amazon.

The simulation results presented in Chapter 6 show that the coupled model produces qualitatively more realistic results than simpler land surface parameterization. Most of the success is due to BATS' ability to appropriately represent evaporation from bare soil and vegetation. BATS also allows for heterogeneity in each grid cell and time-dependent properties of the land surface parameters.

There are still some improvements to be made to the coupled model. As described in Chapter 5, BATS obtains the vegetation type for a particular grid cell from the vegetation index in MM5V2, while the soil texture and soil color are derived from the vegetation type based on Table 4.1. Usually when MM5V2 processes the vegetation data, one vegetation type is assigned in one grid cell. Therefore BATS will have only one type of vegetation in one grid cell, in addition to bare soil. In reality, there may be several different types of vegetation, soil texture and soil color in one grid cell.

BATS is a one-dimensional simulation model which includes a canopy layer and three soil layers. The processes of energy and water transfer between the atmosphere and the land surface are assumed vertical. The horizontal interactions on the land surface are not considered. This poses a problem if we want to study the surface runoff and ground water runoff. Improvement is needed in the treatment of water balance in BATS.

### **7.3 Future work**

Simulations from the MM5V2 coupled with BATS need to be compared to observations such as from ABRACOS, ARME and the future LBA. Future work should also investigate the impact of deforestation in the Amazon basin using the observed deforestation data from the NASA Landsat Pathfinder imagery. The satellite observations of the Amazon deforestation were described by Skole and Tucker (1993). A long term deforestation experiment should be performed to consider seasonal and annual variations. Furthermore, the coupled model must be enhanced to incorporate better vegetation and soil data.

Another improvement that should be made to the coupled model is to make the source code of BATS as a single sub-directory under the PBL directory in MM5V2, so other PBL schemes (besides the high resolution Blackadar PBL scheme) can access BATS easily and



will be coupled with BATS efficiently. The new structure of the coupled model is shown in Figure 7-1. In this new scheme, BATS would be a single sub-directory which would be called by all the PBL parameterizations such as the bulk, dry, hirpbl and mrfpbl.

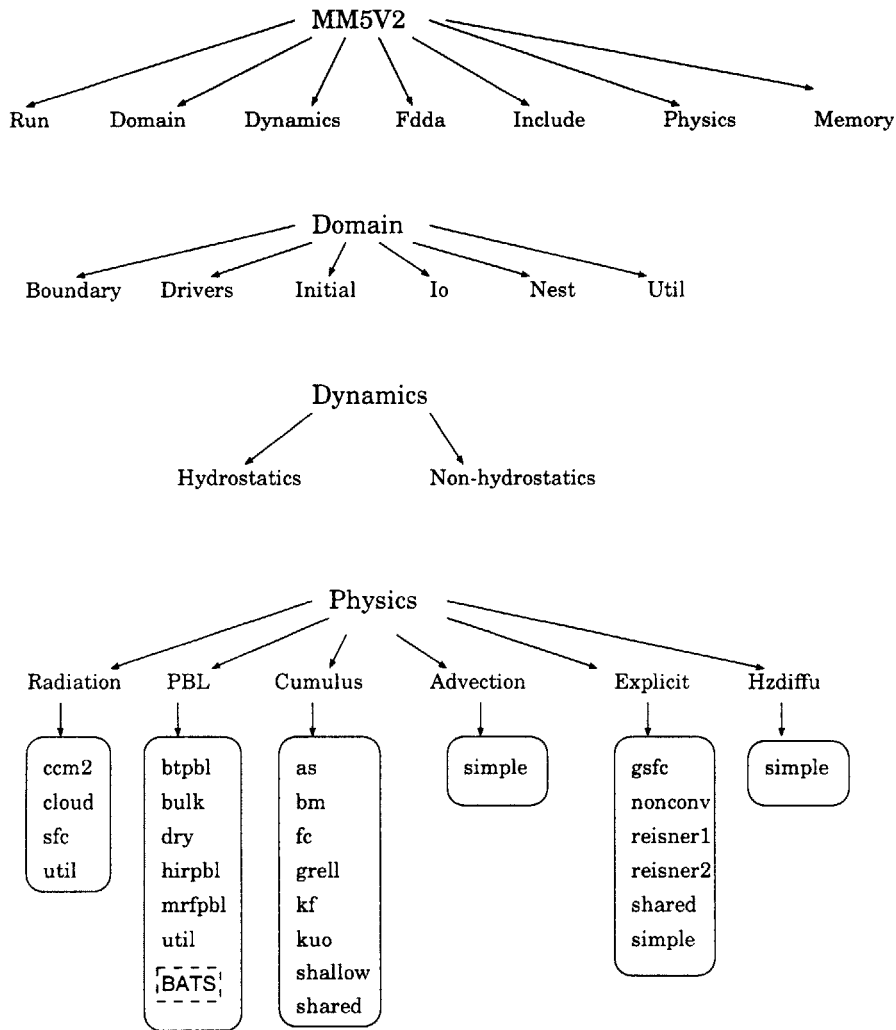


Figure 7-1: The new multi-level directory structure of the MM5V2-BATS coupled model

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# Appendix A

## List of Notations

### A.1 Symbols in Thesis Text

$ALB_{veg}$	effective vegetation albedo [%]
$ALBS_{veg}$	vegetation albedo for wavelength $\lambda$ is less than $0.7 \mu\text{m}$ [%]
$ALBL_{veg}$	vegetation albedo for wavelength $\lambda$ is greater than $0.7 \mu\text{m}$ [%]
$ALBGO$	albedo for a saturated soil [%]
$ALBGS$	albedo of bare soil [%]
$C_D$	drag coefficient [-]
$C_{DN}$	drag coefficient for the neutral condition [-]
$C_p$	specific heat for air [ $\text{J m}^{-3} \text{K}^{-1}$ ]
$C_{pm}$	specific heat for moist air [ $\text{J m}^{-3} \text{K}^{-1}$ ]
$Dep_{sw}$	depth of the upper soil layer [mm]
$Dep_{rw}$	depth of the rootzone soil layer [mm]
$Dep_{tw}$	depth of the total soil layer [mm]
$D_w$	drainage from the leaves [ $\text{mm s}^{-1}$ ]
$E_f$	evaporation [ $\text{mm s}^{-1}$ ]
$E_{tr}$	transpiration [ $\text{mm s}^{-1}$ ]
$E_q$	latent heat flux from bare soil [ $\text{W m}^{-2}$ ]
$E_a$	latent heat flux from the canopy and the soil [ $\text{W m}^{-2}$ ]



$G$	net water mass incident on the surface [ $\text{mm s}^{-1}$ ]
$H_a$	sensible heat flux from the canopy and the soil [ $\text{W m}^{-2}$ ]
$H_f$	sensible heat flux from the canopy [ $\text{W m}^{-2}$ ]
$H_s$	sensible heat flux from the bare soil [ $\text{W m}^{-2}$ ]
$K_{wo}$	flow rate for saturated soil due to gravity [ $\text{m s}^{-1}$ ]
$LAI$	leaf area index [-]
$P_r$	precipitation rate [ $\text{mm s}^{-1}$ ]
$p_s$	the surface pressure [Pa]
$p_t$	the top pressure [Pa]
$P_{ORSL}$	porosity of the soil [-]
$q_a$	specific humidity of the near surface atmosphere [kg/kg]
$q_{af}$	water-vapor specific humidity of the air in the canopy [kg/kg]
$q_f^{SAT}$	saturated water vapor specific humidity of the leaf [[kg/kg]
$q_g$	saturated specific humidity at the ground temperature [kg/kg]
$R_{iB}$	Richardson number [-]
$R_s$	surface runoff [ $\text{mm s}^{-1}$ ]
$R_g$	ground water runoff [ $\text{mm s}^{-1}$ ]
$R_w$	total runoff [ $\text{mm s}^{-1}$ ]
$r_{la}$	aerodynamic resistance to heat and vapor flux [ $\text{s m}^{-1}$ ]
$r_s$	leaf resistance (or stomatal resistance) [ $\text{s m}^{-1}$ ]
$r_{smin}$	minimum leaf resistance [ $\text{s m}^{-1}$ ]
$SAI$	stem area index [-]
$S_m$	snowmelt [ $\text{mm s}^{-1}$ ]
$S_{sw}$	soil moisture of the upper soil layer [mm]
$S_{rw}$	soil moisture of the rootzone soil layer [mm]
$S_{tw}$	soil moisture of the total soil layer [mm]

$s_1$	ratio of the rootzone soil moisture to its maximum [-]
$s_2$	ratio of the upper soil moisture to its maximum [-]
$s$	ratio of the total soil moisture to its maximum [-]
$T_a$	atmosphere temperature near surface [K]
$T_g$	surface temperature [K]
$T_{vir}$	virtual temperature of the atmosphere near surface [K]
$T_{veg}$	canopy temperature [K]
$T_s$	surface bare soil temperature [K]
$u_*$	friction velocity [ $m\ s^{-1}$ ]
$V$	velocity [ $m\ s^{-1}$ ]
$V_c$	convective velocity [ $m\ s^{-1}$ ]
$z_0$	roughness height [m]
$z_1$	height of the lowest level in the atmosphere layer [m]
$\phi_h$	nondimensional stability parameter for sensible heat flux [-]
$\phi_m$	nondimensional stability parameter for moisture heat flux [-]
$\rho_a$	surface air density [ $kg\ m^{-3}$ ]
$\rho_w$	soil water density [ $kg\ m^{-3}$ ]
$\rho_{wsat}$	saturated soil water density [ $kg\ m^{-3}$ ]
$\sigma$	representation of model levels in MM5V2 [-]
$\sigma_f$	fractional vegetation cover [-]
$\theta_a$	atmosphere potential temperature [K]
$\theta_g$	surface potential temperature [K]
$\theta_{va}$	atmosphere virtual potential temperature [K]
$\theta_{vg}$	surface virtual potential temperature [K]
$\zeta$	zenith angle [degree]

## A.2 Variables of BDPONT in bats.incl

<i>NPK</i>	surface pressure [Pa]
<i>NDEL</i>	delta temperature [K]
<i>NDELQ</i>	delta specific humidity [kg/kg]
<i>NTGK</i>	ground temperature [K]
<i>NTSK</i>	near surface atmosphere temperature [K]
<i>NQ GK</i>	ground specific humidity [kg/kg]
<i>NQSK</i>	near surface atmosphere specific humidity [kg/kg]
<i>NUSK</i>	near surface westerly wind [ $\text{m s}^{-1}$ ]
<i>NVSK</i>	near surface southerly wind [ $\text{m s}^{-1}$ ]
<i>NLDOCK</i>	land/ocean mark [-]
<i>NTAFK</i>	temperature of air within foliage [K]
<i>NSCVK</i>	snow cover [mm]
<i>NRNOK</i>	total runoff [ $\text{mm s}^{-1}$ ]
<i>NRNOSK</i>	surface runoff [ $\text{mm s}^{-1}$ ]
<i>TGBK</i>	temperature of the lower soil [K]
<i>NSICEK</i>	sea ice thickness [mm]
<i>NSAGK</i>	non-dimensional snow age [-]
<i>NLDEWK</i>	water on foliage [mm]
<i>NTLEFK</i>	foliage temperature [K]
<i>NRINUSK</i>	surface Richardson number [-]
<i>NWSPDK</i>	wind speed with convective correction [ $\text{m s}^{-1}$ ]
<i>NVEGK</i>	fractional vegetation cover [-]
<i>NEVPRK</i>	surface evaporation [ $\text{mm s}^{-1}$ ]
<i>NFRSK</i>	net absorbed solar radiation [ $\text{W m}^{-2}$ ]
<i>NTVEGK</i>	vegetation type [-]
<i>NRHS</i>	density of surface air [ $\text{kg m}^{-3}$ ]
<i>NGWETK</i>	ground wetness factor [-]
<i>NLATK</i>	surface latent heat flux [ $\text{W m}^{-2}$ ]

<i>NSOILK</i>	heat flow into soil [ $W m^{-2}$ ]
<i>NPRCPK</i>	instantaneous precipitation [ $mm s^{-1}$ ]
<i>NIRCPK</i>	interception [ $mm s^{-1}$ ]
<i>EVPRK</i>	evaporation [ $mm s^{-1}$ ]
<i>NRSWK</i>	rootzone soil moisture [mm]
<i>NTSWK</i>	total soil moisture [mm]
<i>NMAVAK</i>	moisture availability for soil [%]
<i>NHOLK</i>	height of the planetary boundary layer [m]
<i>NRIBK</i>	Richardson number [-]
<i>NRIBYAVEGTK</i>	time-averaged Richardson number [-]
<i>NREBK</i>	stability class [-]
<i>NUSTK</i>	friction velocity [ $m s^{-1}$ ]
<i>NRSK</i>	stomatal resistance [ $s m^{-1}$ ]
<i>NRAK</i>	aerodynamic resistance [ $s m^{-1}$ ]
<i>NBOWEK</i>	bowen ratio [-]
<i>ALBEK</i>	albedo (over the grid cell) [%]
<i>NSENTK</i>	surface sensible heat flux [ $W m^{-2}$ ]
<i>NZ1K</i>	height of th lowest atmosphere layer [m]
<i>NFRLK</i>	net long wave radiation [ $W m^{-2}$ ]
<i>NALBGK</i>	albedo (over the bare soil) [%]
<i>NALBVK</i>	albedo (over vegetation) [%]
<i>NAEMIK</i>	atmosphere emissivity [%]
<i>NCPM</i>	specific heat for atmosphere [ $J m^{-3} K^{-1}$ ]
<i>NFRLAK</i>	accumulated long wave radiation [ $s \times Wm^{-2}$ ]
<i>NFRSAK</i>	accumulated short wave radiation [ $s \times Wm^{-2}$ ]
<i>NSENAK</i>	accumulated sensible heat flux [ $s \times Wm^{-2}$ ]
<i>NEVPAK</i>	accumulated evaporation [mm]
<i>NPRCAK</i>	accumulated precipitation [mm]
<i>NTMINK</i>	accumulated surface runoff [mm]
<i>NTMAXK</i>	accumulated total runoff [mm]

### A.3 Variables of BDCN in bats.incl

<i>CHS</i>	latent heat constant for snow [J/kg]
<i>CHSW</i>	latent heat constant for water and snow [J/kg]
<i>CHW</i>	latent heat constant for water [J/kg]
<i>GRV</i>	gravity constant [ $m/s^2$ ]
<i>C(10)</i>	array of constants used in bats
<i>CH2O</i>	specific heat for water [ $Jm^{-3}K^{-1}$ ]
<i>CICE</i>	specific heat for ice [ $Jm^{-3}K^{-1}$ ]
<i>CP</i>	specific heat constant for dry air [ $Jkg^{-1}K^{-1}$ ]
<i>CSNW</i>	specific heat for snow [ $Jm^{-3}K^{-1}$ ]
<i>CSOILC</i>	cso drag coefficient for soil under canopy [-]
<i>CWI</i>	ratio of specific heat of water to ice [-]
<i>CWS</i>	ratio of specific heat of water to snow [-]
<i>DEPR</i>	depth of root zone soil layer [mm]
<i>DEPU</i>	depth of surface soil layer [mm]
<i>DEWMX</i>	maximum allowed dew [mm]
<i>DEWMXI</i>	inverse of maximum allowed dew [1/mm]
<i>GASCNT</i>	gas constant for dry air [ $Jkg^{-1}K^{-1}$ ]
<i>PI</i>	pi constant [-]
<i>PORSL</i>	soil porosity [-]
<i>RMAX0</i>	maximum stomatal resistance [s/m]
<i>ROTF</i>	ratio of roots in upper layer to root layer [-]
<i>STEFNC</i>	stefans constant [ $Wm^{-2}K^{-4}$ ]
<i>STDPR</i>	standrard pressure [Pa]
<i>TAU1</i>	day length [s]
<i>TFRE</i>	freezing temperature [K]
<i>TRSMX0</i>	maximum transpiration for saturated soil [mm/s]
<i>VTYRB</i>	turbulent wind for stable conditions [m/s]
<i>VONKAR</i>	Von Karman constant [-]

<i>ZLND</i>	roughness length for soil [m]
<i>ZOCE</i>	roughness length for ocean [m]
<i>ZSNO</i>	roughness length for snow [m]
<i>ALBVGL</i> (18)	veg. albedo for wavelengths > 0.7 microns [-]
<i>ALBVG</i> (18)	veg. albedo for wavelengths <0.7 microns [-]
<i>BEE</i> (12)	Clapp and Hornbereger "b" parameter [-]
<i>DEPRV</i> (18)	array for depth of rootzone soil layer [mm]
<i>DEPTV</i> (18)	depth of total soil layer [mm]
<i>DEPUV</i> (18)	array for depth of surface soil layer [mm]
<i>DISPLA</i> (18)	displacement height [m]
<i>FC</i> (18)	light dependence of stomatal resistance [ $m^2/w$ ]
<i>FREZA</i> (18)	min unfrozen ground depth for annual soil layer [mm]
<i>FREZU</i> (18)	min unfrozen ground depth for daily soil layer [mm]
<i>ROOTF</i> (18)	ratio of roots in upper layer to in root layer [-]
<i>ROUGH</i> (18)	aerodynamic roughness length [m]
<i>RSMIN</i> (18)	minimum stomatal resistance [s/m]
<i>SAI</i> (18)	stem area index [-]
<i>SEASF</i> (18)	diff. between vegc and fractional cover at 269 k [-]
<i>SKRAT</i> (18)	ratio of soil thermal conduct. to that of loam [-]
<i>SOLOUR</i> (18)	soil albedo for different colored soils [-]
<i>SQRTDI</i> (18)	inverse sqrt of leaf dimension [ $m^{-0.5}$ ]
<i>VEGC</i> (18)	maximum fractional cover of vegetation [-]
<i>XLA</i> (18)	maximum leaf area index [-]
<i>XLAI0</i> (18)	minimum leaf area index [-]
<i>XMOFC</i> (12)	ratio of field capacity to sat water content [-]
<i>XMOHYD</i> (12)	maximum hydraulic conductivity of soil [mm/s]
<i>XMOPOR</i> (12)	fraction of soil that is voids [%]
<i>XMOSUC</i> (18)	minimum soil suction [mm]
<i>XMOWIL</i> (12)	fraction of water content at permanent wilting [%]

## A.4 Variables of SURFAR and BATS2D in bats.icnl

<i>TAF</i>	temperature of air in the canopy [K]
<i>TLEF</i>	foliage temperature [K]
<i>SSW</i>	water content in the upper soil layer [mm]
<i>RSW</i>	water content in the rootzone soil layer [mm]
<i>TSW</i>	water content in the total soil layer [mm]
<i>RNOS</i>	surface runoff [ $\text{mm s}^{-1}$ ]
<i>RNO</i>	total runoff [ $\text{mm s}^{-1}$ ]
<i>DEW</i>	leaf drainage [ $\text{mm s}^{-1}$ ]
<i>SAG</i>	non-dimensional snow age [-]
<i>SCV</i>	snow cover [mm]
<i>SICE</i>	sea ice thickness [mm]
<i>IRCP</i>	interception [ $\text{mm s}^{-1}$ ]
<i>GWET</i>	ground wetness factor [-]
<i>TVEG</i>	canopy temperature [K]
<i>LDOC</i>	land/ocean mark [-]
<i>VEG</i>	fractional vegetation cover [-]
<i>SWET</i>	surface wetness factor [-]
<i>NGLW</i>	net long wave radiation [ $\text{W m}^{-2}$ ]
<i>NGSW</i>	net short wave radiation [ $\text{W m}^{-2}$ ]
<i>RIBYAVGT</i>	time-averaged Richardson number [-]
<i>PRCA2D</i>	accumulated precipitation [mm]
<i>EVPA2D</i>	accumulated evaporation [mm]
<i>RNOS2D</i>	accumulated surface runoff [mm]
<i>RNO2D</i>	accumulated total runoff [mm]
<i>SENA2D</i>	accumulated sensible heat flux [ $s \times \text{W m}^{-2}$ ]
<i>FLWA2D</i>	accumulated long wave radiation [ $s \times \text{W m}^{-2}$ ]
<i>FSWA2D</i>	accumulated shortwave radiation [ $s \times \text{W m}^{-2}$ ]
<i>USLYU</i>	surface velocity at western-eastern [ $\text{m s}^{-1}$ ]
<i>VSLYU</i>	surface velocity at southern-northern [ $\text{m s}^{-1}$ ]

## A.5 Other Variables in bats.incl

<i>WTLH</i>	heat conductance for leaf [m/s]
<i>WTG</i>	heat conductance for ground [m/s]
<i>WTSHI</i>	heat resistance for air, ground and leaf [s/m]
<i>WTL0</i>	normalized heat conductance for air [-]
<i>WTG0</i>	normalized heat conductance for ground [-]
<i>WTGL</i>	normalized heat conductance for leaf and ground [-]
<i>WTA0</i>	normalized heat conductance for air [-]
<i>WTGA</i>	normalized heat cond. for air and ground [-]
<i>WTLQ</i>	latent heat conductance for leaf [m/s]
<i>WTGQ</i>	latent heat conductance for ground [m/s]
<i>RGR</i>	ground wetness [-]
<i>WTSQI</i>	latent heat resistance for air, grd and leaf [s/m]
<i>WTGQ0</i>	normalized heat conductance for ground [-]
<i>WTLQ0</i>	normalized latent heat conductance for leaf [-]
<i>WTGLQ</i>	normalized latent heat cond. for leaf and ground [-]
<i>WTAQ0</i>	normalized latent heat conductance for air [-]
<i>WTGAQ</i>	normalized latent heat cond. for air and ground [-]
<i>WTG2</i>	variable used in potential evaporation [m/s]
<i>CN1</i>	product of air density and air conductance [mm/s]
<i>DF</i>	product of cp, density and conduct of air [ $Wm^{-2}K^{-1}$ ]
<i>SIGF</i>	fraction of veg cover, excluding snow-covered veg [-]
<i>SCRAT</i>	fraction of soil covered by snow [-]
<i>VVA</i>	wind speed above canopy [m/s]
<i>UAF</i>	velocity of air within foliage [m/s]
<i>CDR</i>	surface drag coefficient [-]
<i>HTVP</i>	latent heat of vapor of water (or sublimation) [J/kg]
<i>AAREA</i>	fraction of lead water [-]
<i>CDR</i>	surface drag coefficient [-]
<i>QICE</i>	specific humidity above snow surface [kg/kg]



<i>PS</i>	precipitation as snow [mm/s]
<i>PW</i>	precipitation as water [mm/s]
<i>ETR</i>	transpiration rate [mm/s]
<i>EFPR</i>	moisture flux to atmosphere [mm/s]
<i>CGRND</i>	deriv. of soil energy flux wrt to soil temp [ $Wm^{-2}K^{-1}$ ]
<i>CGRNDS</i>	deriv of soil latent heat flux wrt soil temp [ $Wm^{-2}K^{-1}$ ]
<i>CGRNDL</i>	deriv, of soil sensible heat flux wrt soil temp [ $Wm^{-2}K^{-1}$ ]
<i>CF</i>	heat transfer coefficient from leaves [-]
<i>DENSI</i>	ratio of snow density to fresh snow density [-]
<i>XLAI</i>	adjusted leaf area index for seasonal variation [-]
<i>SCVK</i>	snow cover, water equivalent [mm]
<i>WATA</i>	average of watr and watu
<i>WATR</i>	ratio of rootzone soil moisture to max allowance [-]
<i>WATT</i>	ratio of total soil moisture to max allowance [-]
<i>WATU</i>	ratio of upper soil moisture to max allowed [-]
<i>TM</i>	reference temp for precp as snow or water [K]
<i>FLNET</i>	long wave radiation flux from canopy to ground [ $Wm^{-2}$ ]
<i>FLNETO</i>	IR from canopy to ground (previous leaf temp)[ $Wm^{-2}$ ]
<i>RLAI</i>	sum of leaf and stem area indices [-]
<i>EG</i>	saturated vapor pressure [Pa]
<i>QSATL</i>	sat specific humidity for leaf temp [kg/kg]
<i>RHOSW</i>	density of snow relative to water [-]
<i>EVAPS</i>	moisture flux from ground to atmosphere [mm/s]
<i>EVAPW</i>	soil evaporation [mm/s]
<i>FSENG</i>	sensible heat flux from ground [ $Wm^{-2}$ ]
<i>FEVPG</i>	evaporation heat flux from ground [mm/s]
<i>LVEG</i>	index for land cover type [-]
<i>IMELT</i>	flag for sea ice melting [-]

# Appendix B

## BATS Files Descriptions

<i>ALBEDO</i>	Calculate fragmented albedos in wavelength regions split at $0.7\mu m$
<i>BATS</i>	Main drive program
<i>BDCON</i>	Define constant
<i>BDPONT</i>	Define BATS pointer variables
<i>BLKDAT</i>	Assign constants that appear in common block
<i>BNDRY</i>	Main subroutine, advance time information
<i>CONDCH</i>	Provide sensible heat conductances for canopy and soil fluxes
<i>CONDCQ</i>	Provide latent heat conductances for canopy and soil fluxes
<i>DEPTH</i>	Provide snow depth parameters
<i>DERIV</i>	Compute derivatives of energy fluxes to leaf temperature
<i>DRAG</i>	Determine surface transfer coefficient
<i>DRAGN</i>	Calculate neutral drag coefficient
<i>DRIP</i>	Compute water draining from leaf
<i>FRAWAT</i>	Determine fraction of foliage covered by water
<i>INITB</i>	Initialize fields
<i>LEFTEM</i>	Calculate leaf temperature, leaf fluxes and net transpiration
<i>LFDRAG</i>	Recalculate stability dependent drag coefficient for vegetation
<i>SATUR</i>	Calculate saturation vapor pressure

*SNOW* Update snow cover and snow age  
*STOMAT* Compute leaf stomatal resistance  
*TGRUND* Calculate ground temperature  
*VCOVER* Provide leaf and stem area parameters  
*WATER* Update soil moisture and runoff  
*ZENITH* Calculate the solar height used in calculating radiation

# Appendix C

## The MM5V2-BATS Coupled Model User Manual

### C.1 Introduction

This document describes the use of the model which couples the Biosphere-Atmosphere Transfer Scheme(BATS) to the mesoscale atmospheric model MM5V2. The coupling of the two models is supported by NASA Goddard Space Flight Center under grant NAG5-3726. The coupled model is described in Li Yu's master' thesis at MIT. Her thesis title is "Coupling A Biosphere-Atmosphere Transfer Scheme with a Mesoscale Atmospheric Model: A Case Study in Deforestation".

The MM5V2-BATS coupled model was originally developed to study the impact of the Amazonia deforestation on the regional climate and hydrological processes using a complex and realistic land surface parameterization BATS. It has been shown that accurately representing land surface processes is important in simulating the evolution of the planetary boundary and climatic variables such as rainfall, evaporation, surface temperature and soil moisture.

Validation of the MM5V2-BATS coupled model was conducted on a DEC-ALPHA workstation running Digital UNIX V4.0B operating system and using Fortran 77 compiler.

## C.2 Modifications of MM5V2 when Coupling BATS

1) The MM5V2 planetary boundary layer scheme “hirpbl” under directory “physics/pbl” is replaced by “hirpbl-BATS”. The surface process module in ‘hirpbl’ is replaced by BATS. All the source code of BATS is included in “hirpbl-BATS”.

2) Data interfaces between MM5V2 and BATS are described in a new subroutine INTERF (see Appendix E).

3) The formula for Richardson number in BATS is replaced by the Richardson number used in directory “hirpbl” of MM5V2. The formula was modified to consider the effect of the canopy temperature. To avoid unstable punctual fluctuations, changes in the Richardson number are limited to the average of the previous 30 minutes, a time-averaged Richardson number is built.

4) A new “bats.incl” file is added in directory incl. The file “bats.incl” is included in every subroutine in MM5V2-BATS which contains any of the variables described in “bats.incl”. The address is /include/bats.incl.

5) A formulation of a new defined variable instantaneous precipitation rate is added in file “cupara3.F” in the Grell cumulus scheme. The address is /physics/cumulus/grell/cupara3.F.

6) A new initialization file initb.F was created. This file provides the initialization for BATS. Its address is /domain/initial/initb.F.

7) The output files in MM5V2 are modified in order to include the output from BATS. The modified output files are outprt.F and outtap.F which are under directory /domain/io. Appendix N shows the modifications in these output files.

## C.3 Structure of the Coupled Model

MM5V2 has more than 200 subroutines which are grouped according to function or atmospheric physics option. For example, a single directory may include routines that are relevant to the Grell cumulus parameterization, while another would have the Kuo scheme’s. The structure of MM5V2 is shown in Figure 3.2 . The “include” directory contains the include

files for the various subroutines. The “Domain”, “Dynamics”, “Fdda”, “Physics”, and “Util” directories contain the subroutines divided by functions or atmospheric physics options. The “Run” directory holds the main program source code.

BATS is used as a stand-alone module in each grid cell of the atmospheric model MM5V2. BATS contains over 20 subroutines which follow the BATS computation flow. A new subroutine INTERF was built. This subroutine implements the data interface between BATS and MM5V2. There is an index 'INNEX' in INTERF to denote the direction of the data flow. If the index equals one, the data from the overlying atmospheric layer are transferred to BATS, otherwise the results from BATS simulation are transferred into MM5V2. The coupled BATS computation flow is shown in Figure 5.1 . The high-resolution Blackadar PBL scheme contains a simple surface module which will be replaced by BATS when BATS is coupled to MM5V2.

The structure of the coupled model is almost the same as that of the original MM5V2, except the directory hirpbl under the directory Physics/PBL is replaced by hirpbl-BATS. The new structure of the hirpbl-BATS scheme, as well as that of the original hirpbl scheme, is illustrated in Figure 5.2.

## C.4 Inputs to the Coupled Model

There are two classes of model input: data files and configuration files. Data files, which contain the actual numerical values needed to initialize and run the model, include terrain height, land use, initial conditions and boundary conditions. Configuration files contain information specifying domain, physics options, and length of run. The configuration files are 'configure.user' and 'mm5.deck'.

The data files are prepared by running three pre-processors. The first processor TERRAIN creates topography and land use categories by implementing user-specified information, i.e. the center latitude and longitude of the desired simulation domain, the number of grid points in both east-west and north-south directions. Once it is completed, a second processor DATAGRID uses this information to create initial condition files. These initial files have two purposes. One is to initialize the model with numerical values needed to begin

the simulation; the other is to be used to create the boundary files, which will be done by the third processor. Boundary conditions are used throughout the length of the model run. The third processor INTERP performs the vertical interpolation of the meteorological data from pressure levels to the sigma coordinate system of MM5V2, and produces the initial files and the boundary files. The data processing flow is illustrated in Figure 3.1. The three pre-processors are performed on the NCAR Cray machines. The data are obtained from the NCAR dataset archive.

### **C.4.1 Input Data Information**

#### **Terrain**

##### A) Input Information

- i) desired center latitude/longitude of the simulation domain
- ii) desired resolution
- iii) desired number of grid points

##### B) Output Variables

- i) terrain height over the entire domain
- ii) vegetation/land use categories for the entire domain

#### **Initial Conditions**

##### A) Input Information

- i) output from terrain
- ii) archived low-resolution meteorological analyses, such as the output from NMC, ECMWF, TOGA and Unidata.
- iii) SST(sea surface temperature) data, if needed

##### B) Output Variables

- i) 5 3-d arrays(Surface, 1000 mb, 850 mb, 700 mb, ..., Ptop):
  - 1. temperature (K)

2. u wind ( $ms^{-1}$ )
  3. v wind ( $ms^{-1}$ )
  4. geopotential height (m)
  5. relative humidity (%)
- ii) 13 2-d arrays:
1. terrain height (m)
  2. land use category (category)
  3. map-scale factor at corner point (non-dimensional)
  4. map-scale factor at dot point (non-dimensional)
  5. latitude ( $^{\circ}N$ )
  6. longitude ( $^{\circ}E$ )
  7. sea surface temperature (K)

## Boundary Conditions

### A) Input Information

output from DATAGRID

### B) Output Variables

1. pressure and pressure tendencies
2. west wind and west wind tendencies
3. south wind and south wind tendencies
4. temperature and temperature tendencies
5. specific humidity and specific humidity tendencies
6. ground temperature

Note: tendency units are unit/sec.

## C.4.2 Configuration Files

Configuration files include two files: `configure.user` and `mm5.deck`. Compilation and physical options are chosen in `configure.user`, and run-time options are made in `mm5.deck`. The



explanations about the variables and parameters used in the two files are included in file README.namelist (see Appendix F).

## C.5 How to Run MM5V2-BATS

There are two steps to compile and run the MM5V2-BATS coupled model.

- a) Choose compilation options and compile the code.
- b) Modify the run-time options and execute the program.

### C.5.1 Compiling MM5V2-BATS

1. Edit the file 'configure.user'
2. Type 'make'

The user chooses the compilation options that are appropriate to the computer system by editing 'configure.user'. There are three things needed to do.

- Set the "RUNTIME SYSTEM" variable according to the type of computer you are using.
- Choose the appropriate fortran compiler for your hardware and operating system the computer is running.
- Select the model options which include simulation domain sizes, dynamics and physics options. Only the option 'Blackadar' (that means hirpbl scheme) can be chosen in the options for planetary boundary layer if you want to run the MM5V2-BATS coupled model.

Once you have chosen all the necessary parameters, save the file 'configure.user'. Type 'make', and the system will compile.

Some notes about the compilation: If your 'make' fails, locate the problems through the clues given after the failure of compilation. Check the options you made for correctness. The

coupled model works well on Dec-Alpha machines. It is a good habit to do a 'make clean' and then do 'make' to compile.

## C.5.2 Running MM5V2-BATS

1. edit 'mm5.deck'
2. execute the code by typing 'mm5.deck'

There are additional physics options and the I/O file names to choose when you edit the script 'mm5.deck'. After you save 'mm5.deck', type 'mm5.deck' to execute the program.

Some notes about the execution: The execute file mm5.exe and all the input files are stored in the directory Run. If you want to run the model in background mode, just type 'mm5.deck &'.

If the model fails at the beginning, the problem may be one of the following:

- I/O parameters are not matched with parameters specified in 'parame'.
- The format of the input data mismatches that required by your machine system.

If the model fails after several time steps, the problem may be:

- The time step is not compatible with the model resolution. Change the time step.
- Some kind of general computation instability caused the problem. One possible reason is that the initial conditions contain some anomalous data. Another possible reason may be some undefined or uninitialized variables which are then automatically assigned zero as initial value. Check the include files in the directory include, or the initialization files.

## C.6 Outputs from the Coupled Model

The outputs from the coupled model is stored in /Run/fort.41. File rdmm5.f (see Appendix G) is used to read the output data from the MM5V2-BATS coupled model.

There are 10 3-d variables (on 23 sigma levels):

1. U wind ( $kPa\ ms^{-1}$ )
2. V wind ( $kPa\ ms^{-1}$ )
3. Temperature ( $kPa\ K$ )
4. Mixing ratio ( $kPa\ kg/kg$ )
5. Cloud water ( $kPa\ kg/kg$ )
6. Rain water ( $kPa\ kg/kg$ )
7. Relative humidity ( $kPa\ \%$ )
8. Pressure perturbation ( $kPa\ Pa$ )
9. Vertical wind ( $kPa\ ms^{-1}$ )
10. Geopotential height ( $kPa\ m$ )

There are 32 2-d variables, which include 22 BATS surface variables. The BATS variables are:

1. Anemometer west wind ( $ms^{-1}$ )
2. Anemometer south wind ( $ms^{-1}$ )
3. Ground temperature ( $K$ )
4. Temperature of air within foliage ( $K$ )
5. Temperature of foliage ( $K$ )
6. Sensible heat flux ( $Wm^{-2}$ )
7. Latent heat flux ( $Wm^{-2}$ )
8. Accumulated convective rainfall ( $cm$ )
9. Accumulated nonconvective rainfall ( $cm$ )
10. Surface soil moisture ( $mm$ )
11. Rootzone soil moisture ( $mm$ )
12. Total soil moisture ( $mm$ )
13. Surface runoff ( $mm^{-1}$ )
14. Total runoff ( $mm^{-1}$ )
15. Leaf interception ( $mm^{-1}$ )

16. Accumulated precipitation ( $mm$ )
17. Accumulated evaporation ( $mm$ )
18. Accumulated surface runoff ( $mm$ )
19. Accumulated total runoff ( $mm$ )
20. Accumulated sensible heat flux ( $s \times Wm^{-2}$ )
21. Accumulated long wave radiation ( $s \times Wm^{-2}$ )
22. Accumulated net absorbed solar radiation ( $s \times Wm^{-2}$ )

Other 2-d variables include:

23. Pstar(surface pressure - Ptop) ( $kpa$ )
24. Terrain elevation ( $m$ )
25. Map scale factor at corner point ( dimensionless)
26. Map scale factor at dot point (dimensionless)
27. Coriolis parameter ( $s^{-1}$ )
28. Land use (category)
29. Latitude (degree)
30. Longitude (degree)
31. Infinite reservoir temperature ( $K$ )
32. Snow cover (dimensionless)

## C.7 Examples

The examples are based on the experiments in Chapter 6. Two sites were simulated in Chapter 6 using the coupled model. One site is in the eastern Amazonia, and the other is in the south-western Amazonia which includes the Rondonia region. Both sites are highly deforested. The first experiment is a 5-day simulation. Appendixes H and I show the files 'configure.user' and 'mm5.deck' used in the first experiment, respectively. The second one is a 25-day simulation. The files 'configure.user' and 'mm5.deck' used in the second experiment are provided by Appendixes J and K, respectively. Following the two preliminary

experiments, a deforestation experiment and a control experiment are carried out, which share the same 'configure.user' (see Appendix L) and 'mm5.deck' (see Appendix M).

Appendix D

BATS VARIABLES

File bats.incl

```
C-----  
      INTEGER FLDMAX,FLDM  
  
C*****      number of BATS variables      *****  
  
      PARAMETER(FLDMAX = 83)  
  
      PARAMETER(FLDM   = FLDMAX)  
  
C*****      vegetation and soil parameters      *****  
  
      COMMON/BDCN/ CH2O,  CICE, CWI  , CSNW ,    CWS, PORSL, CWSOIL,  
1  RMAX0,    GWMX0, GWMX1, GWMX2, EVMX0,  DEWMX, DEWMI,CSOILC,  
2  XRUN,  TAU1,    WILTR, RELFC,  BFC,    XKMX,   BSW, TRSMX0,  
3  ROTF,    PI,    C(130), IHIS,  ZLND,   ZOCE,   ZSNO, VONKAR,  
4  VEGC(18), SEASF(18), SQRTDI(18),    FC(18),  RSMIN(18),  
5  XLAI0(18),  SAI(18),  ROUGH(18),    XLA(18), ALBVGS(18),  
6  ALBVGL(18), KOLSOL(18),  ROOTF(18), XMOSUC(12), XMOHYD(12),  
7  XMOFC(12),  BEE(12),  SKRAT(12), VGTRAN(13),  SOLOUR(8),
```

8 GWMI0, GWMI1, GWMI2, displa(18)

C\*\*\*\*\* displa is a new parameters I added in July 10, 1998. It describes  
C\*\*\*\*\* the displacement height

C

```
COMMON/BDPRM/ SIGF, SCRAT, VVA, UAF, ETR, EFPR, CDR,  
1 CDRHEAT, CDRMOIS, CDRHEX, CDRMOX, HTVP, AAREA, QICE, PS,  
2 SM, Z1OZ0, ZNOT, XLAI, SCVK, SDRP, CLEAD, CF,  
3 WATA, WATR, WATP, WATU, RSCS, ETRRUN, TM, FLNET,  
4 SEASB, D1, RLAI, EG, QSATL, RPP, DTSAF, DQSAF,  
5 RHOSW, DENSI, PW, EVAPS, EVAPW, FSENG, FEVPG, RIBD,  
6 CGRND, CGRND, CGRNDL, XLSAI, LVEG, I, JSLC, IMELT,  
7 WTA, WTAQ, DRAIN, FLNETO, SKD, SKA, RSCSD, RSCSA
```

C

```
COMMON/BPNT/ NPK, NDELTK, NDELQK, NTGK, NTSK, NQ GK,  
1 NQSK, NUSK, NVSK, NLDOCK, NSCVK, NRNOK, NRNOSK,  
2 NTGBK, NSICEK, NSAGK, NLDEWK, NTLEFK, NVEGK, NEVPRK,  
3 NSENTK, NZ1K, NMAVAK, NFRLK, NFRSK, NRHSK, NSSWK,  
4 NTVEGK, NPRCPK, NIRCPK, NHOLK, NWSPDK, NTAFK, NGWETK,  
5 NRSWK, NTSWK, NRIBK, NUSTK, NRINUK, NREGIK, NHPBLK,  
6 NCDHBK, NCDMBK, NCDHVK, NCDMVK, NRSK, NRAK, NBOWEK,  
7 NALBEK, NALBGK, NALBVK, NSWETK, NTPRCK, NAEMIK, NLATK,
```

```

      8      NSOILK,  NCPMK,  NREVK,  NREBK,  NVAVK,  NVABK,
      9      NHOLVK, NHOLBK, NRIBVK, NRIBBK,  NUSVK,  NUSBK,  NHVK,
      $      NHBK,  NFLHCK,  NFLQCK,  NTHVXK,  NKP3BK,  NKP3VK
      $      ,NRIBYAVGTK,
CCCCCCCc  accumulative bats 2d fields(1998.07.19)  CCCCCC
      $      NFRLAK, NFRSAK, NSENAK, NEVPAK, NPRCAK, NTMINK, NTMAXK
C
      COMMON/FLDBND/   FFF (MIX,FLDM)
C
      COMMON/FRAH2O/   VEGT,  FDRY,  FWET
C
      COMMON/LEAFWT/   WTLH,   WTG,  WTSHI,  WTL0,  WTG0,  WTGL,
1          WTA0,  WTGA,  WTLQ,  WTGQ,   RGR,  WTSQI,  WTGQ0,
2          WTLQ0,  WTGLQ,  WTAQ0,  WTGAQ,  WTG2H,  WTG2M,   CN1,  DF
C
      COMMON/DSL/   DEPUV(18),  DEPRV(18),  DEPTV(18),  IEXSOL(18),
1          FREZA,          FREZU,          TEXRAT,          DEPU,
2          DEPR,          DEPT
C
      COMMON/MOSOL/   RATH2O

```



C

COMMON/BNDRYRD/ SABVEG (MIX) , SOLIS (MIX)

C

COMMON/SOILBD/ XMOPOR (12) , XMOWIL (12)

C

COMMON/ANGLE/ COSZEN (MIX)

C

REAL LDOC, IRCP

COMMON/PRECIP/ PRECIP (MIX, MJX) , PREOLD (MIX, MJX)

COMMON/SURFAR/ TAF (MIX, MJX, MAXSES) , TLEF (MIX, MJX, MAXSES) ,

1 SSW (MIX, MJX, MAXSES) , RSW (MIX, MJX, MAXSES) ,

1 RNO (MIX, MJX, MAXSES) , RNOS (MIX, MJX, MAXSES) ,

2 TSW (MIX, MJX, MAXSES) , DEW (MIX, MJX, MAXSES) ,

3 SAG (MIX, MJX, MAXSES) , SCV (MIX, MJX, MAXSES) ,

4 SICE (MIX, MJX, MAXSES) , IRCP (MIX, MJX, MAXSES) ,

5 GWET (MIX, MJX, MAXSES) , TVEG (MIX, MJX, MAXSES) ,

6 LDOC (MIX, MJX, MAXSES) , VEG (MIX, MJX, MAXSES) ,

7 SWET (MIX, MJX, MAXSES) , NGLW (MIX, MJX, MAXSES) ,

8 NGSW (MIX, MJX, MAXSES) , RIBY (MIX, MJX, MAXSES)

9

,RIBYAVGT(MIX,MJX)

CCCCCCCc accumulative bats 2d fields CCCCCCCCCCCC

COMMON/BATS2D/ prca2d(MIX,MJX), EVPA2D(MIX,MJX)

1 ,RNOS2D(MIX,MJX), RNO2D(MIX,MJX)

2 ,SENA2D(MIX,MJX), FLWA2D(MIX,MJX)

3 ,FSWA2D(MIX,MJX), SVGA2D(MIX,MJX)

4 ,USLYU(MIX,MJX), VSLYU(MIX,MJX)

Appendix E

```
C-----  
C  
C           Data Interface between BATS and MM5V2  
C  
C-----
```

```
      SUBROUTINE INTERF (IYY, JXX, KZZ, INNEX, IN, MITPAS)
```

```
C  THIS SUBROUTINE INTERFACES MM5V2  AND BATS VARIABLES
```

```
C  INNEX = 1 ,   MM5V2 (PBL)   --> BATS
```

```
C  INNEX = 2 ,   BATS         --> MM5V2 (PBL)
```

```
C  IN   = 1 ,   COARSE MESH
```

```
C  IN   = 2 ,   FIRST NEST
```

```
C  IN   = 3 ,   SECOND NEST,  and so on
```

```
C***** Descriptions of the arguments
```

```
C  IYY  latitude grid point
```

```
C  IXX  longitude grid point
```

```
C  KZZ  vertical sigma level
```

C -----

C -----  
C Descriptions of variables  
C  
C All the variables in this file are described in Appendix A.  
C  
C GENERALLY TO OBTAIN THE PARAM TO WHICH THE POINTER POINTS YOU  
C DROP THE NBEFORE AND THE K FOLLOWING  
C  
C NPK=SURFACE PRESS.(in PA) \* NFRSK= NET ALBSORBED SOLAR  
C (1 PA = 1.E-2mb = 1.E-3cb) \* NTVEGK=VEG TYPE (IE LAND TYPE)  
C NDELTK= DELTA TEMP \* NRHSK=DENSITY OF SURFACE AIR  
C NDELQK=DELTA Q (SPEC. HUM) \* NGWETK=GROUND WETNESS FACTOR (\*)  
C NSSWK=WATER IN UPPER SOIL(MM) \* (MAVAIL FOR LOWER BDY)  
C NTGK=GROUND TEMP \*  
C NTSK=ANEMOM.TEMP \* (\*)--GROUND WETNESS FACTOR IS  
C NQGK=GROUND SPECIFIC HUMID. \* RATIO OF FLUX OF H2O FROM  
C NQSK=ANEMOM.SPEC.HUMID. \* SURFACE TO THAT FROM A TOTALLY  
C NUSK=ANEMOM WESTERLY WIND \* SATURATED SURFACE AT THE SAME  
C NVSK=ANEMOM SOUTHERLY WIND \* TEMP.  
C NLDCK=LAND/OCEAN MASK \*  
C (0=OCEAN,1=LAND,2=SEAICE) \* NLATK=SFC.LAT.HEAT FL.(W/M\*\*2)  
C NTAFK=TEMP OF AIR WITHIN FOLIAGE\* NSOILK=HEAT FLOW INTO SOIL(W/M\*\*2)  
C NSCVK=SNOW COVER (MM H2O) \* NIRCPK=INTERCEPTION (MM)  
C NRNOK= TOTAL RUNOFF (MM/S) \* NPRCPK=INSTANT. PRECP (MM/S)  
C NRNOSK=SURFACE RUNOFF (MM/S) \* NEVPRK=EVAPN (KG/M\*\*2/S)  
C NTGBK=TEMP LOWER SOIL \* NRSWK=ROOT ZONE SOIL WATER (MM)  
C NSICEK=SEA ICE THICKNESS (MM) \* NTSWK=TOTAL SOIL WATER (MM)  
C (SEA ICE HELD CONSTANT) \* NMAVAK=MAVAIL FOR SOIL ONLY  
C NSAGK=NON DIM SNOW AGE \* NHOLK =HOL FOR HIRPBL  
C NLDEWK=WATER ON FOLIAGE(KG/M\*\*2) NRIBK=BULK RICHARDSON NUMBER  
C NTLEFK=FOLIAGE TEMP \* NUSTK=FRICITION VELOCITY  
C NRINUK=SFC RICHARDSON NUMBER \* NRSK =STOMATAL RESISTANCE  
C NWSPDK=WIND SPEED W/CONV.CORRECT.\*NRAK =AERODYNAMIC RESISTANCE  
C NVEGK=FRACTIONAL VEG COVER \* NBOWEK= BOWEN RATIO  
C NEVPRK=SFC. EVAPORATION \* NALBEK= ALBEDO(OVER GRID AREA)  
C NSENTK=SFC.SENS.HEAT FL(W/M\*\*2)\* NALBGK= ALBEDO(OVER GROUND)  
C NZ1K=HEIGHT OF MID LAYER 1 \* NALBVK= ALBEDO(OVER VEGETATION)

```

C  NFRLK=NET IR                      *  NAEMIK= ATM.EMISSIVITY
C  *****

C  Define function AREA AV (average)

      AREA AV(X1,X2)= SIGF*X1 + (1.-SIGF)*X2

C*****
C      Data Transfer from MM5V2 to BATS
C*****

      IF (INNEX.EQ.1) THEN

C  SIGMA OF BOTTOM MODEL LEVEL

      SGBLEV=A(KL)

C

      DO 10 ILL=1,ILX

      IF (INHYD .EQ. 1) THEN

          FFF(ILL,NPK)      = (PSB(ILL,JSLC)+PTOP)*1000.

&                                +PPB(ILL,JSLC,KL)/PSB(ILL,JSLC)

      ELSE

          FFF(ILL,NPK)      = (PSB(ILL,JSLC)+PTOP)*1000.

      ENDIF

```

```

C***** Explanation of the transfer from MM5V2 to BATS*****
C***** THX   atmophseric temperature
C***** ILL   grid point in J slice
C***** KL    vertical sigma level
C***** FFF(ILL,NTSK) BATS point variable -- atmospheric temperature
C*****      near surface at grid point ILL in J slice
C*****

```

```

      FFF(ILL,NTSK)      = THX(ILL,KL)

      FFF(ILL,NQSK)      = QX(ILL,KL)

      FFF(ILL,NUSK)      = UX(ILL,KL)

      FFF(ILL,NVSK)      = VX(ILL,KL)

      FFF(ILL,NRHSK)     = RHOX(ILL)

      FFF(ILL,NCPMK)     = CPM(ILL)

      FFF(ILL,NTAFK)     = TAF(ILL,JSLC,IN)

      FFF(ILL,NTLEFK)    = TLEF(ILL,JSLC,IN)

      FFF(ILL,NSSWK)     = SSW(ILL,JSLC,IN)

      FFF(ILL,NRSWK)     = RSW(ILL,JSLC,IN)

      FFF(ILL,NTSWK)     = TSW(ILL,JSLC,IN)

      FFF(ILL,NRNOK)     = RNO(ILL,JSLC,IN)

```

FFF ( ILL, NRNOSK) = RNOS ( ILL, JSJC, IN)  
 FFF ( ILL, NLDEWK) = DEW ( ILL, JSJC, IN)  
 FFF ( ILL, NSAGK) = SAG ( ILL, JSJC, IN)  
 FFF ( ILL, NSCVK) = SCV ( ILL, JSJC, IN)  
 FFF ( ILL, NSICEK) = SICE ( ILL, JSJC, IN)  
 FFF ( ILL, NGWETK) = GWET ( ILL, JSJC, IN)  
 FFF ( ILL, NSWETK) = SWET ( ILL, JSJC, IN)  
 FFF ( ILL, NTVEGK) = TVEG ( ILL, JSJC, IN)  
 FFF ( ILL, NLDOCK) = LDOC ( ILL, JSJC, IN)  
 FFF ( ILL, NVEGK) = VEG ( ILL, JSJC, IN)  
 FFF ( ILL, NIRCPK) = IRCP ( ILL, JSJC, IN)  
 C  
 FFF ( ILL, NRIBK) = RIBY ( ILL, JSJC, IN)  
 FFF ( ILL, NRIBYAVGTK) = RIBYAVGT ( ILL, JSJC)  
 FFF ( ILL, NHOLBK) = HOL ( ILL, JSJC)

```

      FFF ( ILL, NHOLVK)      = HOL ( ILL, JSLC)
      FFF ( ILL, NHBK)       = PBL ( ILL, JSLC)
      FFF ( ILL, NHVK)       = PBL ( ILL, JSLC)
      FFF ( ILL, NREBK)      = REGIME ( ILL, JSLC)
      FFF ( ILL, NREVK)      = REGIME ( ILL, JSLC)
10  CONTINUE
C
      ELSE
C
      IF ( MITPAS .LT. 1) THEN
          DO 31 ILL=1, ILX
              FLHC ( ILL)      = FFF ( ILL, NFLHCK)
              FLQC ( ILL)      = FFF ( ILL, NFLQCK)
              HFX ( ILL, JSLC)  = FFF ( ILL, NSENTK)
              QFX ( ILL, JSLC)  = FFF ( ILL, NEVPRK)
              IF ( FFF ( ILL, NVEGK) .GT. 0.001) THEN
C          SIGF IS FRACTIONAL VEG. COVER
                  SIGF= FFF ( ILL, NVEGK)
                  REGIME ( ILL, JSLC) =AREAAV ( FFF ( ILL, NREVK) , FFF ( ILL, NREBK) ) + 0.99
                  IREG          = REGIME ( ILL, JSLC)

```



```

REGIME(ILL,JSLC) = IREG
C
IF (FFF(ILL,NREVK) .NE. FFF(ILL,NREBK)) GO TO 120
100  WSPD(ILL)          = AREA AV(FFF(ILL,NVAVK),FFF(ILL,NVABK))
UST(ILL,JSLC) = AREA AV(FFF(ILL,NUSVK),FFF(ILL,NUSBK))
GO TO 200
120  CONTINUE
IF (FFF(ILL,NREVK) .EQ. REGIME(ILL,JSLC)) THEN
IF (REGIME(ILL,JSLC) .EQ. 4) THEN
WSPD(ILL)          = FFF(ILL,NVAVK)
UST(ILL,JSLC)     = FFF(ILL,NUSVK)
ELSE
GO TO 100
ENDIF
ENDIF
IF (FFF(ILL,NREBK) .EQ. REGIME(ILL,JSLC)) THEN
IF (REGIME(ILL,JSLC) .EQ. 4) THEN
WSPD(ILL)          = FFF(ILL,NVABK)
UST(ILL,JSLC)     = FFF(ILL,NUSBK)
ELSE

```

```

        GO TO 100

        ENDIF

ENDIF

ELSE

REGIME ( ILL, JSLC ) = FFF ( ILL, NREBK )

WSPD ( ILL )         = FFF ( ILL, NVABK )

UST ( ILL, JSLC )   = FFF ( ILL, NUSBK )

ENDIF

200  CONTINUE

      FFF ( ILL, NREGIK ) = REGIME ( ILL, JSLC )

      FFF ( ILL, NWSPDK ) = WSPD ( ILL )

      FFF ( ILL, NUSTK )  = UST ( ILL, JSLC )

31   CONTINUE

      ELSE

C*****
C           Data Transfer from BATS to MM5V2
C*****

C
      DO 32 ILL=1, ILX

C***** Explanation of the transfer from MM5V2 to BATS*****
C*****   TGB   ground temperature
C*****   ILL   grid point in J slice
C*****   JSLC  grid point (equals to J)

```

```

C*****   FFF(ILL,NTGK) BATS point variable -- ground temperature
C*****   at grid point (ILL, JSLC)
C*****
TGB(ILL,JSLC)   = FFF(ILL,NTGK)

TMN(ILL,JSLC)   = FFF(ILL,NTGBK)

NLVEG           = INT(FFF(ILL,NTVEGK) + 0.001)

IF(NLVEG.EQ.0) NLVEG=15

ITEX            = IEXSOL(NLVEG)

MAVAIL(ILL,JSLC) = (FFF(ILL,NSSWK) / (DEPUV(NLVEG)*XMOPOR(ITEX)) -
&              XMOWIL(ITEX)) / (1.-XMOWIL(ITEX))

NGSW(ILL,JSLC)   = FFF(ILL,NFRSK)

HFX(ILL,JSLC)   = FFF(ILL,NSENTK)

QFX(ILL,JSLC)   = FFF(ILL,NEVPRK)

SNOWC(ILL,JSLC) = FFF(ILL,NSCVK)

C*****   US VS on the surface fields in order to output *****
USLYU(ILL,JSLC) = FFF(ILL,NUSK)

VSLYU(ILL,JSLC) = FFF(ILL,NVSK)

C
TAF(ILL,JSLC,IN) = FFF(ILL,NTAFK)

TLEF(ILL,JSLC,IN) = FFF(ILL,NTLEFK)

SSW(ILL,JSLC,IN) = FFF(ILL,NSSWK)

```

```

RSW ( ILL, JSLC, IN) = FFF ( ILL, NRSWK)
TSW ( ILL, JSLC, IN) = FFF ( ILL, NTSWK)
RNO ( ILL, JSLC, IN) = FFF ( ILL, NRNOK)
RNOS ( ILL, JSLC, IN) = FFF ( ILL, NRNOSK)
DEW ( ILL, JSLC, IN) = FFF ( ILL, NLDEWK)
SAG ( ILL, JSLC, IN) = FFF ( ILL, NSAGK)
SCV ( ILL, JSLC, IN) = FFF ( ILL, NSCVK)
SICE ( ILL, JSLC, IN) = FFF ( ILL, NSICEK)
GWET ( ILL, JSLC, IN) = FFF ( ILL, NGWETK)
SWET ( ILL, JSLC, IN) = FFF ( ILL, NSWETK)
VEG ( ILL, JSLC, IN) = FFF ( ILL, NVEGK)
NGLW ( ILL, JSLC, IN) = FFF ( ILL, NFRLK)
NGSW ( ILL, JSLC, IN) = FFF ( ILL, NFRSK)
RIBY ( ILL, JSLC, IN) = FFF ( ILL, NRIBK)
RIBYAVGT ( ILL, JSLC) = FFF ( ILL, NRIBYAVGTK)

```

C\*\*\*\*\* time average of Richarson number \*\*\*\*\*

RIBYAVGT ( ILL, JSLC) = RIBYAVGT ( ILL, JSLC) \*19/20+

& RIBY ( ILL, JSLC, IN) /20

C\*\*\*\*\*

```

IRCP (ILL, JSLC, IN) = FFF (ILL, NIRCPK)
FLHC (ILL)           = FFF (ILL, NFLHCK)
FLQC (ILL)           = FFF (ILL, NFLQCK)
C
IF (FFF (ILL, NVEGK) .GT. 0.001) THEN
C
SIGF                 = FFF (ILL, NVEGK)
REGIME (ILL, JSLC) = AREA AV (FFF (ILL, NREVK) , FFF (ILL, NREBK) ) + 0.99
IREG                 = REGIME (ILL, JSLC)
REGIME (ILL, JSLC) = IREG
C
IF (FFF (ILL, NREVK) .NE. FFF (ILL, NREBK) ) GO TO 320
300 WSPD (ILL)        = AREA AV (FFF (ILL, NVAVK) , FFF (ILL, NVABK) )
HOL (ILL, JSLC)      = AREA AV (FFF (ILL, NHOLBK) , FFF (ILL, NHOLBK) )
BR (ILL)             = AREA AV (FFF (ILL, NRIBVK) , FFF (ILL, NRIBBK) )
UST (ILL, JSLC)      = AREA AV (FFF (ILL, NUSVK) , FFF (ILL, NUSBK) )
PBL (ILL, JSLC)      = AREA AV (FFF (ILL, NHVK) , FFF (ILL, NHBK) )
KPBL3 (ILL)          = AREA AV (FFF (ILL, NKP3VK) , FFF (ILL, NKP3BK) )
GO TO 400
320 CONTINUE
IF (FFF (ILL, NREVK) .EQ. REGIME (ILL, JSLC) ) THEN

```

```

IF (REGIME(ILL,JSLC) .EQ. 4) THEN
WSPD(ILL)      = FFF(ILL,NVAVK)
HOL(ILL,JSLC)  = FFF(ILL,NHOLBK)
BR(ILL)        = FFF(ILL,NRIBVK)
UST(ILL,JSLC)  = FFF(ILL,NUSVK)
PBL(ILL,JSLC)  = FFF(ILL,NHVK)
KPBL3(ILL)     = FFF(ILL,NKP3VK)
ELSE
GO TO 300
ENDIF
ENDIF
IF (FFF(ILL,NREBK) .EQ. REGIME(ILL,JSLC)) THEN
  IF (REGIME(ILL,JSLC) .EQ. 4) THEN
WSPD(ILL)      = FFF(ILL,NVABK)
HOL(ILL,JSLC)  = FFF(ILL,NHOLBK)
BR(ILL)        = FFF(ILL,NRIBBK)
UST(ILL,JSLC)  = FFF(ILL,NUSBK)
PBL(ILL,JSLC)  = FFF(ILL,NHBK)
KPBL3(ILL)     = FFF(ILL,NKP3BK)
ELSE

```

GO TO 300

ENDIF

ENDIF

ELSE

REGIME ( ILL, JSLC ) = FFF ( ILL, NREBK )

WSPD ( ILL ) = FFF ( ILL, NVABK )

HOL ( ILL, JSLC ) = FFF ( ILL, NHOLBK )

BR ( ILL ) = FFF ( ILL, NRIBBK )

UST ( ILL, JSLC ) = FFF ( ILL, NUSBK )

PBL ( ILL, JSLC ) = FFF ( ILL, NHBK )

KPBL3 ( ILL ) = FFF ( ILL, NKP3BK )

ENDIF

400 CONTINUE

C

FFF ( ILL, NREGIK ) = REGIME ( ILL, JSLC )

FFF ( ILL, NWSPDK ) = WSPD ( ILL )

FFF ( ILL, NHOLK ) = HOL ( ILL, JSLC )

FFF ( ILL, NRIBK ) = BR ( ILL )

FFF ( ILL, NUSTK ) = UST ( ILL, JSLC )

FFF ( ILL, NHPBLK ) = PBL ( ILL, JSLC )

32      CONTINUE

        ENDIF

        ENDIF

C      \*\*\*\*

        RETURN

        END



## Appendix F

A brief notes about configure.user and options inside mm5.deck

=====

\*\*\* configure.user:

```
#-----  
# 5. Options for making ./include/parame.incl  
#-----  
#  
# NHYDRO (integer)          - "1" -> NonHydrostatic run  
#                          - "0" -> Hydrostatic run  
# NHYDRO = 1  
# FDDAGD (integer)         - "1" -> FDDA gridded run  
#                          - "0" -> NonFDDA run  
# FDDAGD = 0  
# FDDAOBS (integer)        - "1" -> FDDA obs run  
#                          - "0" -> NonFDDA run  
# FDDAOBS = 0  
# MAXNES (integer)         - Max Number of Domains in simulation  
# MAXNES = 2  
# MIX,MJX,MKX (integer)    - Maximum Dimensions of any Domain  
#                          MIX = 34  
#                          MJX = 37  
#                          MKX = 23
```

Note:

1. NHYDRO is equivalent to INHYD in MM5V1;
2. FDDAGD and FDDAOBS are similar to IFDDA in MM5V1. Note that the grid nudging and obs nudging are separated in MM5V2.

```
#-----
```

```

# 6. Physics Options
#   The first MAXNES values in the list will be used for the corresponding
#   model nests; the rest in the list can be used to compile other options.
#   The exception is FRAD, of which only the first value is used in the model,
#   (i.e., only one radiation option is used for all nests). The rest allow
#   other options to be compiled.
#-----
# IMPHYS - for explicit moisture schemes (array,integer)
# IMPHYS = "4,4,1,1,1,1,1,1,1,1"
#           - Dry,stable precip.,warm rain,simple ice
#           - 1 ,2 ,3 ,4
#           - mix phase,graupel(gsf),graupel(reisner2)
#           - 5 ,6 ,7
# MPHYSTBL = 0
#           - 0=do not use look-up tables for moist
#           physics
#           - 1=use look-up tables for moist physics
#           (currently only simple ice and mix phase
#           are available)
# ICUPA - for cumulus schemes (array,integer)
#           - None,Kuo,Grell,AS,FC,KF,BM - 1,2,3,4,5,6,7
# ICUPA = "3,3,1,1,1,1,1,1,1,1"
# IBLTYP - for planetary boundary layer (array,integer)
#           - PBL type 0=no PBL fluxes,1=bulk,
#           2=Blackadar,3=Burk-Thompson,5=MRF
#           (if MRF is chosen, ISOIL must = 1)
# IBLTYP = "2,2,2,2,2,2,2,2,2,2"
# FRAD - for atmospheric radiation (integer)
#           - Radiation cooling of atmosphere
#           0=none,1=simple,2=cloud,3=ccm2
# FRAD = 2,0,0,0,0
# ISOIL - for multi-layer soil temperature model (integer)
#           - 0=no,1=yes (only works with IBLTYP=2,5)
# ISOIL = 1
#

```

```
# ISHALLO (array,integer)      - Shallow Convection Option
#                               1=shallow convection,0=No shallow convection
# ISHALLO = "0,0,0,0,0,0,0,0,0,0"
#-----
```

Note:

1. IMPHYS=1 --> IMOIST = 0  
 IMPHYS=2 --> IMOIST = 1  
 IMPHYS>=3 --> IMOIST =2
2. FRAD is equivalent to IFRAD in V1

\*\*\* mmlif:

```
&OPARAM
;
; ***** OUTPUT/RESTART OPTIONS *****
;
IFREST = .FALSE.,      ; whether this is a restart
IXTIMR = 720,          ; restart time in minutes
LEVIDN = 0,1,1,1,1,1,1,1,1,1, ; level of nest for each domain
NUMNC = 1,1,1,1,1,1,1,1,1,1, ; ID of mother domain for each nest
IFSAVE = .TRUE.,      ; save data for restart
SVLAST = .FALSE.,    ; T: only save the last file for restart
; F: save multiple files
SAVFRQ =360.,         ; how frequently to save data (in minutes)
IFTAPE = 1,           ; model output: 0,1
TAPFRQ =60.,          ; how frequently to output model results (in minutes)
IFSKIP = .FALSE.,    ; whether to skip input files - DO NOT use this for restart
MDATEST = 00000000,  ; the MDATE for the start file
IFPRT = 0,            ; sample print out: =1, a lot of print
PRTFRQ = 720.,        ; Print frequency for sample output (in minutes)
MASCHK = 60,          ; mass conservation check (KTAU or no. of time steps)
&END
&LPARAM
;
; ***** PHYSICS OPTIONS *****
;
; 1. user-chosen options I
```

```

;
RADFRQ = 30., :atmospheric radiation calculation frequency (in minumtes)
IMVDIF = 1, ;moist vertical diffusion in clouds - 0, 1 (IBLTYP=2,5 only)
IVQADV = 0, ;vertical moisture advection uses log interpolation(0),linear(1)
IVTADV = 0, ;vertical temp. advection uses theta interpolation(0),linear(1)
ITPDIF = 1, ;diffusion using perturbation temperature - 0,1 (NH run only)
ICOR3D = 1, ;3D Coriolis force (for NH run only) - 0, 1
IFUPR = 1, ;upper radiative boundary condition (NH) - 0, 1
;
; 2. keep the following two variables as they are
; unless doing sensitivity runs
;
IFDRY = 0, ;fake-dry run (no latent heating) - 0, 1
; for IMPHYS = 2,3,4,5,6,7 (requires ICUPA = 1)
ICUSTB = 1, ;stability check for Anthes-Kuo CPS only - 0, 1
;
; 3. user-chosen options II
;
IBOUDY = 3, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, ;boundary conditions
; (fixed, relaxation, time-dependent,
; time and inflow/outflow dependent (HY)/relaxation (NH),
; SPONGE (HY only) - 0, 1, 2, 3, 4)
IFSNOW = 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, ;SNOW COVER EFFECTS - 0, 1
; (only if snow data are generated in DATAGRID)
;
; 4. keep the following 9 variables as they are
; unless doing sensitivity runs
;
ISFFLX = 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, ;surface fluxes - 0, 1
ITGFLG = 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, ;surface temperature prediction - 1, 3
ISFPAR = 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, ;surface characteristics - 0, 1
ICLOUD = 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, ;cloud effects on radiation - 0, 1
; currently for IFRAD = 1,2
ICDCON = 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, ;constant drag coefficients - 0, 1
; (IBLTYP=1 only)
IVMIXM = 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, ;vertical mixing of momentum - 0, 1
; (IBLTYP=2 only)
HYDPRE = 1.,1.,1.,1.,1.,1.,1.,1.,1.,1.,1.,;HYDRO EFFECTS OF LIQ WATER - 0., 1.
; (HY run only)

```

```

IEVAP = 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, ;EVAP OF CLOUD/RAINWATER - <0, 0, >0
;
;
;
;      ***** NESTING OPTIONS *****
;
NESTIX = 25, 34, 31, 46, 46, 46, 46, 46, 46, 46, ; domain size i
NESTJX = 28, 37, 31, 61, 61, 61, 61, 61, 61, 61, ; domain size j
NESTI = 1, 8, 8, 1, 1, 1, 1, 1, 1, 1, ; start location i
NESTJ = 1, 9, 9, 1, 1, 1, 1, 1, 1, 1, ; start location i
XSTNES = 0., 0.,900., 0., 0., 0., 0., 0., 0., 0., ; domain initiation
KENNES =1440.,1440.,1440.,720.,720.,720.,720.,720.,720., ; domain termination
IOVERW = 1, 1, 0, 0, 0, 0, 0, 0, 0, 0, ; overwrite nest input
;      0=interpolate from coarse mesh (for nest domains);
;      1=read in domain initial conditions
IACTIV = 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, ;
;      in case of restart: is this domain active?
;
;
;
;      ***** MOVING NEST OPTIONS *****
;
IMOVE = 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, ; move domain 0,1
IMOVCO = 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, ; 1st move #
;      imovei(j,k)=L, ; I-INCREMENT MOVE (DOMAIN J, MOVE NUMBER K) IS L
IMOVEI = 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, ; I move #1
0, 0, 0, 0, 0, 0, 0, 0, 0, 0, ; I move #2
0, 0, 0, 0, 0, 0, 0, 0, 0, 0, ; I move #3
0, 0, 0, 0, 0, 0, 0, 0, 0, 0, ; I move #4
0, 0, 0, 0, 0, 0, 0, 0, 0, 0, ; I move #5
IMOVEJ = 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, ; J move #1
0, 0, 0, 0, 0, 0, 0, 0, 0, 0, ; J move #2
0, 0, 0, 0, 0, 0, 0, 0, 0, 0, ; J move #3
0, 0, 0, 0, 0, 0, 0, 0, 0, 0, ; J move #4
0, 0, 0, 0, 0, 0, 0, 0, 0, 0, ; J move #5
IMOVET = 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, ; time of move #1
0, 0, 0, 0, 0, 0, 0, 0, 0, 0, ; time of move #2
0, 0, 0, 0, 0, 0, 0, 0, 0, 0, ; time of move #3
0, 0, 0, 0, 0, 0, 0, 0, 0, 0, ; time of move #4
0, 0, 0, 0, 0, 0, 0, 0, 0, 0, ; time of move #5
&PPARAM

```

```

;
; ***** FORECAST TIME AND TIME STEP *****
;
TIMAX = 1440.,      ; forecast length in minutes
TISTEP = 270.,     ; coarse domain DT in model, use 3*DX
;
; ***** MISCELLANEOUS OPTIONS *****
;
; The values for the following 5 variables are only used if ISFPAR = 0
; (i.e. only land/water surface categories)
;
ZLND = 0.1,        ; roughness length over land in meters
ZZWTR = 0.001,    ; roughness length over water in meters
ALBLND = 0.15,    ; albedo
THINLD = 0.04,    ; surface thermal inertia
XMAVA = 0.3,      ; moisture availability over land as a decimal fraction of one
CONF = 1.0,       ; non-convective precipitation saturation threshold (=1: 100%)
IFEED = 3,        ; old feedback, no/light smoothing in feedback, and heavy
;                  ; smoothing - 1,2,3, and 4
IABSOR = 0,       ; sponge upper boundary (HYD only) - 0,1
&END
&FPARAM
;
; ***** 4DDA OPTIONS *****
;
; THE FIRST DIMENSION (COLUMN) IS THE DOMAIN IDENTIFIER:
; COLUMN 1 = DOMAIN #1, COLUMN 2 = DOMAIN #2, ETC.
;
; START TIME FOR FDDA (ANALYSIS OR OBS) FOR EACH DOMAIN
; (IN MINUTES RELATIVE TO MODEL INITIAL TIME)
FDATA=0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.
;
; ENDING TIME FOR FDDA (ANALYSIS OR OBS) FOR EACH DOMAIN
; (IN MINUTES RELATIVE TO MODEL INITIAL TIME)
FDAEND=780.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.
;
; ***** ANALYSIS NUDGING *****
;
; THE FIRST DIMENSION (COLUMN) OF THE ARRAYS DENOTES THE
; DOMAIN IDENTIFIER:

```

```

;      COLUMN 1 = DOMAIN #1, COLUMN 2 = DOMAIN #2, ETC.
;      THE SECOND DIMENSION (ROW OR LINE) EITHER REFERS TO THE 3D VS
;      SFC ANALYSIS OR WHICH VARIABLE IS ACCESSED:
;      LINE 1 = 3D, LINE 2 = SFC   OR
;      LINE 1 = U, LINE 2 = V, LINE 3 = T, LINE 4 = Q
;
;      IS THIS A GRID 4DDA RUN? 0 = NO; 1 = YES
I4D= 0,0,0,0,0,0,0,0,0,0,0,
     0,0,0,0,0,0,0,0,0,0,0,
;
;      SPECIFY THE TIME IN MINUTES BETWEEN THE INPUT (USUALLY
;      FROM INTERP) USED FOR GRID FDDA
DIFTIM=720.,720.,0.,0.,0.,0.,0.,0.,0.,0.,    ; 3D ANALYSIS NUDGING
       180.,180.,0.,0.,0.,0.,0.,0.,0.,0.,    ; SFC ANALYSIS NUDGING
;
;      GRID NUDGE THE WIND FIELD? 0 = NO; 1 = YES
IWIND=1,1,0,0,0,0,0,0,0,0,    ; 3D ANALYSIS NUDGING
      1,1,0,0,0,0,0,0,0,0,    ; SFC ANALYSIS NUDGING
;
;      NUDGING COEFFICIENT FOR WINDS ANALYSES
GV=2.5E-4,1.0E-4,0.,0.,0.,0.,0.,0.,0.,0.,    ; 3D ANALYSIS NUDGING
    2.5e-4,1.0E-4,0.,0.,0.,0.,0.,0.,0.,0.,    ; SFC ANALYSIS NUDGING
;
;      GRID NUDGE THE TEMPERATURE FIELD? 0 = NO; 1 = YES
ITEMP=1,1,0,0,0,0,0,0,0,0,    ; 3D ANALYSIS NUDGING
      1,1,0,0,0,0,0,0,0,0,    ; SFC ANALYSIS NUDGING
;
;      NUDGING COEFFICIENT FOR TEMPERATURE ANALYSES
GT=2.5e-4,1.0E-4,0.,0.,0.,0.,0.,0.,0.,0.,    ; 3D ANALYSIS NUDGING
    2.5e-4,1.0E-4,0.,0.,0.,0.,0.,0.,0.,0.,    ; SFC ANALYSIS NUDGING
;
;      GRID NUDGE THE MIXING RATIO FIELD? = 0 ; NO = 1 ; YES
IMOIS=1,1,0,0,0,0,0,0,0,0,    ; 3D ANALYSIS NUDGING
      1,1,0,0,0,0,0,0,0,0,    ; SFC ANALYSIS NUDGING
;
;      NUDGING COEFFICIENT FOR THE MIXING RATIO ANALYSES
GQ=1.E-5,1.E-5,0.,0.,0.,0.,0.,0.,0.,0.,    ; 3D ANALYSIS NUDGING
    1.E-5,1.E-5,0.,0.,0.,0.,0.,0.,0.,0.,    ; SFC ANALYSIS NUDGING
;

```

```

;      GRID NUDGE THE ROTATIONAL WIND FIELD? 0 = NO; 1 = YES
IROT=0,0,0,0,0,0,0,0,0,0,      ; 3D ANALYSIS NUDGING
;
;      NUDGING COEFFICIENT FOR THE ROTATIONAL COMPONENT OF THE WINDS
GR=5.E6,5.E6,0.,0.,0.,0.,0.,0.,0.,      ; 3D ANALYSIS NUDGING
;
;      IF GRID NUDGING (I4D(1,1)=1) AND YOU WISH TO EXCLUDE THE
;      BOUNDARY LAYER FROM FDDA OF COARSE GRID THREE DIMENSIONAL
;      DATA (USUALLY FROM INTERP),
;      0 = NO,  INCLUDE BOUNDARY LAYER NUDGING
;      1 = YES, EXCLUDE BOUNDARY LAYER NUDGING
INONBL =0,0,0,0,0,0,0,0,0,0,      ; U WIND
      0,0,0,0,0,0,0,0,0,0,      ; V WIND
      0,0,0,0,0,0,0,0,0,0,      ; TEMPERATURE
      0,0,0,0,0,0,0,0,0,0,      ; MIXING RATIO
;
;      RADIUS OF INFLUENCE FOR SURFACE ANALYSIS (KM).
;      IF I4D(2,1)=1 OR I4D(2,2)=1, ETC, DEFINE RINBLW (KM) USED
;      IN SUBROUTINE BLW TO DETERMINE THE HORIZONTAL VARIABILITY
;      OF THE SURFACE-ANALYSIS NUDGING AS A FUNCTION OF SURFACE
;      DATA DENSITY.  OVER LAND, THE STRENGTH OF THE SURFACE-
;      ANALYSIS NUDGING IS LINEARLY DECREASED BY 80 PERCENT AT
;      THOSE GRID POINTS GREATER THAN RINBLW FROM AN OBSERVATION
;      TO ACCOUNT FOR DECREASED CONFIDENCE IN THE ANALYSIS
;      IN REGIONS NOT NEAR ANY OBSERVATIONS.
RINBLW=250.,
;
;      SET THE NUDGING PRINT FREQUENCY FOR SELECTED DIAGNOSTIC
;      PRINTS IN THE GRID (ANALYSIS) NUDGING CODE (IN CGM
;      TIMESTEPS)
NPGF=50,
;
;      ***** OBSERVATION NUDGING *****
;
;      INDIVIDUAL OBSERVATION NUDGING.  VARIABLES THAT ARE ARRAYS
;      USE THE FIRST DIMENSION (COLUMN) AS THE DOMAIN IDENTIFIER:
;      COLUMN 1 = DOMAIN #1, COLUMN 2 = DOMAIN #2, ETC.
;

```



```

;      IS THIS INDIVIDUAL OBSERVATION NUDGING? 0 = NO; 1 = YES
I4DI  =0,0,0,0,0,0,0,0,0,0,
;
;      OBS NUDGE THE WIND FIELD FROM STATION DATA? 0 = NO; 1 = YES
ISWIND =1,0,0,0,0,0,0,0,0,0,
;
;      NUDGING COEFFICIENT FOR WINDS FROM STATION DATA
GIV   =4.E-4,4.E-4,0.,0.,0.,0.,0.,0.,0.,0.,
;
;      OBS NUDGE THE TEMPERATURE FIELD FROM STATION DATA? 0 = NO; 1 = YES
ISTEMP=1,0,0,0,0,0,0,0,0,0,
;
;      NUDGING COEFFICIENT FOR TEMPERATURES FROM STATION DATA
GIT   =4.E-4,4.E-4,0.,0.,0.,0.,0.,0.,0.,0.,
;
;      OBS NUDGE THE MIXING RATIO FIELD FROM STATION DATA? 0 = NO; 1 = YES
ISMOIS=1,0,0,0,0,0,0,0,0,0,
;
;      NUDGING COEFFICIENT FOR THE MIXING RATIO FROM STATION DATA
GIQ   =4.E-4,4.E-4,0.,0.,0.,0.,0.,0.,0.,0.,
;
;      THE OBS NUDGING RADIUS OF INFLUENCE IN THE
;      HORIZONTAL IN KM FOR CRESSMAN-TYPE DISTANCE-WEIGHTED
;      FUNCTIONS WHICH SPREAD THE OBS-NUDGING CORRECTION
;      IN THE HORIZONTAL.
RINXY=240.,
;
;      THE OBS NUDGING RADIUS OF INFLUENCE IN THE
;      VERTICAL IN SIGMA UNITS FOR CRESSMAN-TYPE DISTANCE-
;      WEIGHTED FUNCTIONS WHICH SPREAD THE OBS-NUDGING
;      CORRECTION IN THE VERTICAL.
RINSIG=0.001,
;
;      THE HALF-PERIOD OF THE TIME WINDOW, IN MINUTES, OVER
;      WHICH AN OBSERVATION WILL AFFECT THE FORECAST VIA OBS
;      NUDGING. THAT IS, THE OBS WILL INFLUENCE THE FORECAST
;      FROM TIMEOBS-TWINDO TO TIMEOBS+TWINDO. THE TEMPORAL
;      WEIGHTING FUNCTION IS DEFINED SUCH THAT THE OBSERVATION
;      IS APPLIED WITH FULL STRENGTH WITHIN TWINDO/2. MINUTES

```

```

;      BEFORE OR AFTER THE OBSERVATION TIME, AND THEN LINEARLY
;      DECREASES TO ZERO TWINDO MINUTES BEFORE OR AFTER THE
;      OBSERVATION TIME.
TWINDO=40.0,
;
;      THE NUDGING PRINT FREQUENCY FOR SELECTED DIAGNOSTIC PRINT
;      IN THE OBS NUDGING CODE (IN CGM TIMESTEPS)
NPFI=20,
;
;      FREQUENCY (IN CGM TIMESTEPS) TO COMPUTE OBS NUDGING WEIGHTS
IONF=2,
IDYNIN=0, ;for dynamic initialization using a ramp-down function to gradually
;      turn off the FDDA before the pure forecast, set idynin=1 [y=1, n=0]
DTRAMP=60.,;the time period in minutes over which the
;      nudging (obs nudging and analysis nudging) is ramped down
;      from one to zero. Set dtramp negative if FDDA is to be ramped
;      down BEFORE the end-of-data time (DATEND), and positive if the
;      FDDA ramp-down period extends beyond the end-of-data time.
&END

```

Appendix G

PROGRAM RDMM5

```
C
C   This program reads the output from the MM5V2-BATS couple model
C
C
C   IX : Output domain grid dimension in I direction (north-south)
C   JX : Output domain grid dimension in J direction (east-west)
C   KX : Output domain grid dimension in K direction (vertical)
C
PARAMETER(IX=32,JX=40,KX=11)
PARAMETER(JUNIT=18)

INTEGER MIF(1000,20)
REAL MRF(1000,20)
CHARACTER*80 MIFC(1000,20),MRFC(1000,20)
CHARACTER*8 ID
DIMENSION DUM3D(IX,JX,KX),DUM2D(IX,JX)
LOGICAL RdData

open(10,file='mmoutp_domain1',status='old',form='unformatted')
open(JUNIT,file='mm52dout.dat',status='unknown',form='formatted')

C
C   RdData : .TRUE.  Print record header information and output data
C             .FALSE. Print record header information only
C
RdData = .TRUE.
C   RdData = .FALSE.
N=0     ! time period counter
```

```

5      CONTINUE
      N=N+1
C
C      MIF : Array store integer variables information
C      MIFC: Character array describes the MIF array
C      MRF : Array store real variables information
C      MRFC: Character array describes the MRF array
C
      READ(10,END=999) MIF,MRF,MIFC,MRFC
C
C      get record header information
C
      PRINT *, 'MM5 version 2 record header information'
      PRINT *, ' '
      PRINT *, ' '
      IF(N.EQ.1) CALL GETGIST(MIF,MRF,MIFC,MRFC)
      PRINT *, ' '
      PRINT *, ' '
      PRINT *, ' '
C
C      INDEX : output is generated by which program?
C              1 TERRAIN
C              2 DATAGRID
C              3 RAWINS 3-D analysis
C              4 RAWINS surface 4DDA
C              5 MM5 initial condition from INTERP
C              6 MM5
C              7 Interpolated model output on pressure levels from INTERP
C
      IF(RdData) THEN

      INDEX=MIF(1,1)
      IF(INDEX.EQ.1) THEN
      PRINT *, 'READING TERRAIN OUTPUT'
      ELSEIF(INDEX.EQ.2) THEN
      PRINT *, 'READING DATAGRID OUTPUT'
      ELSEIF(INDEX.EQ.3) THEN
      PRINT *, 'READING RAWINS 3-D ANALYSIS OUTPUT'
      ELSEIF(INDEX.EQ.4) THEN

```

```

        PRINT *, 'READING RAWINS SURFACE 4DDA OUTPUT'
    ELSEIF(INDEX.EQ.5) THEN
        PRINT *, 'READING MODEL INITIAL CONDITION'
    ELSEIF(INDEX.EQ.6) THEN
        PRINT *, 'READING MM5 OUTPUT'
    ELSEIF(INDEX.EQ.7) THEN
        PRINT *, 'READING INTERPOLATED MODEL OUTPUT ON P'
    END IF
    PRINT *, 'DATE = ', MIF(1, INDEX)
    PRINT *, ' '
    PRINT *, ' '
C
C NUM3D : Number of 3-D fields in this output
C NUM2D : Number of 2-D fields in this output
C NUM1D : Number of 1-D fields in this output
C NUM0D : Number of 0-D fields in this output
C
    NUM3D = MIF(201, INDEX)
    NUM2D = MIF(202, INDEX)
    NUM1D = MIF(203, INDEX)
    NUM0D = MIF(204, INDEX)

    print*, 'NUM3D=', NUM3D
C
C ID : Description of the 3-D fields
C IDOT  : Is this field defined on cross or dot points
C      1 DOT POINT
C      2 CROSS POINT
C
    DO 120 I=1, NUM3D
    IDOT=1-MIF(204+I, INDEX)/10
    ID=MIFC(204+I, INDEX)(1:8)
    IF(ID.EQ.'W' .AND. MIF( 10,1).EQ.2) THEN
C      READ(10) DUM2D, DUM3D
        write(18) DUM2D, DUM3D
    ELSE
        READ (10) DUM3D

    call cleanrows(dum3d, ix, jx, kx, idot)

```

```

        call cleanflow(dum3d,ix,jx,kx,idot)
C        WRITE(JUNIT,100) DUM3D
        ENDIF
        PRINT *, '3D FIELD ID= ',ID,'      IDOT= ',IDOT,
*          '      SAMPLE VALUE= ',DUM3D(10,10,10)
120 CONTINUE
        PRINT *, ' '
        PRINT *, ' '
        DO 140 I=1,NUM2D
            IDOT=1-MIF(204+NUM3D+I,INDEX)/10
            ID=MIFC(204+NUM3D+I,INDEX)(1:8)
            READ (10) DUM2D
                call cleanrows(dum2d,ix,jx, 1,idot)
                call cleanflow(dum2d,ix,jx, 1,idot)
            WRITE (JUNIT,100) DUM2D
100 format(32f20.5)
            PRINT *, '2D FIELD ID= ',ID,'      IDOT= ',IDOT,
*          '      SAMPLE VALUE= ',DUM2D(10,10)
140 CONTINUE

        GO TO 5
        END IF
999 CONTINUE
END

        SUBROUTINE GETGIST(MIF,MRF,MIFC,MRFC)
C
C        PURPOSE INTERPRET THE VERSION 1 HEADER INFO
C
        INTEGER MIF(1000,20)
        REAL MRF(1000,20)
        CHARACTER*80 MIFC(1000,20),MRFC(1000,20)

        DO 30 J=1,20
        DO 10 I=1,1000
            IF(MIF(I,J).NE.-999) PRINT 100,I,J,MIF(I,J),MIFC(I,J)
10 CONTINUE
        DO 20 I=1,1000
            IF(MRF(I,J).NE.-999.) PRINT 110,I,J,MRF(I,J),MRFC(I,J)

```

```

20 CONTINUE
30 CONTINUE

100 FORMAT('MIF(',I4,',',I1,') = ',I10,' : ',A80)
110 FORMAT('MRF(',I4,',',I1,') = ',F10.2,' : ',A80)
    RETURN
    END

```

```

-----
c
    subroutine cleanflow(f,ix,jx,kx,icd)
    dimension f(ix,jx,kx)
    do k=1,kx
    do j=1,jx-icd
    do i=1,ix-icd
        if( f(i,j,k) .gt. 1.e+25) f(i,j,k)= 1.e+25
        if( f(i,j,k) .lt.-1.e+25) f(i,j,k)=-1.e+25
        if(abs(f(i,j,k)).lt. 1.e-25) f(i,j,k)= 0.
    enddo
    enddo
    enddo
    return
    end
    subroutine cleanrows(f,ix,jx,kx,icd)
    dimension f(ix,jx,kx)
    if(icd.eq.0) return
    do k=1,kx
    do j=1,jx-icd
        f(ix,j,k)=f(ix-1,j,k)
    enddo
    do i=1,ix
        f(i,jx,k)=f(i,jx-1,k)
    enddo
    enddo
    return
    end
-----
c

```

## Appendix H

Configur.user used in Exp.1

```
# Sections
# 1. System Variables
# 2. User Variables
# 3. Fortran options
#   3a. Cray (YMP, J90)
#       Note: set RUNTIME_SYSTEM="CRAY_IA" for Cray interactive job
#   3b. IRIX.6.1 (SGI_R8000)
#   3c. IRIX.5.2/5.3 (SGI_R4000/SGI_R4400/SGI_R5000)
#       Note: set RUNTIME_SYSTEM="SGI_R4000" for SGI_R4400/SGI_R5000
#   3d. SUN Fortran (solaris,SPARC20/SPARC64)
#   3e. DEC_ALPHA (OSF/1)
#   3f. IBM (AIX)
#   3g. HP (UX)
# 4. General commands
# 5. Options for making "./include/parame.incl"
# 6. Physics Options (memory related)
#
#-----
# 1. System Variables
#-----
SHELL =          /bin/sh
.SUFFIXES: .F .i .o .f
#-----
# 2. User Variables
#-----
# RUNTIME_SYSTEM          - Currently supported systems.
#                          SGI_R4000,SGI_R8000,CRAY,CRAY_IA,
#                          SUN,DEC_ALPHA,IBM,HP
```



```

RUNTIME_SYSTEM = "DEC_ALPHA"
#
#-----
# 3. Fortran options
#-----
LIBINCLUDE = $(DEVTOP)/include
#-----
# 3a. Cray
# imsl library is only needed if running Arakawa-Schubert cumulus scheme;
# and the location of the library may be different on non-NCAR Crays.
# Note: if you are using the new program environment on Cray, should set
#       CPP = /opt/ctl/bin/cpp
#-----
#FC = cf77
#FCFLAGS = -D$(RUNTIME_SYSTEM) -I$(LIBINCLUDE) -Zu -Wf"-o aggress"
#       CFLAGS =
#CPP = /lib/cpp
#CPP = /opt/ctl/bin/cpp
#CPPFLAGS = -I$(LIBINCLUDE) -C -P
#LDOPTIONS =
#LOCAL_LIBRARIES = -L /usr/local/lib -l imsl
#MAKE = make -i -r
#-----
# 3b. IRIX.6.2 (SGI_R8000)
#       - use the second LDOPTIONS if compiling Burk-Thompson PBL scheme
#       - use the second FCFLAGS if using 7.0 and above compiler
#-----
#FC = f77
#FCFLAGS = -I$(LIBINCLUDE) -O3 -SWP:=ON -n32 -mips4 -mp \
#-OPT:roundoff=3:IEEE_arithmetic=3 -OPT:fold_arith_limit=2001:fprop_limit=1000 \
#-SWP:body_ins_count_max=0
##FCFLAGS = -I$(LIBINCLUDE) -O3 -SWP:=ON -n32 -mips4 -mp \
##-OPT:roundoff=3:IEEE_arithmetic=3 -OPT:fold_arith_limit=2001
#CFLAGS =
#       CPP = /usr/lib/cpp
#CPPFLAGS = -I$(LIBINCLUDE) -C -P
#LDOPTIONS = -n32 -O3 -mp
##LDOPTIONS = -n32 -O3 -mp -Wl,-Xlocal,blt1_,-Xlocal,blk1_,-Xlocal,blk2_
#       LOCAL_LIBRARIES = -lfastm

```

```

#MAKE = make -i -r
#-----
#   3c. IRIX.5.2 (SGI_R4400/SGI_R4000/SGI_R5000)
#-----
#FC = f77
#FCFLAGS = -I$(LIBINCLUDE) -mips2 -32 -O1 -Nn30000 -Olimit 1500
#CFLAGS =
#CPP = /usr/lib/cpp
#CPPFLAGS = -I$(LIBINCLUDE) -C -P
#           LDOPTIONS =
#LOCAL_LIBRARIES = -lfastm
#MAKE = make -i -r
#-----
#   3d. SUN (solaris,SPARC20/SPARC64)
#-----
#FC = f77
#FCFLAGS = -fast -O2 -I$(LIBINCLUDE)
#CFLAGS =
#LDOPTIONS = -fast -O2
#CPP = /usr/lib/cpp
#CPPFLAGS = -I$(LIBINCLUDE) -C -P
#LOCAL_LIBRARIES =
#MAKE = make -i -r
#-----
#   3e. DEC_ALPHA (OSF/1)
#-----
FC = f77
FCFLAGS = -cpp -D$(RUNTIME_SYSTEM) -I$(LIBINCLUDE) -c -g -Olimit 2000 -i8 \
-fpe0 -align dcommons -align records -warn nounreachable -convert big_endian
CFLAGS =
CPP = /usr/lib/cpp
CPPFLAGS = -I$(LIBINCLUDE) -C -P
LDOPTIONS = -math_library accurate
LOCAL_LIBRARIES =
MAKE = make -i -r
#-----
#   3f. IBM (AIX)
#           for xlf compiler, use 'make little_f' instead of 'make' to compile
#-----

```

```

#FC = xlf
#FCFLAGS = -I$(LIBINCLUDE) -O -qmaxmem=-1
#CPP = /usr/lib/cpp
#CFLAGS =
#CPPFLAGS = -I$(LIBINCLUDE) -C -P
#LDOPTIONS = -O -qmaxmem=-1 -pg
#LOCAL_LIBRARIES =
#MAKE = make -i
#-----
#      3g. HP (UX)
#-----
#FC = f77
#FCFLAGS = -I$(LIBINCLUDE) -O
#CPP = /usr/lib/cpp
#CFLAGS = -Aa
#CPPFLAGS = -I$(LIBINCLUDE) -C -P
#LDOPTIONS =
#LOCAL_LIBRARIES =
#MAKE = make -i -r
#-----
# 4. General commands
#-----
AR = ar ru
RM = rm -f
RM_CMD = $(RM) *.CKP *.ln *.BAK *.bak *.o *.i core errs ,* *~ *.a \
.emacs_* tags TAGS make.log MakeOut *.f !
GREP = grep -s
CC = cc
#-----
# 5. Options for making ./include/parame.incl
#-----
#
# NHYDRO (integer)          - "1" -> NonHydrostatic run
#                          - "0" -> Hydrostatic run
NHYDRO = 1
# FDDAGD (integer)         - "1" -> FDDA gridded run
#                          - "0" -> NonFDDA run
FDDAGD = 0
# FDDAOBS (integer)        - "1" -> FDDA obs run

```

```

#           - "0" -> NonFDDA run
FDDAOBS = 0
# MAXNES (integer)           - Max Number of Domains in simulation
MAXNES = 1
# MIX,MJX,MKX (integer)     - Maximum Dimensions of any Domain
MIX = 25
MJX = 28
MKX = 23
#-----
# 6. Physics Options
#   The first MAXNES values in the list will be used for the corresponding
#   model nests; the rest in the list can be used to compile other options.
#   The exception is FRAD, of which only the first value is used in the model,
#   (i.e., only one radiation option is used for all nests). The rest allow
#   other options to be compiled.
#-----
# IMPHYS - for explicit moisture schemes (array,integer)
IMPHYS = "4,4,4,1,1,1,1,1,1,1"
#           - Dry,stable precip.,warm rain,simple ice
#           - 1 ,2           ,3           ,4
#           - mix phase,graupel(gsfc),graupel(reisner2)
#           - 5           ,6           ,7
MPHYSTBL = 1
#           - 0=do not use look-up tables for moist
#           physics
#           - 1=use look-up tables for moist physics
#           (currently only simple ice and mix phase
#           are available)
# ICUPA - for cumulus schemes (array,integer)
#           - None,Kuo,Grell,AS,FC,KF,BM - 1,2,3,4,5,6,7
ICUPA = "3,3,3,1,1,1,1,1,1,1"
#           IBLTYP - for planetary boundary layer (array,integer)
#           - PBL type 0=no PBL fluxes,1=bulk,
#           2=Blackadar,3=Burk-Thompson,5=MRF
BLTYP = "2,2,2,2,2,2,2,2,2,2"
#
# FRAD - for atmospheric radiation (integer)

```

```

#                                     - Radiation cooling of atmosphere
#                                     0=none,1=simple,2=cloud,3=ccm2
FRAD = "2,2,2,0,0"
#
# ISOIL - for multi-layer soil temperature model (integer)
#                                     - 0=no,1=yes
ISOIL =1
#
# ISHALLO (array,integer)             - Shallow Convection Option
#                                     1=shallow convection,0=No shallow convection
ISHALLO = "0,1,1,0,0,0,0,0,0,0"
#-----
# Don't touch anything below this line
#-----
.F.i:
    $(RM) $@
    $(CPP) $(CPPFLAGS) $*.F > $@
    mv $*.i $(DEVTOP)/pick/$*.f
    cp $*.F $(DEVTOP)/pick
.c.o:
    $(RM) $@ && \
    $(CC) -c $(CFLAGS) $*.c
.F.o:
    $(RM) $@
    $(FC) -c $(FCFLAGS) $*.F
.F.f:
    $(RM) $@
    $(CPP) $(CPPFLAGS) $*.F > $@
.f.o:
    $(RM) $@
    $(FC) -c $(FCFLAGS) $*.f

```

## Appendix I

File mm5.deck used in Exp.1

---

```
#      !/bin/sh
#
#  Version 2 of mm5 job deck
#
# temp files should be accessible
umask 022

# Sections
# 1. Options for namelist ("mmlif")
# 2. Options for I/O
# 3. Running...
#
#-----
# 1. Options for namelist ("mmlif")
#-----
#
#      The first dimension (column) of the arrays denotes the domain
#      identifier.
#      Col 1 = Domain #1, Col 2 = Dom #2, etc.
#
cat > ./Run/oparam << EOF
&OPARAM
  IFREST = .False.,
  IXTIMR = 720,
  LEVIDN = 0,1,1,1,1,1,1,1,1,1,
  NUMNC  = 1,1,1,1,1,1,1,1,1,1,
  IFSAVE = .false.,
  SVLAST = .false.,
  SAVFRQ = 360.,
```

```

IFTAPE = 1,
  TAPFRQ = 120,
IFSKIP = .False.,
  MDATEST = 00000000,
IFPRT = 1,
  PRTRFRQ = 120,
MASCHK = 360,
&END
EOF
cat > ./Run/lparam << EOF
&LPARAM
  RADFRQ      = 30.,
  IMVDIF      = 0,
IVQADV       = 0,
  IVTADV      = 0,
  ITPDIF      = 1,
ICOR3D       = 1,
IFUPR        = 1,
  IFDRY       = 0,
  ICUSTB      = 1,
IBOUDY = 3, 2, 2, 2, 2, 2, 2, 2, 2, 2,
  IFSNOW = 0, 0, 0, 0, 0, 0, 0, 0, 0, 0,
  ISFFLX = 1, 1, 1, 1, 1, 1, 1, 1, 1, 1,
  ITGFLG = 1, 1, 1, 1, 1, 1, 1, 1, 1, 1,
ISFPAR = 1, 1, 1, 1, 1, 1, 1, 1, 1, 1,
ICLOUD = 1, 1, 1, 1, 1, 1, 1, 1, 1, 1,
  ICDCON = 0, 0, 0, 0, 0, 0, 0, 0, 0, 0,
  IVMIXM = 1, 1, 1, 1, 1, 1, 1, 1, 1, 1,
  HYDPRE = 1.,1.,1.,1.,1.,1.,1.,1.,1.,1.,
  IEVAP    = 1, 1, 1, 1, 1, 1, 1, 1, 1, 1,
  NESTIX   = 32, 34, 31, 46, 46, 46, 46, 46, 46, 46,
  NESTJX   = 40, 37, 31, 61, 61, 61, 61, 61, 61, 61,
  NESTI    = 1, 8, 8, 1, 1, 1, 1, 1, 1, 1,
  NESTJ    = 1, 9, 9, 1, 1, 1, 1, 1, 1, 1,
  XSTNES   = 0., 0., 360., 0., 0., 0., 0., 0., 0., 0.,
  XENNES   = 10080.,1440.,1440.,720.,720.,720.,720.,720.,720.,720.,
IOVERW    = 1, 1, 0, 0, 0, 0, 0, 0, 0, 0,
IACTIV    = 1, 0, 0, 0, 0, 0, 0, 0, 0, 0,
IMOVE     = 0, 0, 0, 0, 0, 0, 0, 0, 0, 0,

```

```

IMOVCO = 1, 1, 1, 1, 1, 1, 1, 1, 1, 1,
IMOVEI = 0, 0, 0, 0, 0, 0, 0, 0, 0, 0,
          0, 0, 0, 0, 0, 0, 0, 0, 0, 0,
IMOVEJ = 0, 0, 0, 0, 0, 0, 0, 0, 0, 0,
          0, 0, 0, 0, 0, 0, 0, 0, 0, 0,
IMOVET = 0, 0, 0, 0, 0, 0, 0, 0, 0, 0,
          0, 0, 0, 0, 0, 0, 0, 0, 0, 0,
          0, 0, 0, 0, 0, 0, 0, 0, 0, 0,

EOF
cat > ./Run/pparam << EOF
&PPARAM
TIMAX = 7200,
  TISTEP = 30.,
  ZZLND = 0.1,
  ZZWTR = 0.0001,
  ALBLND = 0.15,
THINLD = 0.04,
  XMAVA = 0.3,
  CONF = 1.0,
IFEED = 3,
  IABSOR = 0,

&END
EOF
cat > ./Run/fparam << EOF
&FPARAM
FDASTA=0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,
FDAEND=780.,0.,0.,0.,0.,0.,0.,0.,0.,0.,
I4D= 0,0,0,0,0,0,0,0,0,0,
0,0,0,0,0,0,0,0,0,0,
DIFTIM=720.,720.,0.,0.,0.,0.,0.,0.,0.,0.,
180.,180.,0.,0.,0.,0.,0.,0.,0.,0.,
IWIND=1,1,0,0,0,0,0,0,0,0,
1,1,0,0,0,0,0,0,0,0,
GV=2.5E-4,1.0E-4,0.,0.,0.,0.,0.,0.,0.,0.,
2.5e-4,1.0E-4,0.,0.,0.,0.,0.,0.,0.,0.,
ITEMP=1,1,0,0,0,0,0,0,0,0,
1,1,0,0,0,0,0,0,0,0,

```



```

GI=2.5e-4,1.0E-4,0.,0.,0.,0.,0.,0.,0.,0.,
  2.5e-4,1.0E-4,0.,0.,0.,0.,0.,0.,0.,0.,
IMOIS=1,1,0,0,0,0,0,0,0,0,
  1,1,0,0,0,0,0,0,0,0,
GQ=1.E-5,1.E-5,0.,0.,0.,0.,0.,0.,0.,0.,
  1.E-5,1.E-5,0.,0.,0.,0.,0.,0.,0.,0.,
  IROT=0,0,0,0,0,0,0,0,0,0,
GR=5.E6,5.E6,0.,0.,0.,0.,0.,0.,0.,0.,
INONBL =0,0,0,0,0,0,0,0,0,0,
  0,0,0,0,0,0,0,0,0,0,
  0,0,0,0,0,0,0,0,0,0,
  0,0,0,0,0,0,0,0,0,0,
RINBLW=250.,
NPGF=50,
I4DI =0,0,0,0,0,0,0,0,0,0,
ISWIND =1,0,0,0,0,0,0,0,0,0,
GIV =4.E-4,4.E-4,0.,0.,0.,0.,0.,0.,0.,0.,
ISTEMP=1,0,0,0,0,0,0,0,0,0,
GIT =4.E-4,4.E-4,0.,0.,0.,0.,0.,0.,0.,0.,
ISMOIS=1,0,0,0,0,0,0,0,0,0,
GIQ =4.E-4,4.E-4,0.,0.,0.,0.,0.,0.,0.,0.,
  RINXY=240.,
RINSIG=0.001,
TWINDO=40.0,
NPFI=20,
IONF=2,
&END
EOF
#
make mmlif
#
#-----
# 2. Options for I/O
# Names of input/output files in ./Run directory:
#
# Input files:
# 1) hydrostatic: bdyout_hy_domain1
#                 mminput_hy_domain1 [mminput_hy_domain2, ....]
# 2) nonhydrostatic: bdyout_nh_domain1

```

```

#           mminput_nh_domain1 [mminput_nh_domain2, ....]
# 3) restart files: save_domain1 [save_domain2, ....]
# 4) fdda sfc files: rw4dda_domain1 [rw4dda_domain2, ....]
# 5) fdda obs files: mm5obs_domain1 [mm5obs_domain2, ....]
#
# Output files
# 6) model output:           fort.41 [fort.42, ....]
# 7) restart files:         fort.51 [fort.52, ....]
# 8) shutdown/restart files: fort.61 [fort.62, ....]
#-----
#
#
STARTsw=NoReStart           # start model run at hour 0
#STARTsw=ReStart           # restart model run
echo "STARTsw = $STARTsw"
#
FDDAsw=NoFDDA              # no FDDA input files
#FDDAsw=Anly               # gridded FDDA input files
#FDDAsw=Obs                # obs FDDA input files
#FDDAsw=Both               # gridded and obs FDDA input files
echo "FDDAsw = $FDDAsw"
#
#HYDROsw=Hydro             # hydrostatic input files
HYDROsw=NonHydro          # nonhydrostatic input files
echo "HYDROsw = $HYDROsw"
#
NumDomInp=1                # number of initial condition input files
echo "NumDomInp = $NumDomInp"
DomIDInp="1"               # domain ID no. for the initial condition inputs
echo "DomIDInp = $DomIDInp"
#
#
#       boundary condition
#       initial conditions
#
DD=./Run
if [ $HYDROsw = Hydro ]; then
  InBdy=bdyout_hy_domain1
#   InMM="mminput_hy_domain1 mminput_hy_domain2"

```

```

        InMM="mminput_hy_domain1"
else
    if [ $HYDROsw = NonHydro ]; then
        InBdy=bdyout_nh_domain1
    #       InMM="mminput_nh_domain1 mminput_nh_domain2"
        InMM="mminput_nh_domain1"
    fi
fi
echo "InBdy      = $InBdy"
echo "InMM       = $InMM"
#
#
#       the input restart file
#
if [ $STARTsw = ReStart ]; then
    InRst="save_domain1 save_domain2"
    echo "InRst    = $InRst"
fi
#
#       4dda surface analyses
#
NumFDGDDom=2                                # number of sfc grid 4dda input files
echo "NumFDGDDom = $NumFDGDDom"
DomFDGDInp="1 2"                             # domain ID no. for sfc grid 4dda inputs
echo "DomFDGDInp = $DomFDGDInp"
if [ $FDDAsw = Anly ]; then
    In4DSfc="rw4dda_domain1 rw4dda_domain2"
else
    if [ $FDDAsw = Both ]; then
        In4DSfc="rw4dda_domain1 rw4dda_domain2"
    fi
fi
echo "In4DSfc   = $In4DSfc"
#
#       4dda observations
#
NumFDOBDom=2                                # number of 4dda obs input files
echo "NumFDOBDom = $NumFDOBDom"
DomFDOBIinp="1 2"                            # domain ID no. for 4dda obs inputs

```

```

echo "DomFDOBInp = $DomFDOBInp"
if [ $FDDAsw = Obs ]; then
    In4DObs="mm5obs_domain1 mm5obs_domain2"
else
    if [ $FDDAsw = Both ]; then
        In4DObs="mm5obs_domain1 mm5obs_domain2"
    fi
fi
echo "In4DObs = $In4DObs"
#
ForUnit=fort.
#
#-----
# 3. Running...
#   This section should not have to be modified by the user!!
#-----
#
cd ./Run
rm -rf ${ForUnit}*
rm fparam lparam oparam pparam
#
# namelist file
ln -s mmlif fort.10
# transmisivity file "ehtran"
ln -s ehtran fort.8
# boundary file
ln -s $InBdy fort.9
#
#
#ln -s /spare/lyu/fort.41 fort.41
#ln -s /datasets/d5/lyu/fort.41 fort.41
#ln -s /spare/lyu/mm5.print.out mm5.print.out
#ln -s /datasets/d5/lyu/mm5.print.out mm5.print.out
#
#
NUM=0
while [ $NUM -lt $NumDomInp ]
do
    NUM=`expr $NUM + 1`
                                # Current Index

```

```

NUMd=0
for i in $DomIDInp
do
    NUMd=`expr $NUMd + 1`
    if [ $NUMd -eq $NUM ]; then
        DomI=$i
        echo "Current Domain Id = $DomI"
    fi
done

```

```

NUMd=0
for i in $InMM
do
    NUMd=`expr $NUMd + 1`
    if [ $NUMd -eq $NUM ]; then
        MMd=$i
        echo "InMM[$NUMd] = $MMd"
    fi
done

```

```

NUMd=0
for i in $InRst
do
    NUMd=`expr $NUMd + 1`
    if [ $NUMd -eq $NUM ]; then
        Rst=$i
        echo "InRst[$NUMd] = $Rst"
    fi
done

```

```

NUMd=0
for i in $In4DSfc
do
    NUMd=`expr $NUMd + 1`
    if [ $NUMd -eq $NUM ]; then
        FDSfc=$i
        echo "In4DSfc[$NUMd] = $FDSfc"
    fi
done

```

```

done

NUMd=0
for i in $In4DObs
do
    NUMd=`expr $NUMd + 1`
    if [ $NUMd -eq $NUM ]; then
        FDObs=$i
        echo "In4DObs[$NUMd] = $FDObs"
    fi
done
#
#    initial conditions
#
if [ ! -r ${ForUnit}1$DomI ]; then
    ln -s $MMd ${ForUnit}1$DomI
fi
echo "ln -s $MMd ${ForUnit}1$DomI"
#
#    input restart conditions
#
if [ $STARTsw = ReStart ]; then
    if [ ! -r ${ForUnit}9$DomI ]; then
        ln -s $Rst ${ForUnit}9$DomI
        echo "ln -s $Rst ${ForUnit}9$DomI"
    fi
fi
#
#    get analyses for nudging
#
if [ $FDDAsw = Anly -o $FDDAsw = Both ]; then
    cp ${ForUnit}1$DomI ${ForUnit}3$DomI
    if [ ! -f ${ForUnit}7$DomI ]; then
        ln -s $FDSfc ${ForUnit}7$DomI
    fi
    cp ${ForUnit}7$DomI ${ForUnit}8$DomI
fi
#
#    observations if OBS nudging

```

```
"
if [ $FDDAsw = Obs -o $FDDAsw = Both ]; then
  if [ ! -f ${ForUnit}6$DomI ]; then
    ln -s $FDObs ${ForUnit}6$DomI
  fi
fi
done
#
#       run MM5
#
date
echo "time mm5.exe >! mm5.print.out "
time mm5.exe >mm5.print.out 2>&1
```

## Appendix H

### Configur.user used in Exp.1

```
# Sections
# 1. System Variables
# 2. User Variables
# 3. Fortran options
#   3a. Cray (YMP, J90)
#       Note: set RUNTIME_SYSTEM="CRAY_IA" for Cray interactive job
#   3b. IRIX.6.1 (SGI_R8000)
#   3c. IRIX.5.2/5.3 (SGI_R4000/SGI_R4400/SGI_R5000)
#       Note: set RUNTIME_SYSTEM="SGI_R4000" for SGI_R4400/SGI_R5000
#   3d. SUN Fortran (solaris,SPARC20/SPARC64)
#   3e. DEC_ALPHA (OSF/1)
#   3f. IBM (AIX)
#   3g. HP (UX)
# 4. General commands
# 5. Options for making "./include/parame.incl"
# 6. Physics Options (memory related)
#
#-----
# 1. System Variables
#-----
SHELL =          /bin/sh
.SUFFIXES: .F .i .o .f
#-----
# 2. User Variables
#-----
# RUNTIME_SYSTEM          - Currently supported systems.
#                          SGI_R4000,SGI_R8000,CRAY,CRAY_IA,
#                          SUN,DEC_ALPHA,IBM,HP
```



```

RUNTIME_SYSTEM = "DEC_ALPHA"
#
#-----
# 3. Fortran options
#-----
LIBINCLUDE = $(DEVTOP)/include
#-----
# 3a. Cray
# imsl library is only needed if running Arakawa-Schubert cumulus scheme;
# and the location of the library may be different on non-NCAR Crays.
# Note: if you are using the new program environment on Cray, should set
# CPP = /opt/ctl/bin/cpp
#-----
#FC = cf77
#FCFLAGS = -D$(RUNTIME_SYSTEM) -I$(LIBINCLUDE) -Zu -Wf"-o aggress"
# CFLAGS =
#CPP = /lib/cpp
#CPP = /opt/ctl/bin/cpp
#CPPFLAGS = -I$(LIBINCLUDE) -C -P
#LDOPTIONS =
#LOCAL_LIBRARIES = -L /usr/local/lib -l imsl
#MAKE = make -i -r
#-----
# 3b. IRIX.6.2 (SGI_R8000)
# - use the second LDOPTIONS if compiling Burk-Thompson PBL scheme
# - use the second FCFLAGS if using 7.0 and above compiler
#-----
#FC = f77
#FCFLAGS = -I$(LIBINCLUDE) -O3 -SWP:=ON -n32 -mips4 -mp \
#-OPT:roundoff=3:IEEE_arithmetic=3 -OPT:fold_arith_limit=2001:fprop_limit=1000 \
#-SWP:body_ins_count_max=0
##FCFLAGS = -I$(LIBINCLUDE) -O3 -SWP:=ON -n32 -mips4 -mp \
##-OPT:roundoff=3:IEEE_arithmetic=3 -OPT:fold_arith_limit=2001
#CFLAGS =
# CPP = /usr/lib/cpp
#CPPFLAGS = -I$(LIBINCLUDE) -C -P
#LDOPTIONS = -n32 -O3 -mp
##LDOPTIONS = -n32 -O3 -mp -Wl,-Xlocal,blk1_,-Xlocal,blk1_,-Xlocal,blk2_
# LOCAL_LIBRARIES = -lfastm

```

```

#MAKE = make -i -r
#-----
#   3c. IRIX.5.2 (SGI_R4400/SGI_R4000/SGI_R5000)
#-----
#FC = f77
#FCFLAGS = -I$(LIBINCLUDE) -mips2 -32 -O1 -Nn30000 -Olimit 1500
#CFLAGS =
#CPP = /usr/lib/cpp
#CPPFLAGS = -I$(LIBINCLUDE) -C -P
#   LDOPTIONS =
#LOCAL_LIBRARIES = -lfastm
#MAKE = make -i -r
#-----
#   3d. SUN (solaris,SPARC20/SPARC64)
#-----
#FC = f77
#FCFLAGS = -fast -O2 -I$(LIBINCLUDE)
#CFLAGS =
#LDOPTIONS = -fast -O2
#CPP = /usr/lib/cpp
#CPPFLAGS = -I$(LIBINCLUDE) -C -P
#LOCAL_LIBRARIES =
#MAKE = make -i -r
#-----
#   3e. DEC_ALPHA (OSF/1)
#-----
FC = f77
FCFLAGS = -cpp -D$(RUNTIME_SYSTEM) -I$(LIBINCLUDE) -c -g -Olimit 2000 -i8 \
-fpe0 -align dcommons -align records -warn nounreachable -convert big_endian
CFLAGS =
CPP = /usr/lib/cpp
CPPFLAGS = -I$(LIBINCLUDE) -C -P
LDOPTIONS = -math_library accurate
LOCAL_LIBRARIES =
MAKE = make -i -r
#-----
#   3f. IBM (AIX)
#   for xlf compiler, use 'make little_f' instead of 'make' to compile
#-----

```

```

#FC = xlf
#FCFLAGS = -I$(LIBINCLUDE) -O -qmaxmem=-1
#CPP = /usr/lib/cpp
#CFLAGS =
#CPPFLAGS = -I$(LIBINCLUDE) -C -P
#LDOPTIONS = -O -qmaxmem=-1 -pg
#LOCAL_LIBRARIES =
#MAKE = make -i
#-----
# 3g. HP (UX)
#-----
#FC = f77
#FCFLAGS = -I$(LIBINCLUDE) -O
#CPP = /usr/lib/cpp
#CFLAGS = -Aa
#CPPFLAGS = -I$(LIBINCLUDE) -C -P
#LDOPTIONS =
#LOCAL_LIBRARIES =
#MAKE = make -i -r
#-----
# 4. General commands
#-----
AR = ar ru
RM = rm -f
RM_CMD = $(RM) *.CKP *.ln *.BAK *.bak *.o *.i core errs ,* *~ *.a \
.emacs_* tags TAGS make.log MakeOut *.f !
GREP = grep -s
CC = cc
#-----
# 5. Options for making ./include/parame.incl
#-----
#
# NHYDRO (integer)          - "1" -> NonHydrostatic run
#                          - "0" -> Hydrostatic run
NHYDRO = 1
# FDDAGD (integer)         - "1" -> FDDA gridded run
#                          - "0" -> NonFDDA run
FDDAGD = 0
# FDDA OBS (integer)       - "1" -> FDDA obs run

```

```

# - "0" -> NonFDDA run
FDDAOBS = 0
# MAXNES (integer) - Max Number of Domains in simulation
MAXNES = 1
# MIX,MJX,MKX (integer) - Maximum Dimensions of any Domain
MIX = 32
MJX = 40
MKX = 23
#-----
# 6. Physics Options
# The first MAXNES values in the list will be used for the corresponding
# model nests; the rest in the list can be used to compile other options.
# The exception is FRAD, of which only the first value is used in the model,
# (i.e., only one radiation option is used for all nests). The rest allow
# other options to be compiled.
#-----
# IMPHYS - for explicit moisture schemes (array,integer)
IMPHYS = "4,4,4,1,1,1,1,1,1,1"
# - Dry,stable precip.,warm rain,simple ice
# - 1 ,2 ,3 ,4
# - mix phase,graupel(gsf),graupel(reisner2)
# - 5 ,6 ,7
MPHYSTBL = 1
# - 0=do not use look-up tables for moist
# physics
# - 1=use look-up tables for moist physics
# (currently only simple ice and mix phase
# are available)
# ICUPA - for cumulus schemes (array,integer)
# - None,Kuo,Grell,AS,FC,KF,BM - 1,2,3,4,5,6,7
ICUPA = "3,3,3,1,1,1,1,1,1,1"
# IBLTYP - for planetary boundary layer (array,integer)
# - PBL type 0=no PBL fluxes,1=bulk,
# 2=Blackadar,3=Burk-Thompson,5=MRF
BLTYP = "2,2,2,2,2,2,2,2,2,2"
# FRAD - for atmospheric radiation (integer)

```

```

#                               - Radiation cooling of atmosphere
#                               0=none,1=simple,2=cloud,3=ccm2
FRAD = "2,2,2,0,0"
#
# ISOIL - for multi-layer soil temperature model (integer)
#                               - 0=no,1=yes
ISOIL =1
#
# ISHALLO (array,integer)       - Shallow Convection Option
#                               1=shallow convection,0=No shallow convection
ISHALLO = "0,1,1,0,0,0,0,0,0,0"
#-----
# Don't touch anything below this line
#-----
.F.i:
$(RM) $@
$(CPP) $(CPPFLAGS) $*.F > $@
mv $*.i $(DEVTOP)/pick/$*.f
cp $*.F $(DEVTOP)/pick

.C.o:
$(RM) $@ && \
$(CC) -c $(CFLAGS) $*.c

.F.o:
$(RM) $@
$(FC) -c $(FCFLAGS) $*.F

.F.f:
$(RM) $@
$(CPP) $(CPPFLAGS) $*.F > $@

.f.o:
$(RM) $@
$(FC) -c $(FCFLAGS) $*.f

```

## Appendix I

File mm5.deck used in Exp.1

---

```
#      !/bin/sh
#
#  Version 2 of mm5 job deck
#
# temp files should be accessible
umask 022

# Sections
# 1. Options for namelist ("mmlif")
# 2. Options for I/O
# 3. Running...
#
#-----
# 1. Options for namelist ("mmlif")
#-----
#
#      The first dimension (column) of the arrays denotes the domain
#      identifier.
#      Col 1 = Domain #1, Col 2 = Dom #2, etc.
#
cat > ./Run/oparam << EOF
&OPARAM
  IFREST = .False.,
  IXTIMR = 720,
  LEVIDN  = 0,1,1,1,1,1,1,1,1,1,
  NUMNC   = 1,1,1,1,1,1,1,1,1,1,
  IFSAVE  = .false.,
  SVLAST  = .false.,
  SAVFRQ  = 360.,
```

```

IFTAPE = 1,
  TAPFRQ = 120,
IFSKIP = .False.,
  MDATEST = 00000000,
IFPRT = 1,
  PRTRFRQ = 120,
MASCHK = 360,
&END
EOF
cat > ./Run/lparam << EOF
&LPARAM
  RADFRQ      = 30.,
  IMVDIF      = 0,
IVQADV      = 0,
  IVTADV      = 0,
  ITPDIF      = 1,
ICOR3D      = 1,
IFUPR       = 1,
  IFDRY       = 0,
  ICUSTB      = 1,
IBOUDY = 3, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2,
  IFSNOW = 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0,
  ISFFLX = 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1,
  ITGFLG = 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1,
ISFPAR = 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1,
ICLOUD = 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1,
  ICDCON = 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0,
  IVMIXM = 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1,
  HYDPRE = 1.,1.,1.,1.,1.,1.,1.,1.,1.,1.,1.,
  IEVAP     = 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1,
  NESTIX = 32, 34, 31, 46, 46, 46, 46, 46, 46, 46,
NESTJX = 40, 37, 31, 61, 61, 61, 61, 61, 61, 61,
NESTI  = 1, 8, 8, 1, 1, 1, 1, 1, 1, 1,
NESTJ  = 1, 9, 9, 1, 1, 1, 1, 1, 1, 1,
XSTNES = 0., 0., 360., 0., 0., 0., 0., 0., 0., 0.,
XENNES = 41760.,1440.,1440.,720.,720.,720.,720.,720.,720.,720.,
IOVERW = 1, 1, 0, 0, 0, 0, 0, 0, 0, 0,
IACTIV = 1, 0, 0, 0, 0, 0, 0, 0, 0, 0,
IMOVE  = 0, 0, 0, 0, 0, 0, 0, 0, 0, 0,

```

```

IMOVCO = 1, 1, 1, 1, 1, 1, 1, 1, 1, 1,
IMOVEI = 0, 0, 0, 0, 0, 0, 0, 0, 0, 0,
          0, 0, 0, 0, 0, 0, 0, 0, 0, 0,
IMOVEJ = 0, 0, 0, 0, 0, 0, 0, 0, 0, 0,
          0, 0, 0, 0, 0, 0, 0, 0, 0, 0,
IMOVET = 0, 0, 0, 0, 0, 0, 0, 0, 0, 0,
          0, 0, 0, 0, 0, 0, 0, 0, 0, 0,
          0, 0, 0, 0, 0, 0, 0, 0, 0, 0,

EOF
cat > ./Run/pparam << EOF
&PPARAM
TIMAX = 36000,
  TISTEP = 20.,
  ZZLND = 0.1,
  ZZWTR = 0.0001,
  ALBLND = 0.15,
THINLD = 0.04,
  XMAVA = 0.3,
  CONF = 1.0,
IFEED = 3,
  IABSOR = 0,

  &END
EOF
cat > ./Run/fparam << EOF
&FPARAM
FDASTA=0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,
FDAEND=780.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,
I4D= 0,0,0,0,0,0,0,0,0,0,0,
0,0,0,0,0,0,0,0,0,0,
DIFTIM=720.,720.,0.,0.,0.,0.,0.,0.,0.,0.,0.,
180.,180.,0.,0.,0.,0.,0.,0.,0.,0.,0.,
IWIND=1,1,0,0,0,0,0,0,0,0,
1,1,0,0,0,0,0,0,0,0,
GV=2.5E-4,1.0E-4,0.,0.,0.,0.,0.,0.,0.,0.,0.,
2.5e-4,1.0E-4,0.,0.,0.,0.,0.,0.,0.,0.,0.,
ITEMP=1,1,0,0,0,0,0,0,0,0,0,
1,1,0,0,0,0,0,0,0,0,

```



```

GT=2.5e-4,1.0E-4,0.,0.,0.,0.,0.,0.,0.,0.,0.,
  2.5e-4,1.0E-4,0.,0.,0.,0.,0.,0.,0.,0.,0.,
IMOIS=1,1,0,0,0,0,0,0,0,0,
  1,1,0,0,0,0,0,0,0,0,
GQ=1.E-5,1.E-5,0.,0.,0.,0.,0.,0.,0.,0.,
  1.E-5,1.E-5,0.,0.,0.,0.,0.,0.,0.,0.,
  IROT=0,0,0,0,0,0,0,0,0,0,
GR=5.E6,5.E6,0.,0.,0.,0.,0.,0.,0.,0.,
INONBL =0,0,0,0,0,0,0,0,0,0,
  0,0,0,0,0,0,0,0,0,0,
  0,0,0,0,0,0,0,0,0,0,
  0,0,0,0,0,0,0,0,0,0,
RINBLW=250.,
NPFG=50,
I4DI =0,0,0,0,0,0,0,0,0,0,
ISWIND =1,0,0,0,0,0,0,0,0,0,
GIV =4.E-4,4.E-4,0.,0.,0.,0.,0.,0.,0.,0.,
ISTEMP=1,0,0,0,0,0,0,0,0,0,
GIT =4.E-4,4.E-4,0.,0.,0.,0.,0.,0.,0.,0.,
ISMOIS=1,0,0,0,0,0,0,0,0,0,
GIQ =4.E-4,4.E-4,0.,0.,0.,0.,0.,0.,0.,0.,
RINXY=240.,
RINSIG=0.001,
TWINDO=40.0,
NPFI=20,
IONF=2,
&END
EOF
#
make mmlif
#
#-----
# 2. Options for I/O
# Names of input/output files in ./Run directory:
#
# Input files:
# 1) hydrostatic: bdyout_hy_domain1
#                 mminput_hy_domain1 [mminput_hy_domain2, ....]
# 2) nonhydrostatic: bdyout_nh_domain1

```

```

#               mminput_nh_domain1 [mminput_nh_domain2, ....]
# 3) restart files: save_domain1 [save_domain2, ....]
# 4) fdda sfc files: rw4dda_domain1 [rw4dda_domain2, ....]
# 5) fdda obs files: mm5obs_domain1 [mm5obs_domain2, ....]
#
# Output files
# 6) model output:          fort.41 [fort.42, ....]
# 7) restart files:        fort.51 [fort.52, ....]
# 8) shutdown/restart files: fort.61 [fort.62, ....]
#-----
#
#
STARTsw=NoReStart          # start model run at hour 0
#STARTsw=ReStart          # restart model run
echo "STARTsw = $STARTsw"
#
FDDAsw=NoFDDA             # no FDDA input files
#FDDAsw=Anly              # gridded FDDA input files
#FDDAsw=Obs               # obs FDDA input files
#FDDAsw=Both              # gridded and obs FDDA input files
echo "FDDAsw = $FDDAsw"
#
#HYDROsw=Hydro            # hydrostatic input files
HYDROsw=NonHydro         # nonhydrostatic input files
echo "HYDROsw = $HYDROsw"
#
NumDomInp=1               # number of initial condition input files
echo "NumDomInp = $NumDomInp"
DomIDInp="1"              # domain ID no. for the initial condition inputs
echo "DomIDInp = $DomIDInp"
#
#
# boundary condition
# initial conditions
#
DD=./Run
if [ $HYDROsw = Hydro ]; then
  InBdy=bdyout_hy_domain1
#   InMM="mminput_hy_domain1 mminput_hy_domain2"

```

```

        InMM="mminput_hy_domain1"
else
    if [ $HYDROsw = NonHydro ]; then
        InBdy=bdyout_nh_domain1
    #
    # InMM="mminput_nh_domain1 mminput_nh_domain2"
    InMM="mminput_nh_domain1"
    fi
fi
echo "InBdy    = $InBdy"
echo "InMM     = $InMM"
#
#
#     the input restart file
#
if [ $STARTsw = ReStart ]; then
    InRst="save_domain1 save_domain2"
    echo "InRst  = $InRst"
fi
#
#     4dda surface analyses
#
NumFDGDDom=2                                # number of sfc grid 4dda input files
echo "NumFDGDDom = $NumFDGDDom"
DomFDGDIInp="1 2"                            # domain ID no. for sfc grid 4dda inputs
echo "DomFDGDIInp = $DomFDGDIInp"
if [ $FDDAsw = Anly ]; then
    In4DSfc="rw4dda_domain1 rw4dda_domain2"
else
    if [ $FDDAsw = Both ]; then
        In4DSfc="rw4dda_domain1 rw4dda_domain2"
    fi
fi
echo "In4DSfc  = $In4DSfc"
#
#     4dda observations
#
NumFDOBDom=2                                # number of 4dda obs input files
echo "NumFDOBDom = $NumFDOBDom"
DomFDOBIInp="1 2"                            # domain ID no. for 4dda obs inputs

```

```

echo "DomFDOBInp = $DomFDOBInp"
if [ $FDDAsw = Obs ]; then
    In4DObs="mm5obs_domain1 mm5obs_domain2"
else
    if [ $FDDAsw = Both ]; then
        In4DObs="mm5obs_domain1 mm5obs_domain2"
    fi
fi
echo "In4DObs = $In4DObs"
#
ForUnit=fort.
#
#-----
# 3. Running...
#   This section should not have to be modified by the user!!
#-----
#
cd ./Run
rm -rf ${ForUnit}*
rm fparam lparam oparam pparam
#
# namelist file
ln -s mmlif fort.10
# transmissivity file "ehtran"
ln -s ehtran fort.8
# boundary file
ln -s $InBdy fort.9
#
#
#ln -s /spare/lyu/fort.41 fort.41
#ln -s /datasets/d5/lyu/fort.41 fort.41
#ln -s /spare/lyu/mm5.print.out mm5.print.out
#ln -s /datasets/d5/lyu/mm5.print.out mm5.print.out
#
#
NUM=0
while [ $NUM -lt $NumDomInp ]
do
    NUM=`expr $NUM + 1`
                                     # Current Index

```

```

NUMd=0
for i in $DomIDInp
do
    NUMd=`expr $NUMd + 1`
    if [ $NUMd -eq $NUM ]; then
        DomI=$i
        echo "Current Domain Id = $DomI"
    fi
done

```

```

NUMd=0
for i in $InMM
do
    NUMd=`expr $NUMd + 1`
    if [ $NUMd -eq $NUM ]; then
        MMd=$i
        echo "InMM[$NUMd] = $MMd"
    fi
done

```

```

NUMd=0
for i in $InRst
do
    NUMd=`expr $NUMd + 1`
    if [ $NUMd -eq $NUM ]; then
        Rst=$i
        echo "InRst[$NUMd] = $Rst"
    fi
done

```

```

NUMd=0
for i in $In4DSfc
do
    NUMd=`expr $NUMd + 1`
    if [ $NUMd -eq $NUM ]; then
        FDSfc=$i
        echo "In4DSfc[$NUMd] = $FDSfc"
    fi
done

```

```

done

NUMd=0
for i in $In4DObs
do
    NUMd=`expr $NUMd + 1`
    if [ $NUMd -eq $NUM ]; then
        FDObs=$i
        echo "In4DObs[$NUMd] = $FDObs"
    fi
done
#
#     initial conditions
#
if [ ! -r ${ForUnit}1$DomI ]; then
    ln -s $MMd ${ForUnit}1$DomI
fi
echo "ln -s $MMd ${ForUnit}1$DomI"
#
#     input restart conditions
#
if [ $STARTsw = ReStart ]; then
    if [ ! -r ${ForUnit}9$DomI ]; then
        ln -s $Rst ${ForUnit}9$DomI
        echo "ln -s $Rst ${ForUnit}9$DomI"
    fi
fi
#
#     get analyses for nudging
#
if [ $FDDAsw = Anly -o $FDDAsw = Both ]; then
    cp ${ForUnit}1$DomI ${ForUnit}3$DomI
    if [ ! -f ${ForUnit}7$DomI ]; then
        ln -s $FDSfc ${ForUnit}7$DomI
    fi
    cp ${ForUnit}7$DomI ${ForUnit}8$DomI
fi
#
#     observations if OBS nudging

```

```
#
if [ $FDDAsw = Obs -o $FDDAsw = Both ]; then
  if [ ! -f ${ForUnit}6$DomI ]; then
    ln -s $FDObs ${ForUnit}6$DomI
  fi
fi
done
#
#       run MM5
#
date
echo "time mm5.exe >! mm5.print.out "
time mm5.exe >mm5.print.out 2>&1
```

## Appendix H

### Configur.user used in Exp.1

```
# Sections
# 1. System Variables
# 2. User Variables
# 3. Fortran options
#   3a. Cray (YMP, J90)
#       Note: set RUNTIME_SYSTEM="CRAY_IA" for Cray interactive job
#   3b. IRIX.6.1 (SGI_R8000)
#   3c. IRIX.5.2/5.3 (SGI_R4000/SGI_R4400/SGI_R5000)
#       Note: set RUNTIME_SYSTEM="SGI_R4000" for SGI_R4400/SGI_R5000
#   3d. SUN Fortran (solaris,SPARC20/SPARC64)
#   3e. DEC_ALPHA (OSF/1)
#   3f. IBM (AIX)
#   3g. HP (UX)
# 4. General commands
# 5. Options for making "./include/parame.incl"
# 6. Physics Options (memory related)
#
#-----
# 1. System Variables
#-----
SHELL =          /bin/sh
.SUFFIXES: .F .i .o .f
#-----
# 2. User Variables
#-----
# RUNTIME_SYSTEM          - Currently supported systems.
#                          SGI_R4000,SGI_R8000,CRAY,CRAY_IA,
#                          SUN,DEC_ALPHA,IBM,HP
```



```

#
#-----
# 3. Fortran options
#-----
LIBINCLUDE = $(DEVTOP)/include
#-----
# 3a. Cray
# imsl library is only needed if running Arakawa-Schubert cumulus scheme;
# and the location of the library may be different on non-NCAR Crays.
# Note: if you are using the new program environment on Cray, should set
#       CPP = /opt/ctl/bin/cpp
#-----
#FC = cf77
#FCFLAGS = -D$(RUNTIME_SYSTEM) -I$(LIBINCLUDE) -Zu -Wf"-o aggress"
#       CFLAGS =
#CPP = /lib/cpp
#CPP = /opt/ctl/bin/cpp
#CPPFLAGS = -I$(LIBINCLUDE) -C -P
#LDOPTIONS =
#LOCAL_LIBRARIES = -L /usr/local/lib -l imsl
#MAKE = make -i -r
#-----
# 3b. IRIX.6.2 (SGI_R8000)
#       - use the second LDOPTIONS if compiling Burk-Thompson PBL scheme
#       - use the second FCFLAGS if using 7.0 and above compiler
#-----
#FC = f77
#FCFLAGS = -I$(LIBINCLUDE) -O3 -SWP:=ON -n32 -mips4 -mp \
#-OPT:roundoff=3:IEEE_arithmetic=3 -OPT:fold_arith_limit=2001:fprop_limit=1000 \
#-SWP:body_ins_count_max=0
##FCFLAGS = -I$(LIBINCLUDE) -O3 -SWP:=ON -n32 -mips4 -mp \
##-OPT:roundoff=3:IEEE_arithmetic=3 -OPT:fold_arith_limit=2001
#CFLAGS =
#       CPP = /usr/lib/cpp
#CPPFLAGS = -I$(LIBINCLUDE) -C -P
#LDOPTIONS = -n32 -O3 -mp
##LDOPTIONS = -n32 -O3 -mp -Wl,-Xlocal,blt1_,-Xlocal,blk1_,-Xlocal,blk2_
#       LOCAL_LIBRARIES = -lfastm

```

```

#MAKE = make -i -r
#-----
#   3c. IRIX.5.2 (SGI_R4400/SGI_R4000/SGI_R5000)
#-----
#FC = f77
#FCFLAGS = -I$(LIBINCLUDE) -mips2 -32 -O1 -Nn30000 -Olimit 1500
#CFLAGS =
#CPP = /usr/lib/cpp
#CPPFLAGS = -I$(LIBINCLUDE) -C -P
#           LDOPTIONS =
#LOCAL_LIBRARIES = -lfastm
#MAKE = make -i -r
#-----
#   3d. SUN (solaris,SPARC20/SPARC64)
#-----
#FC = f77
#FCFLAGS = -fast -O2 -I$(LIBINCLUDE)
#CFLAGS =
#LDOPTIONS = -fast -O2
#CPP = /usr/lib/cpp
#CPPFLAGS = -I$(LIBINCLUDE) -C -P
#LOCAL_LIBRARIES =
#MAKE = make -i -r
#-----
#   3e. DEC_ALPHA (OSF/1)
#-----
FC = f77
FCFLAGS = -cpp -D$(RUNTIME_SYSTEM) -I$(LIBINCLUDE) -c -g -Olimit 2000 -i8 \
-fpe0 -align dcommons -align records -warn nounreachable -convert big_endian
CFLAGS =
CPP = /usr/lib/cpp
CPPFLAGS = -I$(LIBINCLUDE) -C -P
LDOPTIONS = -math_library accurate
LOCAL_LIBRARIES =
MAKE = make -i -r
#-----
#   3f. IBM (AIX)
#       for xlf compiler, use 'make little_f' instead of 'make' to compile
#-----

```

```

#FC = xlf
#FCFLAGS = -I$(LIBINCLUDE) -O -qmaxmem=-1
#CPP = /usr/lib/cpp
#CFLAGS =
#CPPFLAGS = -I$(LIBINCLUDE) -C -P
#LDOPTIONS = -O -qmaxmem=-1 -pg
#LOCAL_LIBRARIES =
#MAKE = make -i
#-----
# 3g. HP (UX)
#-----
#FC = f77
#FCFLAGS = -I$(LIBINCLUDE) -O
#CPP = /usr/lib/cpp
#CFLAGS = -Aa
#CPPFLAGS = -I$(LIBINCLUDE) -C -P
#LDOPTIONS =
#LOCAL_LIBRARIES =
#MAKE = make -i -r
#-----
# 4. General commands
#-----
AR = ar ru
RM = rm -f
RM_CMD = $(RM) *.CKP *.ln *.BAK *.bak *.o *.i core errs ,* *~ *.a \
.emacs_* tags TAGS make.log MakeOut *.f !
GREP = grep -s
CC = cc
#-----
# 5. Options for making ./include/parame.incl
#-----
#
# NHYDRO (integer)          - "1" -> NonHydrostatic run
#                          - "0" -> Hydrostatic run
NHYDRO = 1
# FDDAGD (integer)         - "1" -> FDDA gridded run
#                          - "0" -> NonFDDA run
FDDAGD = 0
# FDDA OBS (integer)       - "1" -> FDDA obs run

```

```

# - "0" -> NonFDDA run
FDDAOBS = 0
# MAXNES (integer) - Max Number of Domains in simulation
MAXNES = 1
# MIX,MJX,MKX (integer) - Maximum Dimensions of any Domain
MIX = 32
MJX = 40
MKX = 23
#-----
# 6. Physics Options
# The first MAXNES values in the list will be used for the corresponding
# model nests; the rest in the list can be used to compile other options.
# The exception is FRAD, of which only the first value is used in the model,
# (i.e., only one radiation option is used for all nests). The rest allow
# other options to be compiled.
#-----
# IMPHYS - for explicit moisture schemes (array,integer)
IMPHYS = "4,4,4,1,1,1,1,1,1,1"
# - Dry,stable precip.,warm rain,simple ice
# - 1 ,2 ,3 ,4
# - mix phase,graupel(gsfcr),graupel(reisner2)
# - 5 ,6 ,7
MPHYSTBL = 1
# - 0=do not use look-up tables for moist
# physics
# - 1=use look-up tables for moist physics
# (currently only simple ice and mix phase
# are available)
# ICUPA - for cumulus schemes (array,integer)
# - None,Kuo,Grell,AS,FC,KF,BM - 1,2,3,4,5,6,7
ICUPA = "3,3,3,1,1,1,1,1,1,1"
# IBLTYP - for planetary boundary layer (array,integer)
# - PBL type 0=no PBL fluxes,1=bulk,
# 2=Blackadar,3=Burk-Thompson,5=MRF
BLTYP = "2,2,2,2,2,2,2,2,2,2"
# FRAD - for atmospheric radiation (integer)

```

```

#                               - Radiation cooling of atmosphere
#                               0=none,1=simple,2=cloud,3=ccm2
FRAD = "2,2,2,0,0"
#
# ISOIL - for multi-layer soil temperature model (integer)
#                               - 0=no,1=yes
ISOIL =1
#
# ISHALLO (array, integer)      - Shallow Convection Option
#                               1=shallow convection,0=No shallow convection
ISHALLO = "0,1,1,0,0,0,0,0,0,0"
#-----
# Don't touch anything below this line
#-----
.F.i:
$(RM) $@
$(CPP) $(CPPFLAGS) $*.F > $@
mv $*.i $(DEVTOP)/pick/$*.f
cp $*.F $(DEVTOP)/pick

.c.o:
$(RM) $@ && \
$(CC) -c $(CFLAGS) $*.c

.F.o:
$(RM) $@
$(FC) -c $(FCFLAGS) $*.F

.F.f:
$(RM) $@
$(CPP) $(CPPFLAGS) $*.F > $@

.f.o:
$(RM) $@
$(FC) -c $(FCFLAGS) $*.f

```

Appendix I

File mm5.deck used in Exp.1

```
-----  
#      !/bin/sh  
#  
#  Version 2 of mm5 job deck  
#  
# temp files should be accessible  
umask 022  
  
# Sections  
# 1. Options for namelist ("mmlif")  
# 2. Options for I/O  
# 3. Running...  
#  
#-----  
# 1. Options for namelist ("mmlif")  
#-----  
#  
#      The first dimension (column) of the arrays denotes the domain  
#      identifier.  
#      Col 1 = Domain #1, Col 2 = Dom #2, etc.  
#  
cat > ./Run/oparam << EOF  
&OPARAM  
  IFREST = .False.,  
  IXTIMR = 720,  
  LEVIDN  = 0,1,1,1,1,1,1,1,1,1,  
  NUMNC   = 1,1,1,1,1,1,1,1,1,1,  
  IFSAVE  = .false.,  
  SVLAST  = .false.,  
  SAVFRQ  = 360.,
```

```

IFTAPE = 1,
  TAPFRQ = 120,
IFSKIP = .False.,
  MDATEST = 00000000,
IFPRT = 1,
  PRTFRQ = 120,
MASCHK = 360,
&END
EOF
cat > ./Run/lparam << EOF
&LPARAM
  RADFRQ = 30.,
  IMVDIF = 0,
IVQADV = 0,
  IVTADV = 0,
  ITPDIF = 1,
ICOR3D = 1,
IFUPR = 1,
  IFDRY = 0,
  ICUSTB = 1,
IBOUDY = 3, 2, 2, 2, 2, 2, 2, 2, 2, 2,
  IFSNOW = 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0,
  ISFFLX = 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1,
  ITGFLG = 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1,
  ISFPAR = 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1,
ICLOUD = 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1,
  ICDCON = 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0,
  IVMIXM = 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1,
  HYDPRE = 1.,1.,1.,1.,1.,1.,1.,1.,1.,1.,1.,
  IEVAP = 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1,
  NESTIX = 32, 34, 31, 46, 46, 46, 46, 46, 46, 46,
  NESTJX = 40, 37, 31, 61, 61, 61, 61, 61, 61, 61,
  NESTI = 1, 8, 8, 1, 1, 1, 1, 1, 1, 1,
  NESTJ = 1, 9, 9, 1, 1, 1, 1, 1, 1, 1,
  XSTNES = 0., 0., 360., 0., 0., 0., 0., 0., 0., 0.,
  XENNES = 41760.,1440.,1440.,720.,720.,720.,720.,720.,720.,720.,
  IOVERW = 1, 1, 0, 0, 0, 0, 0, 0, 0, 0,
  IACTIV = 1, 0, 0, 0, 0, 0, 0, 0, 0, 0,
  IMOVE = 0, 0, 0, 0, 0, 0, 0, 0, 0, 0,

```

```

IMOVCO = 1, 1, 1, 1, 1, 1, 1, 1, 1, 1,
IMOVEI = 0, 0, 0, 0, 0, 0, 0, 0, 0, 0,
        0, 0, 0, 0, 0, 0, 0, 0, 0, 0,
        0, 0, 0, 0, 0, 0, 0, 0, 0, 0,
IMOVEJ = 0, 0, 0, 0, 0, 0, 0, 0, 0, 0,
        0, 0, 0, 0, 0, 0, 0, 0, 0, 0,
        0, 0, 0, 0, 0, 0, 0, 0, 0, 0,
IMOVET = 0, 0, 0, 0, 0, 0, 0, 0, 0, 0,
        0, 0, 0, 0, 0, 0, 0, 0, 0, 0,
        0, 0, 0, 0, 0, 0, 0, 0, 0, 0,

```

EOF

```
cat > ./Run/pparam << EOF
```

```
&PPARAM
```

```

TIMAX = 8640,
TISTEP = 20.,
ZZLND = 0.1,
ZZWTR = 0.0001,
ALBLND = 0.15,
THINLD = 0.04,
XMAVA = 0.3,
CONF = 1.0,
IFEED = 3,
IABSOR = 0,

```

```
&END
```

EOF

```
cat > ./Run/fparam << EOF
```

```
&FPARAM
```

```

FDASTA=0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,
FDAEND=780.,0.,0.,0.,0.,0.,0.,0.,0.,0.,
I4D= 0,0,0,0,0,0,0,0,0,0,0,0,
0,0,0,0,0,0,0,0,0,0,0,
DIFTIM=720.,720.,0.,0.,0.,0.,0.,0.,0.,0.,
180.,180.,0.,0.,0.,0.,0.,0.,0.,0.,
IWIND=1,1,0,0,0,0,0,0,0,0,
1,1,0,0,0,0,0,0,0,0,
GV=2.5E-4,1.0E-4,0.,0.,0.,0.,0.,0.,0.,0.,
2.5e-4,1.0E-4,0.,0.,0.,0.,0.,0.,0.,0.,
ITEMP=1,1,0,0,0,0,0,0,0,0,
1,1,0,0,0,0,0,0,0,0,

```



```

GT=2.5e-4,1.0E-4,0.,0.,0.,0.,0.,0.,0.,0.,
  2.5e-4,1.0E-4,0.,0.,0.,0.,0.,0.,0.,0.,
IMOIS=1,1,0,0,0,0,0,0,0,0,
  1,1,0,0,0,0,0,0,0,0,
GQ=1.E-5,1.E-5,0.,0.,0.,0.,0.,0.,0.,0.,
  1.E-5,1.E-5,0.,0.,0.,0.,0.,0.,0.,0.,
  IROT=0,0,0,0,0,0,0,0,0,0,0,
GR=5.E6,5.E6,0.,0.,0.,0.,0.,0.,0.,0.,
INONBL =0,0,0,0,0,0,0,0,0,0,
  0,0,0,0,0,0,0,0,0,0,
  0,0,0,0,0,0,0,0,0,0,
  0,0,0,0,0,0,0,0,0,0,
RINBLW=250.,
NPGF=50,
I4DI   =0,0,0,0,0,0,0,0,0,0,0,
ISWIND =1,0,0,0,0,0,0,0,0,0,0,
GIV   =4.E-4,4.E-4,0.,0.,0.,0.,0.,0.,0.,0.,
ISTEMP=1,0,0,0,0,0,0,0,0,0,0,
GIT   =4.E-4,4.E-4,0.,0.,0.,0.,0.,0.,0.,0.,
ISMOIS=1,0,0,0,0,0,0,0,0,0,0,
GIQ   =4.E-4,4.E-4,0.,0.,0.,0.,0.,0.,0.,0.,
  RINKY=240.,
RINSIG=0.001,
  TWINDO=40.0,
  NPFI=20,
  IONF=2,
  &END
EOF
#
make mmlif
#
#-----
# 2. Options for I/O
#   Names of input/output files in ./Run directory:
#
#   Input files:
#   1) hydrostatic:   bdyout_hy_domain1
#                     mminput_hy_domain1 [mminput_hy_domain2, ....]
#   2) nonhydrostatic: bdyout_nh_domain1

```

```

#               mminput_nh_domain1 [mminput_nh_domain2, ....]
# 3) restart files: save_domain1 [save_domain2, ....]
# 4) fdda sfc files: rw4dda_domain1 [rw4dda_domain2, ....]
# 5) fdda obs files: mm5obs_domain1 [mm5obs_domain2, ....]
#
# Output files
# 6) model output:           fort.41 [fort.42, ....]
# 7) restart files:         fort.51 [fort.52, ....]
# 8) shutdown/restart files: fort.61 [fort.62, ....]
#-----
#
#
STARTsw=NoReStart           # start model run at hour 0
#STARTsw=ReStart           # restart model run
echo "STARTsw = $STARTsw"
#
FDDAsw=NoFDDA              # no FDDA input files
#FDDAsw=Anly              # gridded FDDA input files
#FDDAsw=Obs               # obs FDDA input files
#FDDAsw=Both              # gridded and obs FDDA input files
echo "FDDAsw = $FDDAsw"
#
#HYDROsw=Hydro             # hydrostatic input files
HYDROsw=NonHydro          # nonhydrostatic input files
echo "HYDROsw = $HYDROsw"
#
NumDomInp=1                # number of initial condition input files
echo "NumDomInp = $NumDomInp"
DomIDInp="1"               # domain ID no. for the initial condition inputs
echo "DomIDInp = $DomIDInp"
#
#
#   boundary condition
#   initial conditions
#
DD=./Run
if [ $HYDROsw = Hydro ]; then
  InBdy=bdyout_hy_domain1
#   InMM="mminput_hy_domain1 mminput_hy_domain2"

```

```

        InMM="mminput_hy_domain1"
else
    if [ $HYDROsw = NonHydro ]; then
        InBdy=bdyout_nh_domain1
    #       InMM="mminput_nh_domain1 mminput_nh_domain2"
        InMM="mminput_nh_domain1"
    fi
fi
echo "InBdy      = $InBdy"
echo "InMM       = $InMM"
#
#
#       the input restart file
#
if [ $STARTsw = ReStart ]; then
    InRst="save_domain1 save_domain2"
    echo "InRst    = $InRst"
fi
#
#       4dda surface analyses
#
NumFDGDDom=2                # number of sfc grid 4dda input files
echo "NumFDGDDom = $NumFDGDDom"
DomFDGDIInp="1 2"          # domain ID no. for sfc grid 4dda inputs
echo "DomFDGDIInp = $DomFDGDIInp"
if [ $FDDAsw = Anly ]; then
    In4DSfc="rw4dda_domain1 rw4dda_domain2"
else
    if [ $FDDAsw = Both ]; then
        In4DSfc="rw4dda_domain1 rw4dda_domain2"
    fi
fi
echo "In4DSfc   = $In4DSfc"
#
#       4dda observations
#
NumFDOBDom=2                # number of 4dda obs input files
echo "NumFDOBDom = $NumFDOBDom"
DomFDOIInp="1 2"           # domain ID no. for 4dda obs inputs

```

```

echo "DomFDOBInp = $DomFDOBInp"
if [ $FDDAsw = Obs ]; then
    In4DObs="mm5obs_domain1 mm5obs_domain2"
else
    if [ $FDDAsw = Both ]; then
        In4DObs="mm5obs_domain1 mm5obs_domain2"
    fi
fi
echo "In4DObs = $In4DObs"
#
ForUnit=fort.
#
#-----
# 3. Running...
#   This section should not have to be modified by the user!!
#-----
#
cd ./Run
rm -rf ${ForUnit}*
rm fparam lparam oparam pparam
#
# namelist file
ln -s mmlif fort.10
# transmisivity file "ehtran"
ln -s ehtran fort.8
# boundary file
ln -s $InBdy fort.9
#
#
#ln -s /spare/lyu/fort.41 fort.41
#ln -s /datasets/d5/lyu/fort.41 fort.41
#ln -s /spare/lyu/mm5.print.out mm5.print.out
#ln -s /datasets/d5/lyu/mm5.print.out mm5.print.out
#
#
NUM=0
while [ $NUM -lt $NumDomInp ]
do
    NUM=`expr $NUM + 1`
                                # Current Index

```

```

NUMd=0
for i in $DomIDInp
do
    NUMd=`expr $NUMd + 1`
    if [ $NUMd -eq $NUM ]; then
        DomI=$i
        echo "Current Domain Id = $DomI"
    fi
done

NUMd=0
for i in $InMM
do
    NUMd=`expr $NUMd + 1`
    if [ $NUMd -eq $NUM ]; then
        MMd=$i
        echo "InMM[$NUMd] = $MMd"
    fi
done

NUMd=0
for i in $InRst
do
    NUMd=`expr $NUMd + 1`
    if [ $NUMd -eq $NUM ]; then
        Rst=$i
        echo "InRst[$NUMd] = $Rst"
    fi
done

NUMd=0
for i in $In4DSfc
do
    NUMd=`expr $NUMd + 1`
    if [ $NUMd -eq $NUM ]; then
        FDSfc=$i
        echo "In4DSfc[$NUMd] = $FDSfc"
    fi
done

```

```

done

NUMd=0
for i in $In4DObs
do
    NUMd=`expr $NUMd + 1`
    if [ $NUMd -eq $NUM ]; then
        FDObs=$i
        echo "In4DObs[$NUMd] = $FDObs"
    fi
done
#
#     initial conditions
#
if [ ! -r ${ForUnit}1$DomI ]; then
    ln -s $MMd ${ForUnit}1$DomI
fi
echo "ln -s $MMd ${ForUnit}1$DomI"
#
#     input restart conditions
#
if [ $STARTsw = ReStart ]; then
    if [ ! -r ${ForUnit}9$DomI ]; then
        ln -s $Rst ${ForUnit}9$DomI
        echo "ln -s $Rst ${ForUnit}9$DomI"
    fi
fi
#
#     get analyses for nudging
#
if [ $FDDAsw = Anly -o $FDDAsw = Both ]; then
    cp ${ForUnit}1$DomI ${ForUnit}3$DomI
    if [ ! -f ${ForUnit}7$DomI ]; then
        ln -s $FDSfc ${ForUnit}7$DomI
    fi
    cp ${ForUnit}7$DomI ${ForUnit}8$DomI
fi
#
#     observations if OBS nudging

```

```
#
if [ $FDDAsw = Obs -o $FDDAsw = Both ]; then
  if [ ! -f ${ForUnit}6$DomI ]; then
    ln -s $FDObs ${ForUnit}6$DomI
  fi
fi
done
#
#       run MM5
#
date
echo "time mm5.exe >! mm5.print.out "
time mm5.exe >mm5.print.out 2>&1
```

Appendix N

Modified Output Files

\*\*\*\*\*

Modified outprt.F

The below code is added in outprt.F after line OUTPRT.573.

\*\*\*\*\*

```
      DO I=1,ILX
        DO J=1,JLX
          HSCR1(I,J)=RNO(I,J,1)
HSCR2(I,J)=RNOS(I,J,1)
          ENDDO
        ENDDO

      WRITE (NAME,FMT=785)
785  FORMAT(11X,'TOTAL RUNOFF (MM/S)',10X)
      CALL MAPSMP(HSCR1,MIX,MJX,1,ILX,IXN,1,JLX,JXN,0.,1,NAME,XTH)

      WRITE (NAME,FMT=795)
c    ENCODE(40,795,NAME)
795  FORMAT(11X,'SURFACE RUNOFF (MM/S)',10X)
      CALL MAPSMP(HSCR2,MIX,MJX,1,ILX,IXN,1,JLX,JXN,0.,1,NAME,XTH)

      DO I=1,ILX
DO  J=1,JLX
          HSCR1(I,J)=SSW(I,J,1)
          HSCR2(I,J)=TAF(I,J,1)
        ENDDO
      ENDDO
```



```

        WRITE (NAME,FMT=800)
C      ENCODE(40,800,NAME)
800  FORMAT(11X,'SURFACE SOIL WATER (MM)',10X)
      CALL MAPSMP(HSCR1,MIX,MJX,1,ILX,IXN,1,JLX,JXN,0.,1,NAME,XTH)

        WRITE (NAME,FMT=805)
C      ENCODE(40,805,NAME)
805  FORMAT(11X,'CANOPY TEMPERATURE (K)',10X)
      CALL MAPSMP(HSCR2,MIX,MJX,1,ILX,IXN,1,JLX,JXN,0.,1,NAME,XTH)

      DO I=1,ILX
      DO J=1,JLX
        HSCR1(I,J)=TLEF(I,J,1)
        HSCR2(I,J)=RSW(I,J,1)
      ENDDO
ENDDO

        WRITE (NAME,FMT=810)
C      ENCODE(40,810,NAME)
810  FORMAT(11X,'LEAF TEMPERATURE (K)',10X)
      CALL MAPSMP(HSCR1,MIX,MJX,1,ILX,IXN,1,JLX,JXN,0.,1,NAME,XTH)

        WRITE (NAME,FMT=815)
C      ENCODE(40,815,NAME)
815  FORMAT(11X,'ROOTZONE SOIL WATER (MM)',10X)
      CALL MAPSMP(HSCR2,MIX,MJX,1,ILX,IXN,1,JLX,JXN,0.,1,NAME,XTH)

```

\*\*\*\*\*

Modified File outtap.F

\*\*\*\*\*

C Added header file after line OUTTAP.354

C-----

CCCCC BATS VARIABLES CCCCCCCCCCCCCC

```

JUNKI (NEX, 6)=0
JUNKIC (NEX, 6) ( 1:80)='SENHEATF          SENSIBLE HEAT'
*           // ' FLUX                      CROSS'
  NEX=NEX+1
  JUNKI (NEX, 6)=0
  JUNKIC (NEX, 6) ( 1:80)='LATHEATF          LATENT HEAT'
*           // ' FLUX                      CROSS'

  NEX=NEX+1
  JUNKI (NEX, 6)=0
  JUNKIC (NEX, 6) ( 1:80)='CANOPYTE          CANOPY TEMP'
*           // ' ERATURE                   CROSS'
  NEX=NEX+1
  JUNKI (NEX, 6)=0
  JUNKIC (NEX, 6) ( 1:80)='LEAFTEMP          LEAF TEMPER'
*           // ' ATURE                     CROSS'

  NEX=NEX+1
  JUNKI (NEX, 6)=0
  JUNKIC (NEX, 6) ( 1:80)='SURFSOLM          SURFACE SOIL'
*           // ' MOISTURE                   CROSS'
  NEX=NEX+1
  JUNKI (NEX, 6)=0
  JUNKIC (NEX, 6) ( 1:80)='ROOTSOLM          ROOT SOIL M'
*           // ' OISTUR                     CROSS'
  NEX=NEX+1
  JUNKI (NEX, 6)=0
  JUNKIC (NEX, 6) ( 1:80)='TOTASOLM          TOTAL SOIL '
*           // ' MOISTURE                   CROSS'
  NEX=NEX+1
  JUNKI (NEX, 6)=0
  JUNKIC (NEX, 6) ( 1:80)='LEAFINTE          LEAF INTER'
*           // ' CEPTION                   CROSS'
  NEX=NEX+1
  JUNKI (NEX, 6)=0
  JUNKIC (NEX, 6) ( 1:80)='TOTRUNOF          TOTAL RUNOFF'
*           // '                          CROSS'
  NEX=NEX+1
  JUNKI (NEX, 6)=0

```

```

JUNKIC(NEX,6) ( 1:80)='SURRUNOF
*          // ' FF
NEX=NEX+1
C***** Add 9 fields to the output files *****
CCc      1.  velocity on east-west
CCC      2.  velocity on north-south
CCC      3.  accm. precipitation
CCC      4.  accm. evaporation
CCC      5.  accm. surface runoff
CCC      6.  accm. total runoff
CCC      7.  accm. sensible heat
CCC      8.  accm. net ir radiation
cccc     9.  accm net solar radiation
JUNKI(NEX,6)=0
JUNKIC(NEX,6) ( 1:80)='USLYU
*          // ' CITY U
NEX=NEX+1
JUNKI(NEX,6)=0
JUNKIC(NEX,6) ( 1:80)='VSLYU
*          // ' CITY V
NEX=NEX+1
JUNKI(NEX,6)=0
JUNKIC(NEX,6) ( 1:80)='ACCPREP
*          // ' PRECIP
NEX=NEX+1
JUNKI(NEX,6)=0
JUNKIC(NEX,6) ( 1:80)='ACCEVPA
*          // ' EVPA
NEX=NEX+1
JUNKI(NEX,6)=0
JUNKIC(NEX,6) ( 1:80)='ACCRNOS
*          // ' SURFACE RUNOFF
NEX=NEX+1
JUNKI(NEX,6)=0
JUNKIC(NEX,6) ( 1:80)='ACCRNOT
*          // ' TOTAL RUNOFF
NEX=NEX+1
JUNKI(NEX,6)=0
JUNKIC(NEX,6) ( 1:80)='ACCSINH
SURFACE RUNO'
CROSS'
SURFACE VELO'
CROSS'
SURFACE VELO'
CROSS'
ACCUMULATE'
CROSS'
ACCUMULATE'
CROSS'
ACCUMULATE'
CROSS'
ACCUMULATE'
CROSS'
ACCUMULATE'

```

```

*           // ' SENSIBLE HEAT           CROSS'
NEX=NEX+1
  JUNKI (NEX,6)=0
  JUNKIC (NEX,6) ( 1:80)='ACCFLWA       ACCUMULATE'
*           // ' NET LONGRAD           CROSS'
  NEX=NEX+1
  JUNKI (NEX,6)=0
  JUNKIC (NEX,6) ( 1:80)='ACCFSWA       ACCUMULATE'
*           // ' NET SHORTRA           CROSS'
NEX=NEX+1

```

CC

Added new output fields after line OUTTAP.810

C-----

```

CCCCCCCC      OUTPUT FORM BATS      CCCCCCCCCCCCCCCCCCCCCC
C  BATS OUTPUT VARIABLES
C    (1)  SENSIBLE HEAT FLUX
C    (2)  LATENT HEAT FLUX
C    (3)  TEMPERATURE OF CANOPY
C    (4)  TEMPERATURE OF LEAF
C    (5)  SURFACE SOIL WATER
C    (6)  ROOT SOIL WATER
C    (7)  TOTAL SOIL WATER
C    (8)  LEAF INTERCEPTION
C    (9)  TOTAL RUNOFF
C    (10) SURFACE RUNOFF
C    (11) surface wind at western-eastern
C    (12) surface wind at southern-northern
C    (13) Accumulated precipitation
C    (14) Accumulated evaporation
C    (15) Accumulated surface runoff
C    (16) Accumulated total runoff
C    (17) Accumulated sensible heat flux
C    (18) Accumulated long wave radiation
C    (19) Accumulated short wave radiation

```

```

        CALL EQUATE(HFX,MIX,MJX,1,HSCRL1,IL,JL,1)
        WRITE (IUTL)HSCRL1
C
        DO 1625 I=1,ILX
            DO 1625 J=1,JLX
                TTMP=TA(I,J,KOUT)/PSA(I,J)
                HSCR1(I,J)=QFX(I,J)*XLV
1625    CONTINUE

        CALL EQUATE(HSCR1,MIX,MJX,1,HSCRL1,IL,JL,1)
        WRITE (IUTL)HSCRL1
C
        CALL EQUATE(TAF,MIX,MJX,1,HSCRL1,IL,JL,1)
        WRITE (IUTL)HSCRL1
C
        CALL EQUATE(TLEF,MIX,MJX,1,HSCRL1,IL,JL,1)
        WRITE (IUTL)HSCRL1
C
        CALL EQUATE(SSW,MIX,MJX,1,HSCRL1,IL,JL,1)
        WRITE (IUTL)HSCRL1
C
        CALL EQUATE(RSW,MIX,MJX,1,HSCRL1,IL,JL,1)
        WRITE (IUTL)HSCRL1
C
        CALL EQUATE(TSW,MIX,MJX,1,HSCRL1,IL,JL,1)
        WRITE (IUTL)HSCRL1
C
        CALL EQUATE(IRCP,MIX,MJX,1,HSCRL1,IL,JL,1)
        WRITE (IUTL)HSCRL1
C
        CALL EQUATE(RNO,MJX,1,HSCRL1,IL,JL,1)
        WRITE (IUTL)HSCRL1
C
        CALL EQUATE(RNOS,MIX,MJX,1,HSCRL1,IL,JL,1)
        WRITE (IUTL)HSCRL1
C
        CALL EQUATE(USLYU,MIX,MJX,1,HSCRL1,IL,JL,1)
        WRITE (IUTL)HSCRL1

```

```
C      CALL EQUATE(VSLYU,MIX,MJX,1,HSCRL1,IL,JL,1)
      WRITE (IUTL)HSCRL1
C
      CALL EQUATE(PRCA2D,MIX,MJX,1,HSCRL1,IL,JL,1)
      WRITE (IUTL)HSCRL1
C
      CALL EQUATE(EVPA2D,MIX,MJX,1,HSCRL1,IL,JL,1)
      WRITE (IUTL)HSCRL1
C
      CALL EQUATE(RNOS2D,MIX,MJX,1,HSCRL1,IL,JL,1)
      WRITE (IUTL)HSCRL1
C
      CALL EQUATE(RNO2D,MIX,MJX,1,HSCRL1,IL,JL,1)
      WRITE (IUTL)HSCRL1
C
      CALL EQUATE(SENA2D,MIX,MJX,1,HSCRL1,IL,JL,1)
      WRITE (IUTL)HSCRL1
C
      CALL EQUATE(FLWA2D,MIX,MJX,1,HSCRL1,IL,JL,1)
      WRITE (IUTL)HSCRL1
C
      CALL EQUATE(FSWA2D,MIX,MJX,1,HSCRL1,IL,JL,1)
      WRITE (IUTL)HSCRL1
```