Coupling of Integrated Biosphere Simulator to Regional Climate Model version 3

by

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B.S., SUNY College of Environmental Science and Forestry (2003)

Submitted to the Department of Civil and Environmental Engineering in partial fulfillment of the requirements for the degree of Master of Science in Civil and Environmental Engineering at the MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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Submitted to the Department of Civil and Environmental Engineering on May 22, 2006, in partial fulfillment of the requirements for the degree of Master of Science in Civil and Environmental Engineering

Abstract

Presented in this thesis is a description of the coupling of Integrated Biosphere Simulator (IBIS) to Regional Climate Model version 3 (RegCM3), and an assessment of the coupled model (RegCM3-IBIS). RegCM3 is a 3-dimensional, primitive equation, limited area model used throughout the world for seasonal predictability and regional climate studies. IBIS is a dynamic global vegetation model that includes representations of land surface processes, canopy physiology, vegetation phenology, terrestrial biogeochemistry, and vegetation dynamics.

A single subroutine was created that allows RegCM3 to use IBIS instead of Biosphere-Atmosphere Transfer Scheme 1e (BATS1e) for surface physics calculations. In addition to coupling the two models, a revised initialization scheme was implemented for RegCM3-IBIS, including an IBIS specific prescription of vegetation and soil types, as well as a new scheme for initializing soil moisture, soil ice, and soil temperature based on simulations using the offline version of IBIS.

A series of six 1-year numerical experiments were completed to assess the ability of RegCM3-IBIS to simulate the energy and water budgets, as well as surface temperature. The evaluation of RegCM3-IBIS was primarily based on NCEP reanalysis data, and when available, NASA Surface Radiation Budget data. While RegCM3-IBIS shows reasonable agreement with observations and reanalysis, a deterioration in the ability of RegCM3-IBIS to simulate, most notably, 2 m temperature and latent heat flux, is observed with respect to RegCM3 using BATS1e. However, many aspects of the RegCM3-IBIS results are encouraging, and the problems seen in the untuned version of RegCM3-IBIS are likely to be resolved given further analysis and tuning of parameters.

Thesis Supervisor: Elfatih A.B. Eltahir
Title: Professor of Civil and Environmental Engineering
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Chapter 1

Introduction

1.1 Background

From farmers in Illinois to the fishing industry of Ecuador to residents of Dhaka, Bangladesh, weather and climate affect almost every facet of human activity. This makes the pursuit to understand the hydrologic and atmospheric systems of the Earth, as well as the effects of anthropogenic activities on these systems, one of the most important areas of scientific research today. The three groups mentioned above are all severely impacted by major hydrologic/atmospheric processes (soil moisture, El Niño, monsoon) that are currently poorly understood and largely unpredictable by existing weather and climate models.

In 1992, Nash summarized his opinion on the criticism that the field of hydrology had failed to resolve all of the consequences of human interaction with the water environment using the following quote: “we must consider and decide for ourselves, what hydrology is, where it lies in the spectrum of human knowledge and endeavor, between the extremes of mere technical application and the deeper understanding of science.” Placing the role of the land-atmosphere system in societal and economic context, the importance of gaining a thorough understanding of land surface processes is clear. A transparent example is found in world food production (figure 1-1) [Harrison et al., 2002].

To meet increased demand, a greater percentage of arable land will need to be utilized and land currently producing food must become more efficient (figure 1-2).

The need for efficient use of arable land is clear, however note that the estimations in
Figure 1-1: World demand for cereals, 1980-2030 [Harrison et al., 2002].
Figure 1-2: Cropland in use and total suitable land [Harrison et al., 2002].
figure 1-2 assume a static environment and climate. Even in regions of the world where weather and climate prediction is most accurate, the fluctuations in rainfall (figure 1-3) and temperature that dictate the productivity of arable land are largely unpredictable beyond synoptic time scales at a useful resolution. Variability, both natural (e.g. El Niño, ENSO, Little Ice Age) and human induced (e.g. CO$_2$, land use change, aerosols), make the task of optimizing the use of arable land problematic.

![Yearly averaged rainfall over a Midwest domain](image)

Figure 1-3: Yearly averaged rainfall over a Midwest domain (98.9°W:83.9°W, 37.0°N:48.6°N) for the years 1901-2000 [Mitchell et al., 2003].

One approach used to gain a better understanding of local land-atmosphere processes is regional modeling. Though limited in predictive ability by the use of boundary conditions and prescribed sea surface temperatures (SSTs), regional models are able to resolve important processes at sub-general circulation model (GCM) resolutions. RegCM3, the model used in this study, was chosen because of its ability to accurately represent energy and water dynamics throughout North America [Pal, 2001]. Additionally, RegCM3 has been used extensively in a variety of climate studies including an exploration of the sensitivity of regional climate to deforestation in the Amazon basin [Eltahir and Bras, 1994], an
investigation of the impact of tundra ecosystems on the surface energy budget and climate of Alaska [Lynch et al., 1999], and the implementation of a large-scale cloud/precipitation scheme and model verification using satellite and station based datasets [Pal et al., 2000].

Error is implicit in all modeling results. Even given a perfect model (one that exactly and completely describes a system) and perfect initial conditions (a full and flawless assessment of the current state of the system), numerical inaccuracies in computation will skew results. In reality, neither perfect initial conditions nor a perfect model exist. The description of all of the primary environmental processes in RegCM3 are approximations, parameterizations devised to best represent the true dynamics of the system given limited knowledge and computational resources. Many different parameterizations exist for each set of natural processes, such as vegetation growth, evaporation, convection, radiation, etc., so optimizing the accuracy and variety of parameterizations within the model becomes an efficient method of finding the true solution.

It is this premise that is the rationale for integrating IBIS into the RegCM3 code. IBIS will introduce several key advantages to RegCM3, most notably dynamic vegetation, the coexistence of multiple plant functional types (PFTs) in the same grid cell, more sophisticated plant phenology, plant competition, explicit modeling of soil/plant biogeochemistry, and additional soil and snow layers.

1.2 Hypothesis

The hypothesis of this project is as follows:

To gain a more complete understanding of land surface processes, and the way in which RegCM3 influences and is influenced by varying parameterizations of land surface processes, a new, fundamentally different surface physics model, IBIS, will be integrated into RegCM3. This newly created coupled model will then be tested and its performance assessed so that it can be used in future studies to improve the accuracy and diversity of results derived from regional climate models.
Chapter 2

Regional Climate Model version 3
(RegCM3)

2.1 Model Description

This chapter describes briefly the history and features of Regional Climate Model version 3 (RegCM3). In addition to a broad overview of the various components of RegCM3, a more detailed description of RegCM3’s surface physics model, Biosphere-Atmosphere Transfer Scheme 1e (BATS1e), is provided.

2.2 Model Overview

Regional climate models (RCMs) attempt to strike a compromise between domain size and temporal resolution while minimizing computational expense. Temporal resolution $\Delta t$ is a function of both maximum wind velocity $u$ and grid cell size (spatial resolution) $\Delta x$, as described by the Courant-Freidrichs-Levy condition for numerical stability.

$$\frac{u \Delta t}{\Delta x} \leq 1$$  \hspace{1cm} (2.1)

The idea of limited area climate models (LAMs), originally proposed by Dickinson et al.
[1989] and Giorgi [1990], operates on the premise that a high resolution model can be driven by time-dependent lateral boundary conditions and initial conditions derived from a GCM simulation or reanalysis product [Elguindi et al., 2004]. LAMs explicitly use one-way nesting, meaning the LAM has no influence on the coarse meteorological forcing at the boundaries. This methodology allows RegCM3 to operate at resolutions up to 10 km, while most GCMs have resolutions coarser than 1° (~111 km). Higher spatial resolution offers obvious advantages for studying regional phenomena, but it is important to caveat that while RegCM3 is a powerful tool for examining the local sensitivity of ecosystems to changes in radiative forcing, atmospheric composition, etc., it cannot be used independently to predict climate change.

RegCM3 is a 3-dimensional, sigma-coordinate, hydrostatic, compressible, primitive equation RCM originally developed at the National Center for Atmospheric Research (NCAR) and currently maintained at the International Centre for Theoretical Physics (ICTP). RegCM3 is a descendant of NCAR RegCM, which was developed from the work of Dickinson et al. [1989], Giorgi and Bates [1989], and Giorgi [1990]. RegCM was primarily built using the dynamical core of the Penn State University/NCAR (PSU/NCAR) Mesoscale Model version 4 (MM4) [Anthes et al., 1987].

Through its development and successive revisions, RegCM3 has become a powerful tool for regional climate studies. The first generation of RegCM [Dickinson et al., 1986; Giorgi, 1990] contained the radiation package of NCAR’s Community Climate Model version 1 (CCM1), a medium resolution local planetary boundary layer (PBL) scheme, the cumulus convection scheme (Kuo scheme) of Anthes [1977], Biosphere-Atmosphere Transfer Scheme (BATS) [Dickinson et al., 1986], and the explicit moisture large-scale precipitation scheme of Hsie et al. [1984].

Regional Climate Model version 2 (RegCM2) contained many key improvements, mostly derived from PSU/NCAR’s Mesoscale Model version 5 (MM5) [Grell et al., 1994] and NCAR’s Community Climate Model version 2 (CCM2) [Hack et al., 1993]. The radiation scheme, originally developed from CCM1, was updated using the radiation physics of CCM2 [Briegleb, 1992]. A mass flux cumulus scheme developed by Grell [1993] was added, and the local PBL scheme was replaced by the non-local PBL parameterization of
Figure 2-1: Schematic of the vertical structure of RegCM3. This example is for 16 vertical layers. Dashed lines denote half-sigma levels, solid lines denote full-sigma levels [Elguindi et al., 2004]. (Adapted from the PSU/NCAR Mesoscale Modeling System Tutorial Class Notes and User’s Guide).
Holtslag et al. [1990]. In addition, BATS1e [Dickinson et al., 1993], the latest version of BATS, was included in RegCM2.

A host of improvements were made to RegCM2 to create the current version, RegCM3. The atmospheric radiation transfer computations were again updated to the NCAR Community Climate Model version 3 (CCM3) based package of Kiehl et al. [1996]. Building on the CCM2 radiation package, which employed a $\delta$-Eddington approach and included the effects of $\text{H}_2\text{O}$, $\text{O}_3$, $\text{O}_2$, $\text{CO}_2$, and clouds, the CCM3 radiation package also incorporated the effects of additional greenhouse gasses ($\text{NO}_2$, $\text{CH}_4$, CFCs), atmospheric aerosols, and cloud ice [Elguindi et al., 2004]. Simplified Explicit Moisture Scheme (SIMEX), a reduced version of the fully explicit moisture scheme of Hsie et al., was also formulated for inclusion in RegCM3 to make the program less computationally expensive [Elguindi et al., 2004]. Created by Giorgi and Shields [1999], SIMEX eliminated the prognostic variable for rainwater and associated calculations, while keeping the cloud water variable used directly in the cloud radiation physics and adding key interactions between the hydrologic cycle and energy budget [Elguindi et al., 2004]. Most other parts of the dynamical core were left unaltered, leaving the PBL computations of Holtslag et al. [1990] and BATS1e for land surface processes [Elguindi et al., 2004]. In addition to changes in some of the fundamental physics packages, several features were added to RegCM3. The lake model of Small and Sloan [1999] was coupled to RegCM3, as was a new ocean flux parameterization [Zeng et al., 1998]. Subgrid Explicit Moisture Scheme (SUBEX), a resolvable scale (non-convective) cloud and precipitation formulation created by Pal et al. [2000] was also included, replacing SIMEX. Furthermore, two convection parameterization packages, the Betts-Miller cumulus convection scheme [1986] and the Emanuel scheme [1991], were added to RegCM3. This gives a total of four possible schemes for representing non-resolvable convection, including the Grell scheme from RegCM2 and the Kuo scheme from RegCM. More information regarding the specific parameterization schemes, history, and applications of RegCM3 can be found in Elguindi et al. [2004].
2.3 Radiation Scheme

As noted above, RegCM3 uses the radiation scheme of CCM3. RegCM3 calls the radiation package at an interval of 30 minutes regardless of the spatial or temporal resolution of the simulation [Elguindi et al., 2004]. Between intervals, the fluxes of longwave, shortwave, and surface radiative energy are held constant [Kiehl et al., 1996]. Working with a top down framework, insolation at the top of atmosphere (TOA) $S_I$ is described by the following formula:

$$S_I = S_0 \epsilon \cos \zeta$$

(2.2)

where the solar constant is $S_0$, $\epsilon$ is the eccentricity factor, and $\zeta$ is the solar zenith angle [Kiehl et al., 1996]. Within the model the annual and diurnal cycle are exactly 365 days and 24 hours long, respectively. These variations are calculated using the following equations:

$$\cos \zeta = \sin \phi \sin \delta - \cos \phi \cos \delta \cos(2\pi t_{local})$$

(2.3)

$$\cos \epsilon = 1.000110 + 0.034221 \cos \theta_0 + 0.001280 \sin \theta_0 + 0.000719 \cos 2\theta_0$$

$$+ 0.000077 \sin 2\theta_0$$

(2.4)

$$\delta = 0.006918 - 0.399912 \cos \theta_0 + 0.070257 \sin \theta_0 - 0.006758 \cos 2\theta_0$$

$$+ 0.000907 \sin 2\theta_0 - 0.002697 \cos 3\theta_0 + 0.001480 \sin 3\theta_0$$

(2.5)

where $\theta_0$ is the mean orbit angle, $\phi$ is the latitude in radians, $\delta$ is the solar declination in radians, and $t_{local}$ is the calendar day in local time [Kiehl et al., 1996]. The formula for $\cos \zeta$
is from Sellers [1965] and the equations for $\epsilon$ and $\delta$ are from Paltridge and Platt [1976].

After the calculation of TOA solar insolation, the radiation scheme is then responsible for determining what fraction of TOA energy reaches the surface, and additionally, what portion of that energy is reflected by the surface (albedo). This is accomplished using the so called $\delta$-Eddington approximation, originally ascribed to Joseph et al. [1976] and Coakley Jr. et al. [1983], fully documented in Briegleb [1992].

Fundamentally, this scheme breaks the solar spectrum into 18 spectral intervals, with each spectral interval encompassing wavelengths important for key interactions with atmospheric constituents (7 for $O_3$, 1 for visible, 7 for $H_2O$, 3 for $CO_2$) [Kiehl et al., 1996]. Consistent with the vertical structure of RegCM3 (figure 2-1), each layer of the atmosphere is modeled as a homogenous blend of all radiatively significant elements. For each layer, reflectivity and transmissivity are calculated, and subsequently combined together explicitly allowing scattering between layers [Kiehl et al., 1996]. This yields the upward and downward spectral fluxes at each atmospheric layer interface, which are then accumulated over multiple spectral intervals to yield broad band fluxes. These fluxes are then in turn used to find the radiative heating rate and the cosine of the solar zenith angle, which are inputs to other schemes within RegCM3 (e.g. surface physics, ocean parameterization).

Fluxes of longwave radiation $F^{\downarrow}, F^{\uparrow}$ are based on the absorptivity/emissivity formulation of Ramanathan and Downey [1986], and calculated as follows

$$F^{\downarrow}(p) = B(0)\epsilon(0, p) + \int_0^p \alpha(p, p')dB(p') \quad (2.6)$$

$$F^{\uparrow}(p) = B(T_s) - \int_p^{p_s} \alpha(p, p')dB(p') \quad (2.7)$$

where $B$ is the Stefan-Boltzmann relation
\[ B(T) = \sigma T^4 \]  

(2.8)

\( T \) is temperature, \( T_s \) is surface temperature, \( \sigma \) is the Stefan-Boltzmann constant, \( \alpha \) is the absorptivity, \( \varepsilon \) is the emissivity, \( p_s \) is surface pressure, and \( p, p' \) are pressures [Kiehl et al., 1996].

As noted above, the \( \delta \)-Eddington approximation accounts for absorption of radiative energy by several gases, including CO\(_2\). The effect of clouds on solar radiation follows the radiative parameterizations of Slingo [1989] and Ebert and Curry [1992]. For liquid water droplets, the optical properties of clouds (extinction optical depth, single scattering albedo, asymmetry parameter, forward scattering parameter) are determined based on the cloud water path (CWP) and droplet effective radius, the former an input from the convective and large-scale precipitation schemes [Kiehl et al., 1996]. The cloud radiative properties are explicitly dependent on the phase of water (i.e. liquid water cloud, ice cloud) and are calculated for each individual spectral interval [Kiehl et al., 1996]. For partial cloudiness and cloud overlap, a simplified parameterization tuned to comply with the random overlap assumption, benchmarked by Briegleb [1992], is used.

A full description of the radiation package contained in RegCM3 can be found in Kiehl et al. [1996].

### 2.4 Boundary Layer Physics

RegCM3 also uses the planetary boundary layer (PBL) parameterization contained in CCM3, which is a non-local PBL scheme developed by Holtslag et al. [1990]. Previously (in RegCM), a local diffusion scheme was used [Elguindi et al., 2004]. The fundamental theory underlying a local diffusion approach is that the flux of a substance (e.g. sensible heat, water vapor, momentum) due to turbulence can be determined using the local gradient of that quantity [Kiehl et al., 1996]. While this assumption holds when the length scale of the largest turbulent eddies is smaller than the height of the PBL, it does not hold for relatively
large eddies because the flux can run opposite to the local gradient [Kiehl et al., 1996; Deardorff, 1972; Holtslag and Moeng, 1991]. Often associated with convective or unstable atmospheric conditions, large eddies are generally poorly represented by local diffusion schemes, necessitating the use of a non-local PBL parameterization [Kiehl et al., 1996]. In this case, the diffusion is modified such that the vertical eddy flux of a substance \( C \) (e.g. sensible heat, water vapor, momentum) \( \bar{w}C' \) at height \( z \) is given by

\[
\bar{w}C' = -K_c \left( \frac{\partial C}{\partial z} - \gamma_c \right)
\]  

(2.9)

where \( K_c \) is found by

\[
K_c = kw_t z \left(1 - \frac{z}{h} \right)^2
\]  

(2.10)

and \( w_t \) is the turbulent velocity scale, \( k \) is the von Karman constant, and \( h \) is the PBL height (\( \approx 40 \) m in RegCM3) solved iteratively using

\[
h = \frac{Ri_{cr}[u(h)^2 + v(h)^2]}{(g/\theta_s)(\theta_v(h) - \theta_s)}
\]  

(2.11)

In this formula, \( Ri_{cr} \) is the critical bulk Richardson number for the PBL, \( u(h) \) and \( v(h) \) are the horizontal velocity components at \( h \), \( g \) is the acceleration due to gravity, \( \theta_v(h) \) is the virtual temperature at \( h \), and \( \theta_s \) is a measure of the surface air temperature, calculated as

\[
\theta_s = \theta_v(z_s) + K \frac{w'\theta_o}{w_t}
\]  

(2.12)

for unstable conditions \( (L < 0) \), \( L \) being the Monin-Obukhov height [Holtslag et al., 1990]. For stable conditions
\[ \theta_s = \theta_v(z_s) \]  

(2.13)

Here, \( z_s \) is 2 m, \( K \) is a constant equal to 8.5, and \( \omega^\prime \theta_o^\prime \) is the surface heat flux. The term \( K \frac{\omega^\prime \theta_o^\prime}{w_i} \) describes the strength of convective thermals in the lower part of the PBL, and is therefore zero for stable conditions [Holtslag et al., 1990].

Finally, the countergradient transport \( \gamma_c \) describes the non-local transport of both heat and moisture (\( C = \theta, q \), respectively) from dry convection.

\[ \gamma_c = K \frac{\omega^\prime C_o^\prime}{w_i h} \]  

(2.14)

where \( \omega^\prime C_o^\prime \) is the surface temperature or water vapor flux. In RegCM3, this equation is used from the top of the surface layer (0.1 m) to the top of the PBL [Elguindi et al., 2004]. For heights outside of this range, as well as for stable conditions, \( \gamma_c \) is neglected [Elguindi et al., 2004].

### 2.5 Convection Schemes

As mentioned above, a total of four convection schemes are available in RegCM3, the Kuo scheme [Anthes, 1977], the Grell scheme [Grell, 1993], the Betts-Miller scheme [Betts, 1986], and the Emmanuel scheme [Emanuel, 1991]. The Grell scheme is further divided by closure assumption, and can be implemented using either the Arakawa & Schubert closure (AS74) [Grell et al., 1994] or the Fritsch & Chappell closure (FC80) [Fritsch and Chappell, 1980]. All simulations completed in this study use the Grell Scheme with the FC80 closure, so a more detailed description of the Grell scheme is included. The Kuo scheme is also briefly examined. Descriptions of the Emmanuel scheme and Betts-Miller scheme are not included, as neither was considered for use in this study. The Emmanuel scheme is a relatively new addition to RegCM3 and has not been thoroughly tested, while the Betts-Miller scheme was designed primarily for tropical convection [Elguindi et al., 2004].
documentation and references for all convection schemes can be found in Elguindi et al. [2004].

2.5.1 Grell Scheme

The Grell scheme is a basic representation of convective precipitation similar in structure to the Arakawa & Schubert scheme [1974]. Shown in figure 2-2, the Grell scheme models clouds as two steady-state circulations, an updraft and a downdraft [Grell et al., 1994].

![Diagram of Grell Scheme](image)

Figure 2-2: Conceptual picture of the Grell scheme [Grell et al., 1994].

Mixing is not allowed between the cloudy air and the environment along the length of the column, only at the top and bottom of the circulations [Grell et al., 1994]. Mass flux is constant with height \( z \) and no entrainment or detrainment occurs along the edges of the cloud, or
\[ m_u(z) = m_u(z_b) = m_b \quad (2.15) \]

and

\[ m_d(z) = m_d(z_0) = m_0 \quad (2.16) \]

where \( m_u \) and \( m_d \) are the updraft and downdraft mass flux, respectively, \( z_b \) is the originating level of the updraft mass flux, \( z_0 \) is the originating level of the downdraft mass flux, and \( m_b \) and \( m_0 \) are the mass fluxes of the updraft and downdraft at their originating levels [Grell et al., 1994]. The originating level is a function of maximum and minimum moist static energy \( h \), calculated at height \( z \) by

\[ h(z) = C_p T(z) + gz + L_v q(z) \quad (2.17) \]

with \( C_p \) being the specific heat of air, \( T(z) \) the temperature of air at height \( z \), \( g \) the acceleration due to gravity, \( L_v \) the latent heat of vaporization of water, and \( q(z) \) the specific humidity at height \( z \).

Given boundary conditions, the originating mass flux of the downdraft can be put in terms of the updraft mass flux at the originating level and the precipitation efficiency, yielding

\[ m_0 = \frac{\beta I_1 m_b}{I_2} \quad (2.18) \]

Here \( I_1 \) is the normalized updraft condensation, \( I_2 \) is the normalized downdraft evaporation, and \( \beta \) is the fraction of the updraft condensation that reevaporates in the downdraft [Pal, 1997]. \( 1 - \beta \) is the precipitation efficiency and is dependent on wind shear. Rainfall \( R \)
using the Grell scheme is given by

$$R = I_1 m_b (1 - \beta)$$  \hspace{1cm} (2.19)

The Grell scheme calculates heating and moistening as a function of mass fluxes and detrainment at the top and bottom of the cloud [Pal, 1997]. Additionally, to avoid zero-order sources of error, the cooling effects of moist convective downdrafts are included, as well as an upper limit on lateral mixing [Grell et al., 1994].

The simplicity of the Grell scheme allows for two different closure assumptions. By default, RegCM3 uses the quasi-equilibrium AS74 closure, which assumes that clouds stabilize the environment at the same rate that non-convective processes destabilize it [Elguindi et al., 2004]. This can be expressed as

$$\frac{dAB}{dt} = \frac{dAB_{LS}}{dt} + \frac{dAB_{CU}}{dt} \approx 0$$  \hspace{1cm} (2.20)

where $AB$ is the available buoyant energy, $LS$ is the subscript for large-scale, and $CU$ is the subscript for cumulus convention [Pal, 1997]. Expressed as a mass flux, the relationship is

$$m_b = \frac{AB'' - AB}{NA \Delta t}$$  \hspace{1cm} (2.21)

$AB''$ being the buoyant energy generated by non-convective processes available for convection over the time period $\Delta t$ and $NA$ being the rate of change of $AB$ per unit $m_b$.

The other Grell scheme closure assumption, FC80, assumes that convection removes available buoyant energy as follows

$$m_b = \frac{AB}{NA \tau}$$  \hspace{1cm} (2.22)
where $\tau$ is the $AB$ removal time scale

While both closure schemes strike a statistical equilibrium between convection and large-scale processes, they do so different ways. While the AS74 closure scheme relates convective fluxes to tendencies in the state of the atmosphere, the FC80 closure assumption relates convective fluxes to instability in the atmosphere [Elguindi et al., 2004].

### 2.5.2 Kuo Scheme

Originally developed by Anthes [1977], and simplified by Anthes et al. [1987] for inclusion in MM4, the Kuo scheme, named after the work of Kuo [1974], is triggered when the total horizontal moisture convergence exceeds a critical value [Anthes, 1977]. A simple conceptual picture of the scheme is included in figure 2-3 below.

Vertically integrated moisture convergence $M_t$ is described as

$$
M_t = \left( \frac{m^2}{g} \right) \int_0^1 \nabla p^* \hat{V} q_v d\sigma
$$

(2.23)

where $m$ is the mass flux, $g$ is acceleration due to gravity, $\nabla p^*$ is a function of surface and top of model pressure, $\hat{V}$ is dependent on horizontal velocity, $q_v$ is the mixing ratio of water vapor, and $\sigma$ is the vertical sigma level.

As depicted in figure 2-3, a fraction of the total moisture convergence condensed in cumulus convection is converted to precipitation $R$

$$
R = M_t (1 - \beta)
$$

(2.24)

with $\beta$ being a precipitation efficiency factor dependent on the average relative humidity $\overline{RH}$ as follows
Figure 2-3: Schematic of the Kuo scheme [Anthes, 1977].
\[ \beta = 2(1 - RH) \quad RH \geq 0.5 \\
= 1 \quad \text{otherwise} \quad (2.25) \]

The remaining fraction \( \beta \) stays in the column and increases the humidity of the column [Anthes, 1977]. Ideally, the transfer of latent heat from water that is condensed and subsequently reevaporated before escaping from the cloud would be distributed as a function of the height of condensation and the height of reevaporation [Anthes, 1977]. This is parameterized in the Kuo scheme by dividing the latent heat from condensation along the cloud using a parabolic heating profile, which allocates the majority of heat to the upper part of the cloud [Pal, 1997].

Modifications to the Kuo scheme were made by Giorgi and Bates [1989] and Giorgi and Marinucci [1991] to eliminate numerical point storms via a horizontal diffusion term and a time release constant, so that moisture and latent heat are not redistributed instantaneously.

### 2.6 Large-Scale Precipitation Scheme

Non-convective clouds and precipitation are calculated using Subgrid Explicit Moisture Scheme (SUBEX) [Pal, 2001]. SUBEX employs a formulation that relates the average grid cell relative humidity \( rh \), among other variables, to the cloud fraction and cloud water consistent with the work of Sundqvist et al. [1989].

\[
FC^{LS} = \sqrt{\frac{rh - rh_{min}}{rh_{max} - rh_{min}}} \quad (2.26)
\]

where \( FC^{LS} \) is the fractional cloud cover, \( rh_{min} \) is the relative humidity threshold where clouds begin to form, and \( rh_{max} \) is the relative humidity threshold at which the fractional cloud cover reaches unity [Pal, 2001]. When \( rh \leq rh_{min} \), \( FC^{LS} \) is assumed to be zero, and when \( rh \geq rh_{max} \), \( FC^{LS} \) is assumed to be unity.
When the cloud water $Q_c^{LS}$ content exceeds the autoconversion threshold $Q_c^{th}$, precipitation $P^{LS}$ forms

\[ P^{LS} = C_{ppt} \left( \frac{Q_c^{LS}}{FC_c^{LS}} - Q_c^{th} \right) FC_c^{LS} \]  (2.27)

with $C_{ppt}$ being the autoconversion rate. Conceptually, $1/C_{ppt}$ can be thought of as the characteristic time for cloud droplets converting into rainfall. Once precipitation is formed, it is assumed to fall instantaneously. $Q_c^{th}$ is given by

\[ Q_c^{th} = C_{acs} 10^{-0.49+0.013T} \]  (2.28)

In this formula, $T$ is temperature in degrees Celsius and $C_{acs}$ is the autoconversion scale factor.

SUBEX also includes basic calculations for raindrop accretion and evaporation. Following the work of Beheng [1994], the formulation for the amount of accreted cloud water $P_{acc}$ from falling rain droplets is

\[ P_{acc} = C_{acc} Q_c^{LS} P_{sum} \]  (2.29)

where $C_{acc}$ is the accretion rate coefficient and $P_{sum}$ is the accumulated large-scale precipitation from above falling through the cloud. Evaporation from falling raindrops is calculated using the simple formulation of Sundqvist et al. [1989]

\[ P_{evap} = C_{evap} (1 - rh) P_{sum}^{1/2} \]  (2.30)

Here, $P_{evap}$ is the amount of evaporation and $C_{evap}$ is a rate coefficient.

For a more detailed description of SUBEX and its parameter values, refer to Pal et al.
2.7 Ocean Flux Parameterization

For all experiments in this study the Zeng ocean surface scheme was used, with sensible heat $SH$, latent heat $LH$, and momentum $\tau$ fluxes given by the bulk aerodynamic algorithms

\begin{align}
SH &= -\rho_a C_{pa} u_* \theta_s \tag{2.31} \\
LH &= -\rho_a L_v u_* q_s \tag{2.32} \\
\tau &= \rho_a u_*^2 (u_x^2 + u_y^2)^{1/2} / u \tag{2.33}
\end{align}

where $\rho_a$ is the air density, $C_{pa}$ is the specific heat of air, $u_*$ is the frictional wind velocity, $\theta_s$ is the temperature scaling parameter, $L_v$ is the latent heat of vaporization of water, $q_s$ is the specific humidity scaling parameter, $u_x$ is the mean zonal wind component, $u_y$ is the mean meridional wind component, and $u$ is wind speed [Elguindi et al., 2004]. A complete description the Zeng ocean scheme can be found in Zeng et al. [1998].

2.8 BATS1e

Biosphere-Atmosphere Transfer Scheme 1e (BATS1e) is a comprehensive model of land surface processes that can be run offline, coupled to a GCM, or coupled to RegCM3 [Dickinson et al., 1993]. A full list of the parameter values used in BATS1e can be found in Appendix A.2. BATS1e performs seven major tasks, the overall structure of which is shown
in figure 2-4 [Dickinson et al., 1993].

Figure 2-4: Flow chart for Biosphere-Atmosphere Transfer Scheme version 1e (BATS1e) [Dickinson et al., 1993].

The first function of BATS1e is to assign vegetation and soil characteristics to each grid cell. Vegetation is assigned using the United States Geological Survey’s (USGS) Global Land Cover Characterization (GLCC) dataset [United States Geological Survey, 1997]. It is available in 2, 3, 5, 10, 30, and 60 minute resolutions. In BATS1e, soil characteristics are assigned by vegetation type. For example, a desert grid point would be assigned a coarse, sandy soil, while for a deciduous forest, a finer soil with silt and clay would be specified.

A formulation for finding the albedos of sea ice, bare soil, and vegetation is also included in BATS1e. The albedo of a vegetated surface is determined by the vegetation type (table 2.1), with albedos for each type drawn from a variety of studies, mainly Monteith
Table 2.1: Vegetation types for BATS1e [Dickinson et al., 1993].

Soil albedo $A_{LBG}$ is determined in part by soil type, but is also dependent on soil moisture.

$$A_{LBG} = A_{LBGO} + \Delta \alpha_g(S_{sw})$$

(2.34)

where $A_{LBGO}$ is the albedo for a saturated soil and $\Delta \alpha_g(S_{sw})$ is a function of the surface soil water content $S_{sw}$ and upper soil layer depth, which gives the increase of albedo due to the dryness of the surface soil [Dickinson et al., 1993].

The third major set of computations that BATS1e performs is the calculation of the surface drag coefficient $C_D$, which is a function of the drag coefficient for neutral stability $C_{DN}$ and the surface bulk Richardson number $Ri_B$ [Dickinson et al., 1993].

$$C_D = C_{DN}(1 + 24.5(-C_{DN}Ri_B)^{1/2}) \quad Ri_B < 0$$

$$= C_{DN}/(1 + 11.5Ri_B) \quad Ri_B > 0$$

(2.35)
with \( C_{DN} \) calculated from mixing-length theory

\[
C_{DN} = \left[ \frac{k}{\ln(z_1/z_0)} \right]^2 \tag{2.36}
\]

where \( k \) is the von Karman constant, \( z_0 \) is the roughness length, and \( z_1 \) is the height of the lowest model level [Dickinson et al., 1993].

All plant water budget calculations, including foliage and stem water fluxes, resistance (stomatal and water induced) limited transpiration, and precipitation interception are handled by the fourth set of calculations. A simplistic scheme is used in conjunction with the drip formulae of Massman [1980] to calculate interception.

\[
\tilde{L}_w = \left( \frac{W_{dew}}{W_{D MAX}} \right)^{2/3} \tag{2.37}
\]

Here, \( \tilde{L}_w \) is the fractional area of leaves covered by water, \( W_{dew} \) is the total water intercepted by the canopy, and \( W_{D MAX} \) is the maximum amount of water the canopy can hold.

In BATS1e, interception both encourages evaporation from the wet leaf surfaces while simultaneously suppressing transpiration from leaves [Dickinson et al., 1993]. Root resistance follows from the work of Federer [1979], Hillel [1980], and Molz [1981]. The two aforementioned factors, along with specific environmental variables, such as solar radiation, temperature, soil moisture, and vapor pressure deficit are weighted and combined following the methodology of Jarvis [1976] and Hinckley et al. [1978] to find stomatal resistance \( r_s \), and are ultimately used in a similar manner as presented by Monteith [Thom and Oliver, 1977] to calculate transpiration [Dickinson et al., 1993].

\[
r_s = r_{s min} \times R_f \times S_f \times M_f \times V_f \tag{2.38}
\]

where \( r_{s min} \) is the minimum stomatal resistance, \( R_f \) gives the dependence of \( r_s \) on solar radiation, \( S_f \) is the seasonal temperature factor, \( M_f \) is a function of soil moisture and root
uptake of water, and $V_f$ gives the dependence of $r_s$ on vapor pressure deficit [Dickinson et al., 1993].

Transpiration $E_{tr}$ is calculated by the fifth set of equations. Here, a scheme similar to the one-layer formulation credited to Monteith is used [Thom and Oliver, 1977]. Differences include the ability to have a partially wetted canopy, as well as explicitly separate equations and resistances for energy fluxes between foliage and air within the canopy, and between air within the canopy and air above the canopy [Dickinson et al., 1993]. $E_{tr}$ is given by

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

(2.39)

where $r_{la}$ is the resistance for heat and water vapor flux, $E_f^{WET}$ is the evaporation rate of water from leaves and stems per unit wetted area, $L_d$ is the fraction of foliage allowed to transpire, and $\delta$ is a step function that is 1, 0 when the argument $E_f^{WET}$ is positive, negative, respectively [Dickinson et al., 1993].

After transpiration is computed, the foliage temperature, solved iteratively and mainly dependent on the transfer of heat and moisture within the canopy, is calculated [Dickinson et al., 1993].

Task six employs the primary physics of the model to compute soil, snow, or sea ice temperature as dictated by radiation inputs, soil/snow heat capacity, and thermal conductivity [Dickinson et al., 1993]. The soil temperature model is an adaptation of the force restore method of Deardorff [1978], and is explicitly documented in Dickinson and Sellers [1988]. A simpler scheme handles sea ice, and primarily models a constant heat conduction from the ocean, following the works of Maykut and Untersteiner [1971], and Semtner Jr. [1976]. Surface soil temperature $T_g1$ is calculated by

$$C \Delta t \frac{\partial T_g1}{\partial t} + 2AT_g1 = B$$

(2.40)

Here, $A$ is a function of the diurnal frequency, $B$ is a term proportional to net surface
heating, $C$ is dependent on the thermal inertia of freezing, and $\Delta t$ is the timestep in seconds.

Finally, the last set of formulae determine soil moisture, evaporation, and surface/groundwater runoff. Soil is represented by three reservoirs (layers) in BATS1e, a 10 cm surface soil layer, a 1-2 m root layer, and a 3 m deep soil layer [Pal et al., 2000]. As precipitation is applied to the soil (via snowmelt or rain), it is either partitioned to runoff or infiltration, and is then allowed to move between the three reservoirs based predominantly on vegetation and soil properties [Dickinson et al., 1993]. Evaporation from the soil is parameterized using a scheme dependent on the aerodynamic characteristics of the soil surface and the soil conductivity [Dickinson et al., 1993]. Determining runoff and infiltration is primarily a function of soil moisture, where little runoff occurs from a soil at field capacity, and almost all water is sent to runoff for a saturated soil [Dickinson et al., 1993].

Infiltration is dictated by diffusivity $D$

$$D = K_{wo} \phi_o B s^{B+2}$$

(2.41)

where $K_{wo}$ is the hydraulic conductivity, $s$ is the volume of water divided by the volume of water at saturation, $B$ is the Clapp and Hornberger [1978] exponent, and $\phi_o$ is the minimum soil suction [Dickinson et al., 1993]. At larger length scales infiltration can be influenced by the subsoil drainage [Dickinson et al., 1993].

Runoff $R_s$ is given by

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

$$= \left(\frac{\rho_w}{\rho_{wsat}}\right) G$$

(2.42)

In this formula, $\rho_w$ is the soil water density weighted toward the top layer, $\rho_{wsat}$ is the saturated soil water density, and $G$ is the net water applied to the surface [Dickinson et al., 1993].
2.9 RegCM3 Datasets

A total of four datasets are available for use as boundary conditions in RegCM3: the Centre for Medium-Range Weather Forecasting (ECMWF) reanalysis dataset [European Centre for Medium-Range Weather Forecasts, 1995], the ECMWF 40-year reanalysis (ERA40) dataset [Uppala et al., 2005], the National Centers for Environmental Prediction (NCEP) reanalysis 1 dataset [Kalnay et al., 1996], and the NCEP reanalysis 2 dataset [Ebisuzaki, 2005].

Since RegCM3 lacks an interactive ocean model, SSTs are prescribed using the National Oceanic and Atmospheric Administration (NOAA) Optimum Interpolation Sea Surface Temperature (OISST) dataset [Reynolds et al., 2002] or the Hadley Centre Meteorological Office Global Sea Surface Temperature (GISST) dataset [Rayner et al., 1996].

Two land surface datasets are used to initialize RegCM3. Elevations are derived from the United States Geological Survey’s (USGS) Global 30 arc second elevation dataset (GTOPO30) [United States Geological Survey, 1996] and land cover is given by the USGS GLCC dataset [United States Geological Survey, 1997]. While GTOPO30 and GLCC have spatial resolutions of 30 arc seconds and 1 km respectively, both are used in 2, 3, 5, 10, 30, or 60 minute resolutions [United States Geological Survey, 1996].
Chapter 3

Integrated Biosphere Simulator (IBIS)

3.1 Model Description

Integrated Biosphere Simulator (IBIS), a dynamic global vegetation model (DGVM), is described below. A summary of the model’s core features, as well as some detailed descriptions of parameterizations and formulae are included. Full documentation of IBIS can be found in Foley et al. [1996]. Additionally, a full description of the biophysical processes contained in IBIS can be found in Pollard and Thompson [1995].

3.2 Model Overview

IBIS, which was developed by Foley et al. at the University of Wisconsin-Madison, is a terrestrial biosphere model that uses a modular, physically consistent framework to perform integrated simulations of water, energy, and carbon fluxes [Foley et al., 1996]. A schematic showing a simplified version of the structure of IBIS can be found in Appendix B-1.

IBIS includes four modules organized with respect to their temporal scale: land surface processes (energy, water, carbon, and momentum balance), soil biogeochemistry (carbon and nitrogen cycling from plants through soil), vegetation dynamics, and vegetation phenology (figure 3-1).
3.3 Land Surface Physics

Based on Land Surface Transfer model (LSX), by Thompson and Pollard [1995a,b], the IBIS land surface module simulates energy, water, carbon, and momentum balances of the soil-vegetation-atmosphere system [Kucharik et al., 2000]. A schematic of the land surface module is included in Appendix B-2. The land surface module contains two vegetation layers, three snow layers, and up to six soil layers, allowing it to resolve changes in state variables both within the lower (shrubs, grasses) and upper (trees) canopies, as well as each individual layer of soil and snow [Kucharik et al., 2000]. Accordingly, in all formulae presented in this section, the subscripts $u$, $s$, and $l$ refer to upper canopy leaves, upper canopy stems, and lower canopy vegetation, respectively, and the subscripts $a$, $1$, $12$, $2$, $3$, $34$, $4$ are heights that reference the atmospheric forcing height, top of the upper canopy, middle of the upper canopy, bottom of the upper canopy, top of the lower canopy, middle of the lower canopy, bottom of the lower canopy [Pollard and Thompson, 1995].

IBIS uses separate calculations for solar and infrared radiation. Solar radiation is subdivided into two wavelength bands (visible from 0.4 $\mu$m to 0.7 $\mu$m and near infrared from
0.7 \mu m to 4.0 \mu m) within each vegetation layer. The amount of infrared radiation (IR) reflected, absorbed, and transmitted by a plant is a function of its foliage density and the net upward flux of IR from the surface $I_b$

$$I_b = (1 - f_u)I^\uparrow + f_u[(1 - \epsilon_u)(1 - \epsilon_s)I^\uparrow + \epsilon_u\sigma T_u^4 + \epsilon_s(1 - \epsilon_u)\sigma T_s^4] \quad (3.1)$$

where $f_u$ is fractional cover, $I^\uparrow$ is the upward IR flux between the upper and lower canopies, $\epsilon_u$ and $\epsilon_s$ are emissivities, $\sigma$ is the Stefan-Boltzmann constant, and $T_u$ and $T_s$ are temperatures [Foley et al., 1996].

Within each canopy layer, turbulent fluxes and wind speed are calculated using a diffusive model, the general solution of which is

$$u(z)^2 = Ae^{\lambda z} + Be^{-\lambda z} \quad (3.2)$$

Here $u(z)$ is mean horizontal wind speed at height $z$, $\lambda$ is a function of the effective drag coefficient and effective diffusion coefficient within the canopy, and $A$ and $B$ are arbitrary constants determined by boundary conditions [Pollard and Thompson, 1995].

Above and between layers, $u(z)$ is modeled using mixing-length logarithmic profiles [Foley et al., 1996]. Between $z_a$, $z_1$

$$u(z) = \sqrt{\frac{\tau}{\rho k}} \ln \left( \frac{z - d_u}{z_{0u}} \right) \sigma_{mu}^{-1/2} \quad (3.3)$$

and between $z_2$, $z_3$

$$u(z) = \sqrt{\frac{\tau}{\rho k}} \ln \left( \frac{z - d_l}{z_{0l}} \right) \sigma_{ml}^{-1/2} \quad (3.4)$$

where $\tau$ is the horizontal wind stress; $\rho$ is air density neglecting height variation; $k$ is the
von Karman constant; \( d_u, d_l \) are zero-plane displacement heights; \( z_{0u}, z_{0l} \) are roughness lengths; and \( F_{mu}, F_{ml} \) are non-neutral stratification corrections [Pollard and Thompson, 1995]. Below the lowest canopy layer an empirically derived linear function is used to describe wind speed [Kucharik et al., 2000].

Evapotranspiration is calculated as the sum of evaporation from the soil surface, evaporation from water intercepted by the canopy, and plant transpiration. Evaporation from the soil surface is a function of wind speed and the relative humidity at the surface, which is itself dependent on soil temperature and soil moisture [Foley et al., 1996]. Evaporation from intercepted precipitation is simulated using a parameterization that describes the cascading of rain and snow through the canopy. Transpiration is calculated independently for each plant functional type (PFT), and depends primarily on stomatal conductance, a variable explained in more detail below. Evapotranspiration \( E_u, E_s, \) and \( E_l \) is expressed as

\[
E_u = \rho_s s_u \left[ f_u^{wet} \left(1 - f_u^{wet} f_u^{sto} \right) \frac{1}{1 + r_u s_u} \right] (q_{sat}(T_u) - q_{12})
\]  
(3.5)

\[
E_s = \rho_s s_s f_s^{wet} (q_{sat}(T_s) - q_{12})
\]  
(3.6)

\[
E_l = \rho_s s_l \left[ f_l^{wet} \left(1 - f_l^{wet} f_l^{sto} \right) \frac{1}{1 + r_l s_l} \right] \left( \frac{LAI_l}{LAI_l + SAI_l} \right) (q_{sat}(T_l) - q_{34})
\]  
(3.7)

where \( \rho \) is the density of near surface air; \( s_u, s_s, s_l \) are transfer coefficients; \( f_u^{wet}, f_s^{wet}, f_l^{wet} \) are wetted fractions; \( f_u^{sto}, f_s^{sto} \) are 0.5 for leaves with stomata on one side, and 1 for leaves with stomata on both sides; \( r_u, r_l \) are stomatal resistances; \( q_{sat}(T_u), q_{sat}(T_s), q_{sat}(T_l) \) are saturation specific humidities at the temperatures \( T_u, T_s, T_l \), respectively; \( q_{12}, q_{34} \) are specific humidities; \( LAI_l \) is the leaf area index; and \( SAI_l \) is the stem area index [Pollard and Thompson, 1995].

To capture the diurnal and seasonal cycles of moisture and temperature in the soil, each
layer is independently resolved and defined by temperature, fractional liquid water content relative to ice-free pore space (soil moisture), and fractional ice content relative to total pore space (soil ice) [Foley et al., 1996]. Time dependent changes in soil moisture are calculated using Richard’s equation, and Darcy’s law is used to model the vertical flux of water. Soil matric potentials, required by Darcy’s equations, are derived from soil moisture and texture using the methods of Clapp and Hornberger [1978]. The soil water budget is defined by the rate of infiltration, evaporation of water from the surface, transpiration, and redistribution of water within the soil profile [Kucharik et al., 2000]. The lower boundary of the soil allows no heat or water diffusion, and drainage is a user-defined value between 0 (no drainage) and 1 (free drainage). The attributes of snow layers (temperature, fractional coverage, and total snow thickness) are calculated using a thermodynamic model. All processes within the land surface model operate on time scales of one hour.

Also included in the land surface module is canopy physiology, which regulates water vapor and carbon dioxide fluxes between the vegetation and atmosphere. A table of the plant physiology parameter values used can be found in Appendix A.1. While most surface physics models use empirical relationships between light, temperature, and water vapor pressure to determine the photosynthetic rate and stomatal conductance, IBIS employs a mechanistically based approach for photosynthesis [Farquhar et al., 1980; Farquhar and Sharkey, 1982] and stomatal conductance [Ball et al., 1986; Lloyd, 1991; Lloyd and Farquhar, 1994; Friend, 1995; Leuning, 1995]. Consistent with the physics in the aforementioned papers, photosynthesis in IBIS is a function of absorbed light, leaf temperature, CO₂ concentration in the leaf, and the Rubisco enzyme capacity for photosynthesis, while stomatal conductance is dependent on photosynthetic rate, CO₂ concentration, and water concentration [Foley et al., 1996]. The gross rate of photosynthesis per unit leaf \( A_g \) for C₃ plants is assumed to be limited by light, Rubisco activity, or utilization of triose phosphate, expressed as

\[
A_g \approx \min(J_e, J_c, J_s)
\]  

(3.8)
The light-limited rate of photosynthesis \( J_e \) is

\[
J_e = \alpha_3 Q_p \left( \frac{C_i - \Gamma_*}{C_i + 2\Gamma_*} \right)
\]

(3.9)

Here, \( \alpha_3 \) is the intrinsic quantum efficiency for CO\(_2\) uptake in C\(_3\) plants, \( Q_p \) is the flux density of photosynthetically active radiation absorbed by the leaf, \( C_i \) is the concentration of CO\(_2\) in the intercellular air spaces of the leaf, and \( \Gamma_* \) is the compensation point for gross photosynthesis

\[
\Gamma_* = \frac{[O_2]}{2\tau}
\]

(3.10)

where \([O_2]\) is the concentration of atmospheric oxygen and \( \tau \) describes the partitioning of enzyme activity to carboxylase or oxygenase function [Foley et al., 1996]. The Rubisco-limited rate of photosynthesis \( J_c \) is given by

\[
J_c = \frac{V_m (C_i - \Gamma_*)}{C_i + K_c \left( 1 + \frac{[O_2]}{K_o} \right)}
\]

(3.11)

where \( V_m \) is the maximum capacity of Rubisco to perform the carboxylase function, \( K_c \) is the Michaelis-Menten coefficient for CO\(_2\), and \( K_o \) is the Michaelis-Menten coefficient for O\(_2\) [Foley et al., 1996]. Finally, the triose phosphate utilization-limited photosynthetic rate \( J_s \), which dominates during periods of high intercellular CO\(_2\) and irradiance, is

\[
J_s = 3T \left( 1 - \frac{\Gamma_*}{C_i} \right) + \frac{J_p \Gamma_*}{C_i}
\]

(3.12)

\( T \) being the rate of triose phosphate utilization and \( J_p \) being a function of empirical constants and the other two limiting photosynthetic rates [Foley et al., 1996].

To allow for colimitation, a quadratic equation is used to link the three photosynthetic
rates via $J_p$ [Foley et al., 1996]. Photosynthesis in C$_4$ plants follows a similar structure, where

$$A_g \approx \min(J_i, J_e, J_c)$$  \hspace{1cm} (3.13)

In C$_4$ plants the compensation point is assumed to be zero, and the limiting photosynthetic rates are reduced to

$$J_i = \alpha_4 Q_p$$  \hspace{1cm} (3.14)

$$J_e = V_m$$  \hspace{1cm} (3.15)

$$J_c = k C_i$$  \hspace{1cm} (3.16)

where $J_i$ is the light-limited rate of photosynthesis, $J_e$ is the Rubisco-limited rate of photosynthesis, $J_c$ is the CO$_2$-limited rate of photosynthesis, $\alpha_4$ is the intrinsic quantum efficiency for CO$_2$ uptake in C$_4$ plants, and $k$ is a parameter based on $V_m$ [Foley et al., 1996].

The final gross photosynthetic rate is again calculated by a quadratic equation that conjoins the above three rates.

Stomatal conductance $g_s$ of water vapor is given by

$$g_s = \frac{m A_n}{(C_s - \Gamma_s) \left(1 + \frac{D_s}{D_0}\right)} + b$$  \hspace{1cm} (3.17)

Here, $A_n$ is the net leaf assimilation rate, $C_s$ is the CO$_2$ concentration at the leaf surface, $D_s$
is the water vapor mole fraction difference between the leaf and the air, $D_o$ is a reference value, and $m$ and $b$ are the slope and intercept of the conductance-photosynthesis relationship [Foley et al., 1996]. The following two equations link photosynthesis and stomatal conductance via the CO$_2$ concentration

$$C_s = C_a - \frac{A_n}{g_b}$$

(3.18)

$$C_t = C_s - \frac{1.6A_n}{g_s}$$

(3.19)

with $C_a$ being the atmospheric mole fraction of CO$_2$ and $g_b$ being the CO$_2$ boundary layer conductance [Foley et al., 1996].

This framework has been tested extensively against gas exchange measurements by Delire and Foley [1999]. To account for shading within and between the two canopy layers, the formulation of Norman [1993] is employed. Using the shaded and sunlit fractions for each PFT, individual calculations of photosynthesis and stomatal conductance are computed for each section of the canopy and averaged (weighted average) to find fluxes for the entire canopy.

### 3.4 Vegetation Phenology

Run daily, the vegetation phenology module contains a set of rule-based formulations that describe the relationship between seasonal changes in vegetation and seasonal climatic conditions. This encompasses the annual leaf cycle of deciduous trees, the response of trees to drought, and changes in physiological activity in evergreens [Kucharik et al., 2000]. Values for the parameters used in the vegetation phenology and vegetation dynamics modules can be found in Appendix A.3. Leaves of winter-deciduous plants are stripped when the daily average temperature falls below a critical threshold and repopulated when the temperature rises in spring [Foley et al., 1996]. The equation for senescence, assuming that the average
10-day temperature is less than the temperature threshold $T_{thresh}$

$$T_{thresh} = \max(0, T_c + 5^0C)$$ \hspace{1cm} (3.20)

is given by

$$L_{disp} = \max(0.0, T_{thresh} - d_{frac})$$ \hspace{1cm} (3.21)

where $L_{disp}$ is a fraction used to update leaf area index (LAI) and canopy fractions, $T_c$ is the coldest average monthly temperature, and $d_{frac}$ is the inverse of the number of days to affect phenology change (assumed to be 15) [Foley et al., 1996].

The leaves of drought-deciduous plants (tropical deciduous trees) are removed during the least two productive months of the year as dictated by the previous year’s carbon cycle.

### 3.5 Vegetation Dynamics

At initialization, one of fifteen biomes is specified for each land point in an IBIS simulation using a vegetation input dataset. Then, based on specific climate variables, also contained in input datasets, vegetation cover for both the upper and lower canopies is assigned using a distribution of one or more of the twelve PFTs (table 3.1).

Identified by $LAI$ and the amount of carbon in the leaves, roots, and stems, PFTs are assigned key characteristics, including basic classification (trees, shrubs, grasses), leaf cycle (deciduous, evergreen), leaf type (broadleaf, needleleaf), and physiology ($C_3$ pathway, $C_4$ pathway) [Kucharik et al., 2000]. Geographic bounds for each PFT are defined by climatic constraints [Kucharik et al., 2000]. Any number of PFTs may exist in each grid cell and IBIS explicitly allows different PFTs to compete for resources such as light, water, and nutrients. When running in dynamic vegetation mode, IBIS updates the assignment of biomes annually based on the distribution of $LAI$ among each of the PFTs. For example, in an area where the dominant plant type is temperate broadleaf deciduous trees, if the $LAI$
Table 3.1: Vegetation types for IBIS [Foley et al., 1996].

allocated to trees is high, medium, or low, then the area will be designated as a temperate deciduous forest, savanna, or grassland, respectively.

3.6 Biogeochemistry

Summing hourly fluxes of carbon (gross photosynthesis and respiration rates) yields the annual carbon balance, which is calculated for each PFT. Gross primary productivity \( GPP \) and net primary productivity \( NPP \) are also calculated for each PFT \( i \).

\[
GPP_i = \int A_{g,i} dt \quad (3.22)
\]

\[
NPP_i = (1 - \eta) \int (A_{g,i} - R_{\text{leaf},i} - R_{\text{stem},i} - R_{\text{root},i}) dt \quad (3.23)
\]

where \( \eta \) is the fraction of carbon lost in the construction of net plant material because of growth respiration [Amthor, 1984] and \( R_{\text{leaf}}, R_{\text{stem}}, \) and \( R_{\text{root}} \) are the leaf, stem, and root maintenance respiration, respectively [Foley et al., 1996].
Three basic biomass pools exist in IBIS in which carbon may reside: leaves, transport tissue, and fine roots. Changes in each biomass pool are calculated and mortality and tissue turnover are simulated by assigning residence times to each biomass compartment. LAI is found by dividing the carbon in the leaf biomass pool by the specific leaf area [Foley et al., 1996].

### 3.7 IBIS datasets

The offline version of IBIS requires 13 separate datasets to run. Five of the files initially define the state of the land surface: land mask [National Oceanic and Atmospheric Administration/National Geophysical Data Center, 2006], topography [National Oceanic and Atmospheric Administration/National Geophysical Data Center, 2006], sand percentage [Global Soil Data Task, International Geosphere-Biosphere Programme, Data and Information System, 2000], clay percentage [Global Soil Data Task, International Geosphere-Biosphere Programme, Data and Information System, 2000], and vegetation type [Ramankutty, 1999]. Atmospheric forcings are derived from monthly mean climatology paired with a stochastic weather generator. The monthly mean climatology variables required are cloudiness, precipitation rate, relative humidity, temperature, “wet” days per month, wind speed at $\sigma = 0.995$, and temperature range, which are all products of the Climate Research Unit (CRU) dataset [New et al., 1999]. The last file, minimum temperature ever recorded at a location minus the average temperature of the coldest month, used to initialize vegetation in IBIS, was created at the University of Oregon [Bartlein, 2000].
Chapter 4

Coupling IBIS with RegCM3

The coupling of IBIS to RegCM3, henceforth referred to as RegCM3-IBIS, was the main objective of this thesis. Using some information found in the codes Pal [2002], Delire et al. [2002], and Wang [2002], IBIS was coupled to RegCM3 with one subroutine responsible for interfacing the two models, as well as additional minor changes to the RegCM3 and IBIS source codes.

4.1 Methodology

A single subroutine, ibisdrv, was created to interface the two models, called at and using the same timestep as the current land surface model in RegCM3, BATS1e (RegCM3-BATS1e). Ibisdrv is responsible for five primary tasks: initialization, passing variables from RegCM3 to IBIS, passing variables from IBIS to RegCM3, restart, and output. Consideration was given to future developments of each model, and when possible, changes to the original IBIS and RegCM3 code were avoided. The following sections describe the coupling process by highlighting some of the key differences between BATS1e and IBIS, as well as discussing some of the problems encountered and key improvements made.
4.2 Gridding

The first step in coupling IBIS to RegCM3 was to bridge the gap between a vector based model (IBIS) and the two-dimensional grid used by RegCM3 (and BATS1e). In a vector based model, all points on a grid are initialized and then loaded end to end into a vector. This is easily visualized by thinking of strips of longitude (constant longitude, varying latitude) put end to end into a vector.

![Figure 4-1: Schematic of the transitions between grid and vector based models.](image)

Though RegCM3 uses a grid, it operates by longitudinal strip. For example, assume a grid that is 10 x 10. RegCM3 starts by running the first column (all 10 rows) through each subroutine, then runs the next column, and this continues until the entire domain is run, at which point the model solves the primitive equations and moves to the next timestep. As mentioned above, every measure was taken to minimize changes to the source code of both IBIS and RegCM3. So instead of forcing one model to conform to a certain style of gridding, as information is transferred from RegCM3 to IBIS, it is placed in the appropriate
location on the vector, i.e. the first strip of longitude is placed at the top of the vector, the last strip is placed at the bottom of the vector (figure 4-1). This allows the models to effectively communicate, while also permitting each to retain its native gridding scheme. Naturally, variables passed from IBIS to RegCM3 are taken from the vector and set on the original grid in the correct location (figure 4-1).

4.3 Timing

Another key change made to IBIS was dismantling the timing system. IBIS, when offline, operates as a series of nested time loops, one for hours, one for days, one for months, etc. However, RegCM3 has a variable timestep at which it calls the surface physics model, which often does not conform to a round unit of time like an hour. It was therefore necessary to remove the IBIS timing system and translate the time from RegCM3 into a form that IBIS could interpret and use, thus allowing it to call the correct subroutines at the appropriate times.

4.4 Inputs

The offline version of IBIS creates its input variables from seven files containing monthly mean climatology which are perturbed by a weather generator (subroutine weather) and used by the rest of the model. None of the datasets used by the offline version of IBIS are needed in RegCM3-IBIS, except at initialization, where climatic conditions and the distribution of biomes are required for the allocation of PFTs within the domain. Instead, twelve forcing fields are passed from RegCM3 to IBIS at every timestep. These variables are listed in figure 4-2.

The shift from prescribed atmospheric forcing to full coupling with an atmospheric model required significant changes to IBIS. This presented two key difficulties. First, in addition to the atmospheric forcing variables themselves, variables related to atmospheric forcings, such as cloudiness, needed to be found and removed. Second, certain calculations within subroutine weather are still necessary, so the subroutine could not be eliminated
completely. For example, budburst and senescence are a function of the coldest monthly temperature for the current year, a variable calculated in subroutine weather. Therefore, care had to be taken to remove all extraneous computations, but leave variables calculated from the primary fields received from RegCM3 and used later in IBIS. At any point where information was being passed from one model to the other, variables were closely examined to ensure that both models were using consistent units or that the necessary adjustments were made so that they were compatible.

Figure 4-2: Schematic of RegCM3-IBIS, including passed variables and their associated units.

4.5 Outputs

Two different types of IBIS output were adapted. First, data written to files for analysis, and second, data passed from IBIS to RegCM3. Since IBIS was added to RegCM3 as an alternate land surface model, output statements originating from the IBIS source code were essentially removed, and RegCM3 was employed to write all output files. Significant chal-
Challenges included timing and units, insuring that variables were accumulated and averaged correctly, as well as verifying the output format. The task of correctly initializing accumulation variables also deserves mention as much time was spent fixing variables, both in land and ocean grid points, that were indefinitely accumulating, causing the model to crash.

The transfer of data from IBIS to RegCM3 was handled in much the same way as the input. A list of variables passed from IBIS to RegCM3 is included in figure 4-2. In addition to transferring information from the IBIS vector to the RegCM3 grid, as discussed above, and preventing inconsistencies in units, the output from IBIS had to be meshed with output from the Zeng ocean scheme (subroutine zengocndrv).

### 4.6 Initialization

By default, IBIS always starts January 1st of the beginning year of the simulation, while RegCM3 can be initialized at any date. Because of this, certain parts of the restart subroutine in IBIS had to incorporated into the initialization subroutine of RegCM3-IBIS. The restart subroutine allows a simulation that has been discontinued prematurely, either intentionally or as a result of technical issues, to be restarted mid-simulation, thus saving time. For example, at the start of every calendar year, growing degree days is a parameter used by IBIS to assign vegetation types. To start the model November 1st and only count the growing degree days in November and December would lead to an incorrect vegetation distribution for the following year. So in this case, the IBIS restart code is used to spin-up growing degree days based on average and minimum/maximum temperatures for each grid cell from January 1st to October 31st, thus initializing the model correctly.

### 4.7 Common Blocks

A common block is a set of global variables that can be shared by two or more subroutines. Both RegCM3 and IBIS contain common blocks, and while changes to them were mostly secondary to changes in other parts of RegCM3 and IBIS, it warrants mention as it is fundamental to the correct operation of the model. Consistent with the effort to avoid
altering the source code of either model, no changes were made to the common blocks unless necessary. However, a number of identical variables exist in IBIS and RegCM3, so to prevent the models from interfering with each other when coupled, the variable names in the IBIS common blocks were changed. When constructing subroutine ibisdrv, it was preferred to give IBIS access to as few RegCM3 variables as possible, so some RegCM3 common blocks were split to restrict the access of subroutine ibisdrv. In addition, passed variables, or fields transferred explicitly from one subroutine to another, were used to further restrict the access of IBIS to the RegCM3 common blocks. Note that no part of the original IBIS code has access to any RegCM3 common block, and vice versa, so the subroutine ibisdrv is truly the only interface that allows data to pass between the two models.

4.8 Vegetation

The first scheme implemented for initializing vegetation was based on the GLCC dataset used by BATS1e. In this approach, the BATS1e vegetation dataset was interpolated to the desired grid, and then each BATS1e land cover type was assigned an equivalent IBIS biome when the land surface model was initialized. While this is a reasonable method, there are differences in the way that each model manages vegetation. IBIS uses fifteen biomes and twelve PFTs as discussed in section 3.5. Each grid point is given a biome, then, based on environmental variables, is populated with one or more PFTs. BATS1e, detailed in section 2.8, uses twenty land cover classes. Read in from the initialization file created during preprocessing, each of the twenty classes is assigned its own set of attributes, such as albedo, roughness, minimum stomatal resistance, etc. Thus while using BATS1e land cover classes to set IBIS biomes is adequate, it is not an ideal solution.

To address this, the vegetation dataset used by the offline version of IBIS was added to the RegCM3 preprocessor, allowing IBIS biomes to be assigned during initialization. Two additional biomes, inland water and ocean, were added to the set of biomes contained in the offline version. Originally the offline version of IBIS skipped all water points, and this is still the case in RegCM3-IBIS, however it is necessary to include ocean and inland water biomes for the ocean and lake parameterizations in RegCM3. While using BATS1e land
cover classes to assign IBIS biomes is still possible in the current version of the program, it is not used in any of the simulations presented in this study.

4.9 Soil

Another change to the preprocessing of RegCM3-IBIS is the way in which soil types are defined. As discussed in section 2.8, for BATS1e soil type and classification are determined by vegetation type. In IBIS, two files are read in, one containing the percentage of clay and the other the percentage of sand. This data is then interpolated to the RegCM3 grid and assigned physical properties, such as porosity, albedo, density, etc., based on the clay and sand fractions.

Additionally, a new scheme for initializing soil moisture and temperature is available in RegCM3-IBIS. The vast majority of models initialize the total soil water in a column using porosity, which is dependent on soil type, and a constant value for the fraction of pore space occupied by water. Soil temperature is generally set to a constant value for all soil layers at initialization. Surface soil layers lose these initial conditions rapidly, in a matter of days, while deeper soil layers can be influenced by initial soil conditions for months or even years. Models are commonly allowed to spin-up, which involves running the model for a short period of time before the desired start date of the simulation (the length varies, generally a few weeks), but discarding the data in an attempt to flush the initial conditions from the model and prevent them from influencing the results.

Using IBIS offers a unique opportunity to initialize soil moisture and temperature with a more accurate methodology. Because IBIS is available as an offline model, forced using prescribed atmospheric data, it can be run for decades relatively inexpensively with respect to computational time. By modifying the offline version of IBIS, it is possible to output the soil moisture, soil ice, and soil temperature for each soil layer. This data can then be used in the initialization subroutine of RegCM3-IBIS (subroutine soil2rcm), allowing for a more correct (according to the offline version of IBIS) initialization of soil moisture and temperature. Note that this added feature also has the ability to initialize soil ice, so when RegCM3-IBIS is started in a month where frozen water is present in the soil column, it will
initialize the proper amount and distribution (according to the offline version of IBIS) of both soil ice and water in each layer.

4.10 Initialization Datasets

Three land surface datasets are used to initialize RegCM3-IBIS. Elevations are derived from the USGS GTOPO30 global digital elevation model (DEM), which has a spatial resolution of 30 arc seconds [United States Geological Survey, 1996]. Sand and clay fractions are provided by the Global Soil Dataset, created by the International Geosphere-Biosphere Programme, Data and Information System (IGBP-DIS). The spatial resolution of this dataset is 5 minutes and it is distributed by Oak Ridge National Laboratories (ORNL) [Global Soil Data Task, International Geosphere-Biosphere Programme, Data and Information System, 2000]. Finally, the potential global vegetation of Ramankutty [1999] is used to initialize vegetation. This dataset is model output, and it is not derived from any observed field (besides the observations of atmospheric variables used in the data that forces the model). In addition to the land surface datasets, two additional climatic datasets, one containing the minimum temperature ever recorded at a location minus the average temperature of the coldest month, and the other containing monthly mean temperatures (climatology), are needed. The sources for these two datasets are: Department of Geography, University of Oregon [Bartlein, 2000], and The Climate Research Unit (CRU) 1961-90 mean monthly terrestrial climatology dataset [New et al., 1999], respectively.

4.11 Additional Notes

Subroutine soil2rcm, part of the RegCM3-IBIS preprocessor, is also responsible for interpolating the two climatic datasets discussed above necessary to establish the distribution of PFTs within each biome to the RegCM3 grid.

While many numerical models are tuned in an attempt to match model results to observations, this was not done for any of the simulations presented in this thesis. This includes explicit changes to flows of energy and water, such as “flux adjustments” used by many
GCMs, as well as parameter tuning, or changing the parameters used in the schemes of RegCM3 and/or IBIS to improve results. All parameters (Appendix A.1, A.2, A.3) were set to the default values for both models, which coincided in most cases with the parameters (for RegCM3 only) used in the experiments of Pal [2001].
Chapter 5

Assessment of Coupled Model

The following chapter details the assessment of RegCM3-IBIS compared to RegCM3-BATS1e using two datasets: NCEP reanalysis and National Aeronautics and Space Administration-Langley Research Center Surface Radiation Budget (NASA-SRB). Special attention was paid to the radiation and hydrologic budgets, as the success of a climate model is rooted in the correct representation of these two balances.

5.1 Design of Numerical Experiments

Six 1-year simulations were completed to assess the performance of RegCM3-IBIS. To maintain a standard approach for testing newly coupled parameterizations, the structure of the simulations is consistent with the benchmarking of SUBEX by Pal [2001]. Centered at 40°N, 100°W, using a Lambert Conformal projection, and spanning 90 points zonally, 60 points meridionally at a spatial resolution of 60 km, the domain covers all of the United States, as well as parts of Mexico and Canada (figure 5-1). Each simulation lasted one year and was initialized on March 15th, with the first 17 days being ignored to allow the model to spin-up. The years simulated were: 1986, 1987, 1988, 1989, 1990, and 1993; with 1986, 1987, 1989, and 1990 being average years in terms of summer precipitation; 1993 having above average rainfall (flood); and 1988 having below average rainfall (drought). Each of the six 1-year experiments was performed using RegCM3-IBIS and RegCM3-BATS1e. Boundaries were forced under the exponential relaxation of Davies and Turner [1977]
Figure 5-1: Domain and topography used for numerical simulations.
using the NCEP reanalysis 2 dataset. Interpolated from a 2.5° x 2.5° grid with 17 vertical levels and a temporal resolution of 6 hours, this dataset is based on NCEP reanalysis 1, but rectifies some errors and includes updated parameterizations of physical processes [Ebisuzaki, 2005]. In addition, Pal improved the interpolation of the NCEP datasets to include a correction for the Gibbs phenomenon, which is a product of the spectral to latitude-longitude transformation that adds noise to surface fields [2001].

Sea surface temperatures (SSTs) were prescribed using the NOAA OISST dataset, which has a spatial resolution of 1.0° x 1.0° and is averaged on a weekly basis [Reynolds et al., 2002]. This dataset relies on in situ and satellite SSTs, as well as SSTs simulated from sea-ice cover [Reynolds et al., 2002].

For RegCM3-IBIS, vegetation was assigned using the potential global vegetation dataset of Ramankutty [1999], while for RegCM3-BATS1e, vegetation was initialized using the GLCC dataset of USGS [1997]. Although the disparity between potential and observed vegetation is an important difference between the two sets of simulations, the effects of this were not examined in this study. Topography for both models was given by the USGS GTOPO30 dataset [1996] aggregated to a 0.5° x 0.5° spatial resolution. To initialize soil moisture, soil temperature, and soil ice for RegCM3-IBIS, a global 0.5° x 0.5° 15-year offline IBIS simulation starting in 1980 was used.

5.2 Evaluation Datasets

In order to assess the performance of RegCM3-IBIS, a dataset was needed that contained all facets of both the energy and water budgets over the entire United States. While ideally observations would be used, this data is simply not available. Therefore RegCM3-IBIS was assessed first and foremost by comparison to the NCEP reanalysis 1 dataset, which has global spatial coverage on a T62 Gaussian grid with 192 x 94 points [Kalnay et al., 1996]. NCEP reanalysis 2 was not used because it is primarily available for atmospheric fields, missing key surface fluxes needed for a complete evaluation. The NASA-SRB dataset [Darnell et al., 1996; Gupta et al., 1999] was used for assessing some aspects of the radiation budget for dates available. NASA-SRB is primarily derived from two sources: the
International Satellite Cloud Climatology Project C1 dataset (ISCCP-C1), which provides information on cloud amount and distribution [Rossow and Schiffer, 1991]; and the NASA Earth Radiation Budget Experiment (ERBE) dataset, which contains satellite based measurements of top of atmosphere (TOA) fluxes [Barkstrom, 1984]. NASA-SRB provides a partial energy budget, including net shortwave radiation and net longwave radiation, both used in this study.

5.3 Results: RegCM3-BATS1e vs. RegCM3-IBIS

All direct comparisons of RegCM3-IBIS and RegCM3-BATS1e are presented as a pair of scatter plots that show the observed or reanalysis value of a specific variable (x-axis) versus the simulated value (y-axis). Sources of data are clearly cited in the title and caption. Monthly averages are used, and each number represents the corresponding month (i.e. 1 is January, 12 is December). All six years of monthly averages, or 72 points total for NCEP (60 for NASA-SRB), are included in each plot and no differentiation is made between the same month in different years. The diagonal line represents a perfect correlation and additional statistical information, including root mean squared error (RMSE), bias (Bias), and slope of the best-fit line for the simulated values (m), is shown.

In all presented data, a cropped domain is used (figure 5-2). From the original domain of 60 x 90 points, one point on each edge is allocated for boundary conditions (2:59, 2:89), and is therefore not included in the output. To further mitigate the effects of boundary conditions on the results, an additional four points, or 240 km, were removed from each edge (6:53, 6:83).

5.3.1 Radiation Budget

Correct representation of the energy budget is important to any climate model. Using a basic surface energy balance
Figure 5-2: Domain and topography of presented results.

\[ S(1 - \alpha) + LW^\downarrow - LW^\uparrow = \lambda E + H + G \]  

(5.1)

where \( G \) is the heat flux into or out of the ground, \( S \) is the incident shortwave radiation, \( \lambda E \) is the latent heat flux, \( \alpha \) is the albedo, \( H \) is the sensible heat flux, \( LW^\downarrow \) is the longwave radiation toward the surface, and \( LW^\uparrow \) is the longwave radiation away from the surface. Assuming a negligible contribution by \( G \) (\( G \approx 0 \)), which was confirmed for both models, the remaining five components sum to \( \approx 0 \). A total of six plots are contained in this section. Four contrast the performance of RegCM3-IBIS and RegCM3-BATS1e with respect to NCEP reanalysis, while the other two contain comparisons of the models based on NASA-SRB for the dates available (1987, 1988, 1989, 1990, 1991).

For net shortwave radiation, RegCM3-BATS1e performs slightly better than RegCM3-IBIS based on RMSE with respect to NCEP (figure 5-3), with values of 12.07 W/m\(^2\), 13.39 W/m\(^2\), respectively, and significantly better when compared to NASA-SRB (figure 5-4), where the RMSE value for RegCM3-IBIS is 29.39 W/m\(^2\) and the value for RegCM3-BATS1e is 21.56 W/m\(^2\). Both models are in better general agreement with NCEP reanalysis data. Overall, and especially during the months of June, July, and August, there
Figure 5-3: Plot of simulated net shortwave radiation in W/m$^2$ (y-axis) vs. NCEP reanalysis data (x-axis). Each number is a temporal average over the month indicated, and is derived from a spatial average over the domain shown in figure 5-2, not including water points. (a) RegCM3-IBIS; (b) RegCM3-BATS1e.

Figure 5-4: Plot of simulated net shortwave radiation in W/m$^2$ (y-axis) vs. NASA-SRB data (x-axis). Each number is a temporal average over the month indicated, and is derived from a spatial average over the domain shown in figure 5-2, not including water points. (a) RegCM3-IBIS; (b) RegCM3-BATS1e.
is a clear excess of solar radiation absorbed by RegCM3-IBIS regardless of the evaluation dataset used, which is reflected in a 7.72 W/m$^2$ bias when compared to NCEP, and a 24.69 W/m$^2$ bias when evaluated using NASA-SRB. While RegCM3-BATS1e also has a surplus of shortwave radiation absorbed during the summer months, over the rest of the year it tends to absorb less solar radiation, showing an overall negative bias of -2.47 W/m$^2$ when compared to NCEP, and a smaller positive bias of 14.62 W/m$^2$ when compared to NASA-SRB.

Examination of the vegetation distributions and their associated albedos, as well as of the incident solar radiation lends insight into the differences in net solar radiation between the two models. While both models receive approximately the same amount of incident solar radiation, BATS1e has an overall higher albedo than IBIS, and thus reflects more energy than IBIS. As noted above, a possible explanation for divergent results, especially in albedo, is the use of different datasets to initialize vegetation for each model.

This excess absorption of solar radiation, present in the NCEP figure (5-3) and more dramatically in the NASA-SRB figure (5-4), is one of the primary contributing factors to the overestimation of 2 m temperature, sensible heat flux, and longwave radiation flux observed in the RegCM3-IBIS simulations.

An observation supplementary to the benchmarking of the two models is the large difference in the evaluation datasets. While both have their strengths, and were included in this analysis for different reasons, the disparity shown does prompt questions as to the extent to which each dataset should be used as a benchmark, or “truth”. The features of both datasets are outlined above, and are used as the best datasets available for evaluating simulations. As the NASA-SRB dataset is observationally based, it is likely the more accurate assessment of net shortwave and longwave radiation.

In general, both models do a relatively poor job of simulating longwave radiation with respect to the NCEP reanalysis (figure 5-5) and NASA-SRB (figure 5-6) datasets. Compared with NCEP reanalysis, RegCM3-BATS1e shows a negative bias (-7.26 W/m$^2$), often underpredicting longwave radiation for the non-summer months. In addition, the seasonal variability simulated by RegCM3-BATS1e is much greater than that present in NCEP reanalysis or NASA-SRB, which is also the case for RegCM3-IBIS. RegCM3-IBIS, when
Figure 5-5: Plot of simulated net longwave ($LW^\uparrow - LW^\downarrow$) radiation in W/m$^2$ (y-axis) vs. NCEP reanalysis data (x-axis). Each number is a temporal average over the month indicated, and is derived from a spatial average over the domain shown in figure 5-2, not including water points. (a) RegCM3-IBIS; (b) RegCM3-BATS1e.

Figure 5-6: Plot of simulated net longwave ($LW^\uparrow - LW^\downarrow$) radiation in W/m$^2$ (y-axis) vs. NASA-SRB data (x-axis). Each number is a temporal average over the month indicated, and is derived from a spatial average over the domain shown in figure 5-2, not including water points. (a) RegCM3-IBIS; (b) RegCM3-BATS1e.
evaluated using NCEP reanalysis, has a smaller bias (6.53 W/m²), but a larger RMSE (15.56 W/m²) than RegCM3-BATS1e. When benchmarked using NASA-SRB, RegCM3-IBIS has a larger bias and RMSE (19.00 W/m², 22.11 W/m²) than RegCM3-BATS1e (5.22 W/m², 9.64 W/m²).

The values for longwave radiation are closely associated with those for net shortwave radiation, clearly seen in the biases of figures 5-3 through 5-6. For RegCM3-BATS1e evaluated using NCEP, a negative bias in both net shortwave and longwave radiation is found, while in the rest of the figures, a positive bias in the net shortwave radiation and a positive bias in the net longwave radiation is present. This is logical, as additional shortwave radiation will increase the amount of shortwave radiation reflected by the surface and raise the surface temperature, increasing the amount of longwave radiation emitted by the surface. Exacerbating this bias, as discussed below, is a deficit of latent heat flux in the RegCM3-IBIS model, especially evident during the summer months.

![Figure 5-7: Plot of simulated latent heat flux in W/m² (y-axis) vs. NCEP reanalysis data (x-axis). Each number is a temporal average over the month indicated, and is derived from a spatial average over the domain shown in figure 5-2, not including water points. (a) RegCM3-IBIS; (b) RegCM3-BATS1e.](image)

The correct simulation of latent heat flux is key to a model’s ability to simulate correct energy and water budgets (figure 5-7). Both the bias and RMSE found using RegCM3-
BATS1e (-7.02 W/m$^2$, 8.5 W/m$^2$) are much smaller than the bias and RMSE in the RegCM3-IBIS results (-20.23 W/m$^2$, 22.25 W/m$^2$). Both models have a negative bias when compared to NCEP reanalysis, indicating that not enough evapotranspiration occurs. The bias for RegCM3-BATS1e seems to have no distinct seasonality, while in RegCM3-IBIS, there is clearly a larger deficit of latent heat flux during the summer months.

The incorrect representation of latent heat flux is the most critical weakness of RegCM3-IBIS. With trickle down effects on sensible heat, temperature, longwave radiation, vegetation distributions, etc., the underestimation of latent heat flux is a deficiency in the model that must be addressed.

This problem was noted early in the coupling process, and much effort was spent running simulations of RegCM3-IBIS, RegCM3-BATS1e, and the offline version of IBIS changing parameters, vegetation, initial conditions, and parameterizations to insure that each model and the coupling were performing correctly. In addition, an attempt was made to identify the key differences between RegCM3-BATS1e and RegCM3-IBIS responsible for the discrepancy in simulated latent heat flux. Throughout this process, no evidence was found indicating that a gross error exists in either model or the coupling.

Rather, the problem seems to be a result of the synergy formed between the tendency of RegCM3 to overestimate solar incident radiation and IBIS to underestimate evapotranspiration that, via a positive feedback, causes RegCM3-IBIS to underestimate latent heat flux, overestimate 2 m temperature, and overestimate sensible heat flux. The evaluation of the model’s ability to simulate net shortwave radiation clearly shows that regardless of the benchmark, RegCM3-IBIS receives excess energy. A sensitivity analysis with respect to incident shortwave radiation showed that when incoming solar radiation was reduced by approximately 10% during the summer months, making the net shortwave radiation conform roughly to NASA-SRB values, RegCM3-IBIS did a much better job of simulating the energy and water budgets. Contrasting the reduced incident solar radiation simulations with the control simulations presented here shows RegCM3-IBIS partitions most excess incoming shortwave radiation to sensible heat, while RegCM3-BATS1e partitions it to latent heat. This does not capture the entire problem however, as additional simulations have shown that RegCM3-IBIS systematically underpredicts latent heat flux. More information
on this problem and its implications for use of this model can be found in the section 6.2.

![Figure 5-8: Plot of simulated sensible heat flux in W/m² (y-axis) vs. NCEP reanalysis data (x-axis). Each number is a temporal average over the month indicated, and is derived from a spatial average over the domain shown in figure 5-2, not including water points. (a) RegCM3-IBIS; (b) RegCM3-BATS1e.](image)

Both models overestimate sensible heat flux, which is a logical extension of the underestimation of evapotranspiration (figure 5-8). As RegCM3-IBIS has a larger deficit of latent heat flux compared with NCEP, it also has a larger excess of sensible heat, especially during the summer months. This is reflected in the bias (23.66 W/m²) and RMSE (24.71 W/m²) present in the RegCM3-IBIS results, which are significantly larger than the bias (15.10 W/m²) and RMSE (16.17 W/m²) of RegCM3-BATS1e.

The positive bias in the sensible heat flux of RegCM3-IBIS is one of the effects of the underestimation of evapotranspiration discussed above. Indeed, the positive sensible heat flux bias is approximately equal to the negative latent heat flux bias in RegCM3-IBIS. Figure 5-8 also shows a systematic overestimation of sensible heat flux in both models, which is consistent with the underestimation of latent heat flux shown in figure 5-7.

### 5.3.2 Water Budget

Closely tied to the energy budget is the water budget, which can be written as
\[ P = \lambda E + R \]  

(5.2)

where \( P \) is precipitation, \( \lambda E \) is evapotranspiration, and \( R \) is runoff. Note here that runoff is treated in a very rudimentary way, and overland flow is not explicitly represented in RegCM3-IBIS or RegCM3-BATS1e. In this section, two plots are presented that assess the performance of RegCM3-IBIS and RegCM3-BATS1e using NCEP reanalysis data. Both plots, the former evaluating total rainfall, the latter runoff, are consistent with the format described above.

Figure 5-9: Plot of simulated precipitation in mm/day (y-axis) vs. NCEP reanalysis data (x-axis). Each number is a temporal average over the month indicated, and is derived from a spatial average over the domain shown in figure 5-2, not including water points. (a) RegCM3-IBIS; (b) RegCM3-BATS1e.

For total precipitation, RegCM3-IBIS has a larger RMSE (0.7 mm/day), but a much smaller bias (-0.007 mm/day) than RegCM3-BATS1e (0.57 mm/day, 0.32 mm/day) (figure 5-9). In late winter and early spring months, both models tend to overestimate precipitation. RegCM3-IBIS substantially underestimates the amount of rainfall for late spring and summer months, likely an effect of the lack of evapotranspiration. Overall RegCM3-BATS1e has a wet bias, but like RegCM3-IBIS it does underestimate rainfall during the
mid-summer months.

Figure 5-10: Plot of simulated runoff in mm/day (y-axis) vs. NCEP reanalysis data (x-axis). Each number is a temporal average over the month indicated, and is derived from a spatial average over the domain shown in figure 5-2, not including water points. (a) RegCM3-IBIS; (b) RegCM3-BATS1e.

RegCM3-IBIS has both a smaller bias (0.09 mm/day) and RMSE (0.21 mm/day) than RegCM3-BATS1e for runoff (figure 5-10). As expected from the overestimation of precipitation by RegCM3-BATS1e, runoff is also overestimated, which is apparent in the bias (0.3 mm/day). Worst in early spring months, RegCM3-BATS1e predicts excess runoff for almost all months examined. RegCM3-IBIS also has a slight positive bias, and like RegCM3-BATS1e, severely overpredicts runoff in early spring.

It is worth noting that RegCM3-IBIS, RegCM3-BATS1e, and NCEP reanalysis are not especially adept at simulating runoff or precipitation, and in future studies, observational datasets will be used to assess these fields.

5.3.3 Surface Temperature

Surface temperature is the variable most often used to benchmark models, as it is both intuitive and a good proxy for the accuracy of both the simulated water and energy budgets.

Compared with NCEP, both models overestimate temperature throughout the year, with
a slight increase in the positive bias occurring during the summer months, more apparent in RegCM3-IBIS (figure 5-11). RegCM3-IBIS has both a larger bias (3.50 K) and RMSE (3.58 K) with values shifted up and to the left when compared with RegCM3-BATS1e, which has a bias of 1.58 K and a RMSE of 1.68 K.

Explained with reference to the results above, the higher temperatures seen in RegCM3-IBIS are a result of the underestimation of evapotranspiration, which allows more energy to warm the surface. This both increases the 2 m temperature and ultimately causes an increase in the sensible heat and longwave radiation fluxes from the surface.
Chapter 6

Summary of Results and Future Work

6.1 Summary of Results

In this thesis, RegCM3-IBIS is presented as an alternative to RegCM3-BATS1e. To assess the performance of this newly coupled model, six simulations each lasting one year were completed both for RegCM3-IBIS and RegCM3-BATS1e. NCEP reanalysis data was used to evaluate RegCM3-IBIS and RegCM3-BATS1e for all variables to provide one simple and complete framework to assess both models. Where and when available, NASA-SRB data was used to supplement the analysis with observational data. By comparison to these two datasets, the relative improvement or deterioration of RegCM3-IBIS was assessed.

RegCM3-IBIS does not improve the simulation of the energy and water budgets. The underestimation of latent heat flux cascades down the model, with primary effects on the values of sensible heat flux, longwave radiation flux, and temperature, as well as secondary effects on variables such as precipitation, runoff, cloudiness, net primary production, etc. RegCM3-BATS1e outperforms RegCM3-IBIS in most all fields, regardless of the dataset used to benchmark.

It is important to reiterate that some explicit and implicit tuning has occurred with RegCM3-BATS1e. Explicit tuning is adjusting any number of parameters to specifically help RegCM3-BATS1e more accurately simulate the current climate. Implicit tuning involves model improvements. For example, parameters in a new convection scheme may be altered to improve a simulation. This tuning is done with respect to the current param-
eterizations available, which in the past has only been BATS1e for land surface processes. RegCM3-IBIS was coupled and assessed leaving all parameters at their default values for both models.

6.2 Future Work

There is a clear opportunity for improvement of the ability of RegCM3-IBIS to simulate latent heat flux. A comprehensive assessment of variables used to calculate evapotranspiration, with focus on stomatal and aerodynamic resistances, is necessary to expose the deficiencies in RegCM3-IBIS and create a more mechanistically accurate surface physics model. Complementary to corrections of the latent heat flux computations in IBIS, the overestimation of incoming solar radiation in RegCM3 should be addressed.

In addition to modifications of the fundamental calculations in each model, some implementation changes and additions are needed. The option to restart a simulation should be included. A feature of both RegCM3-BATS1e and the offline version of IBIS, the ability to restart a run that has ended prematurely, either intentionally or as a result of a system crash, is essential to making RegCM3-IBIS a feasible option for computationally intensive runs.

Third, the lake model of Small and Sloan [1999], available when running RegCM3-BATS1e, has not yet been integrated into RegCM3-IBIS. The inclusion of this model would allow for an explicit and more accurate treatment of larger lakes.

Fourth, a new vegetation dataset, which reflects the current land use as opposed to potential vegetation, should be compiled for use with RegCM3-IBIS. In addition to a redistribution of currently existing PFTs, the creation of new PFTs that describe human land uses, such as agricultural land and urban areas, would create a more accurate vegetation distribution and ultimately a more realistic surface physics model.

Fifth, an explicit representation for groundwater would be an improvement over both RegCM3-IBIS and RegCM3-BATS1e. The inclusion of a water table and groundwater flow would create a more realistic parameterization of subsurface water behavior, which would in turn increase the accuracy of fluxes into and out of the surface, as well as the interactions
between the soil and vegetation.

Finally, more information with respect to actual energy and water budgets, specifically latent and sensible heat fluxes, soil moisture, precipitation, and runoff, is needed. While only a limited amount of time was spent in this analysis finding the best dataset with which to compare simulations, more datasets based on surface observations, satellite data, and reanalysis data will be used in the future to evaluate the performance of RegCM3-IBIS.
### Appendix A

#### Tables

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<th>Parameter</th>
<th>$C_i$ (Broadleaf)</th>
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<th>$C_i$</th>
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<td>4500 (-5000)</td>
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<td>$1.5 \times 10^4$ (6000)</td>
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<td>(3000)</td>
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Table A.1: IBIS plant physiology parameter values [Foley et al., 1996].
Table 2: BATS vegetation/land-cover

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<th>Parameter</th>
<th>Land Cover/Vegetation Type</th>
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</thead>
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<tr>
<td>Max fractional vegetation cover</td>
<td>0.85 0.80 0.80 0.80 0.80 0.90 0.80 0.00 0.60 0.80 0.35 0.00 0.80 0.00 0.00 0.80 0.80 0.80 0.80 0.80</td>
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<td>Difference between max fractional vegetation cover and cover at 269 K</td>
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<td>Roughness length (m)</td>
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<td>Displacement height (m)</td>
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Table A.2: Parameters for BATS1e [Elguindi et al., 2004].
Table A.3: Climatic constraints and vegetation dynamics parameters used in IBIS [Foley et al., 1996].

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<tr>
<th>Plant Type</th>
<th>Woody Plant Types (degrees C)</th>
<th>Midsummer</th>
<th>Warm Grasses (degrees C)</th>
<th>Cool Grasses (degrees C)</th>
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<td>17.5</td>
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Note: The values in the table represent the climatic constraints and vegetation dynamics parameters used in IBIS for various plant types. The table includes columns for Woody Plant Types, Midsummer, Warm Grasses, Cool Grasses, Subtropical Coniferous Forests, and Tropical Dry Forests.
Appendix B

Figures
Figure B-1: IBIS state description [Foley et al., 1996].
Figure B-2: Schematic of IBIS land surface module including primary variables calculated [Foley et al., 1996].
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