A Novel Approach to Simulating Land Use Impacts on Regional Climate and Ecosystem Services

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Abstract and Introduction

In order to quantify the impact of shifts in land use patterns on the climate, a complementary approach to global climate models (GCMs) has been developed. The model presented here is specifically designed to investigate the impacts of changing land use on the earth's surface and lower atmosphere. It is capable of testing the impact of an ensemble of land use scenarios quickly and easily with limited input requirements. Here we present a comparison of the modeled land surface and atmospheric boundary layer variables to several field experiment observation sites, as well as initial studies on impacts of a variety of land-use perturbations on regional climate.

The motivation for the development of this model comes from observations that use of land by humans has become a strong forcing on the global climate system. Since 1850, changes in anthropogenic land use have accounted for nearly 35% of global CO2 emissions, and croplands and pastures have now become one of the largest biomes on earth (Foley et al 2005). While the carbon emissions associated with land use change are critical, the impact of changing land cover on earth's climate is not limited to the sequestration or release of carbon. Conversion of natural biomes to croplands or pastures also upsets the services that an ecosystem provides by perturbing the surface water, energy and momentum balances.

Historically, the tool used to investigate the impacts of changing land use has been the GCM. However, GCM experiments can be both expensive to run and difficult to interpret. In addition, the strength of GCMs lie in their ability to simulate changes of large-scale patterns and circulations of the climate system over long periods of time, and not local and regional scales where results are commonly biased relative to observations. The model presented in this work attempts to alleviate some of these problems. This is partially achieved through the following highlights of the model:

- o A data driven land surface model that has been simplified to the basic physics necessary to accurately reproduce observed seasonal cycles of fluxes and state variables for both natural biomes and croplands/pastures.
- o A bulk quasi 3-D boundary layer model that maintains the first order response of the lower atmosphere state variables to changing land surfaces, but discards secondary 3-D effects.
- o Land cover and phenology that can be easily manipulated.
- o Statistical impacts of land use change on precipitation using data described in Dirmeyer and Brubaker (1999)

The simplicity of our new model comes at the cost of assuming that changes to the land cover are relatively small perturbations to the overall climate. This model does not currently simulate circulation changes in the atmosphere, ocean or sea ice that are important to the distribution and balance of earth's long-term global energy budget. However, for many applications associated with land use scenarios this assumption is valid.

Model Objectives and Poster Focus

As shown in figure 1, the current extent of Earth's usable land appropriated for use by humans now stands at approximately 40% (Foley 2005), rivalling global forests in extent. The large majority of this area is appropriated for the production of food necessary to feed 6.7 billion people. While the Green Revolution that began in the 1960's has nearly doubled the global food yield with only a 12% increase in cropland, it has also led to environmental concerns such as large-scale salinization, soil erosion, and loss of native vegetation. With global population expected increase to approximately 9 billion by 2050, it is inevitable that the alterations of the world's will continue. These alterations will directly impact the goods and services that are provided by present vegetation. This work focuses on modeling and assessing changes in ecosystem goods and services associated with land use changes.

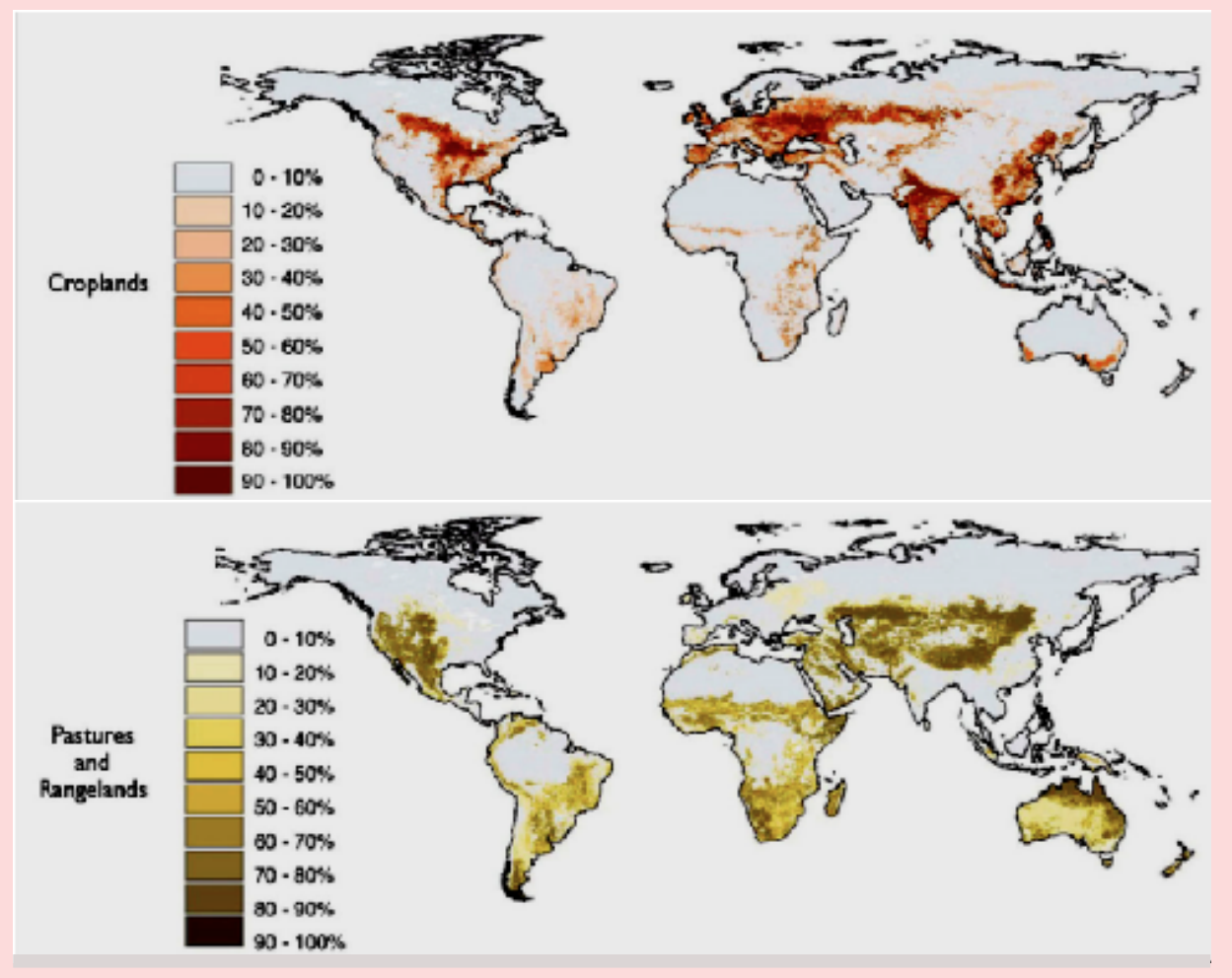

Figure 1: The worldwide extent of human land use change. The map gives the extent of croplands (top) and pastures and rangelands (bottom). (From Foley 2005 [1])

- ***The underlying philosophy here is that a niche exists for a simple model designed to test the first order impacts of land use scenarios on regional to global scales***
- This model provides a toolbox with the following emphasis:
  - -captures first order features associated with land use change
  - -key attributes such as land type and phenology can be simply manipulated
  - -model is computationally inexpensive with modular code, allowing researchers from a variety of disciplines to access, modify and run an ensemble of scenarios
- ***This poster will focus on our model's representation of the boundary layer, and how land-atmosphere interactions in the tropical rainforest are impacted by land use.***

Model Properties

In the past, the common tool used to explore the impacts of large scale land use change was the GCM. While the GCM is incredibly powerful, the cost of simulating the earth system is high and resolution is low. Here we take a complementary approach, by specifying the mean climate, and assuming that land use changes represent relatively small perturbations on the global climate. This allows us to greatly simplify our model by reducing the atmosphere to the region directly interacting with the land.

We use a bulk model similar to that of [4] to represent the convective boundary layer and interaction of the land with the atmosphere. A schematic of the bulk model is shown in figure 2.

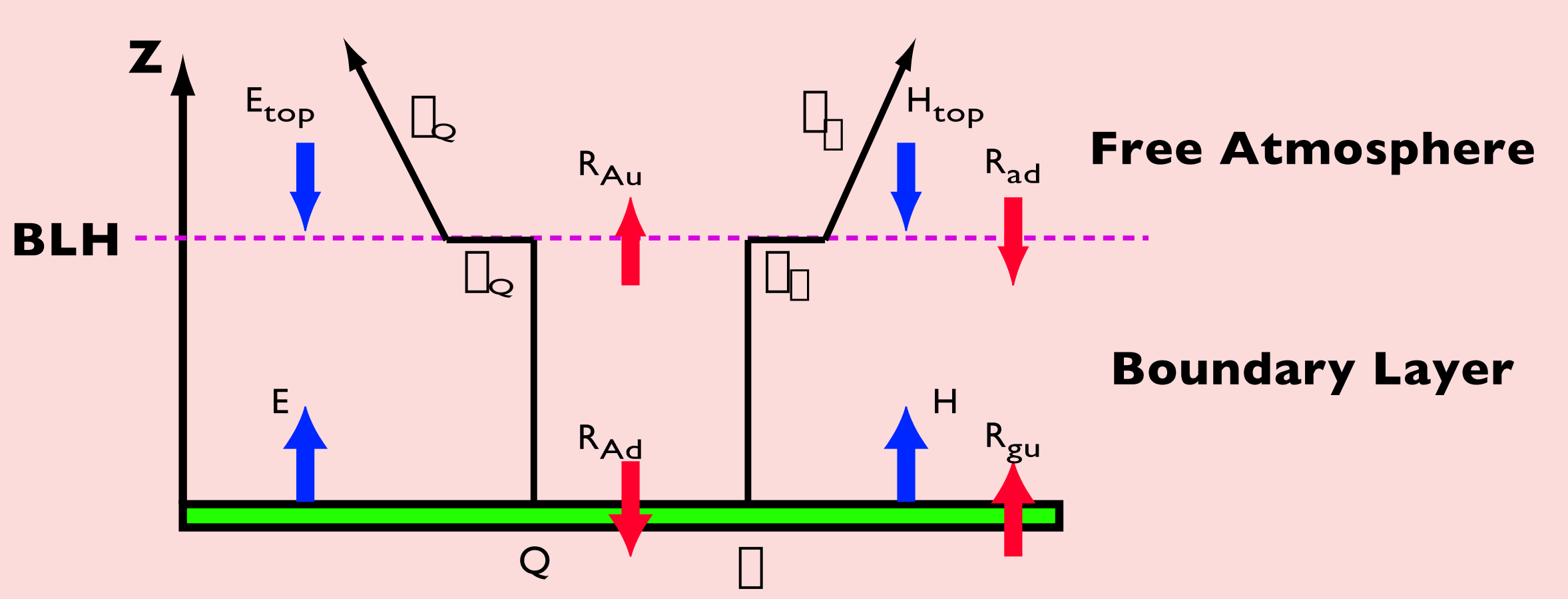

Figure 2: Schematic of boundary layer model. Blue arrows represent sensible and latent heat fluxes into the boundary layer. Red arrows are radiation energy fluxes into and out of the boundary layer. The black lines indicate the general profiles of water vapor (Q) and PT (q). d designates a discrete jump at the boundary layer, and g represents gradients of Q and PT above the boundary layer.

The surface fluxes change the energy and water content of the boundary layer. As these fluxes change through the day, the boundary layer height rises entraining dry warm air from the free atmosphere above. In addition, radiative effects are also included. At night the boundary layer collapses back to climatological values.

In addition to the boundary layer form there are a host of other properties important to this model. Some of the key properties include:

- .16 x .16 degree resolution
- Daily timestep (except boundary layer and radiation modules, which use variable timestep that depend on the length of day and hence latitude)
- Penman- Monteith estimation of evapotranspiration
- Assume perfect surface energy balance with surface energy storage = 0
- Constant Bowen Ratio assumption
- Driven by 30 year CRU temperature, precipitation, and cloud cover data.

Treatment of Precipitation

One aspect of land use change that is clear, is that as land cover changes the amount of water that is evaporated into the atmosphere also changes. This will have nonlocal impacts on precipitation. With the importance of precipitation to human enterprise, it is vital that our model is capable of estimating this change. In the absence of an atmospheric circulation model, we use a statistical model to estimate precipitation impacts.

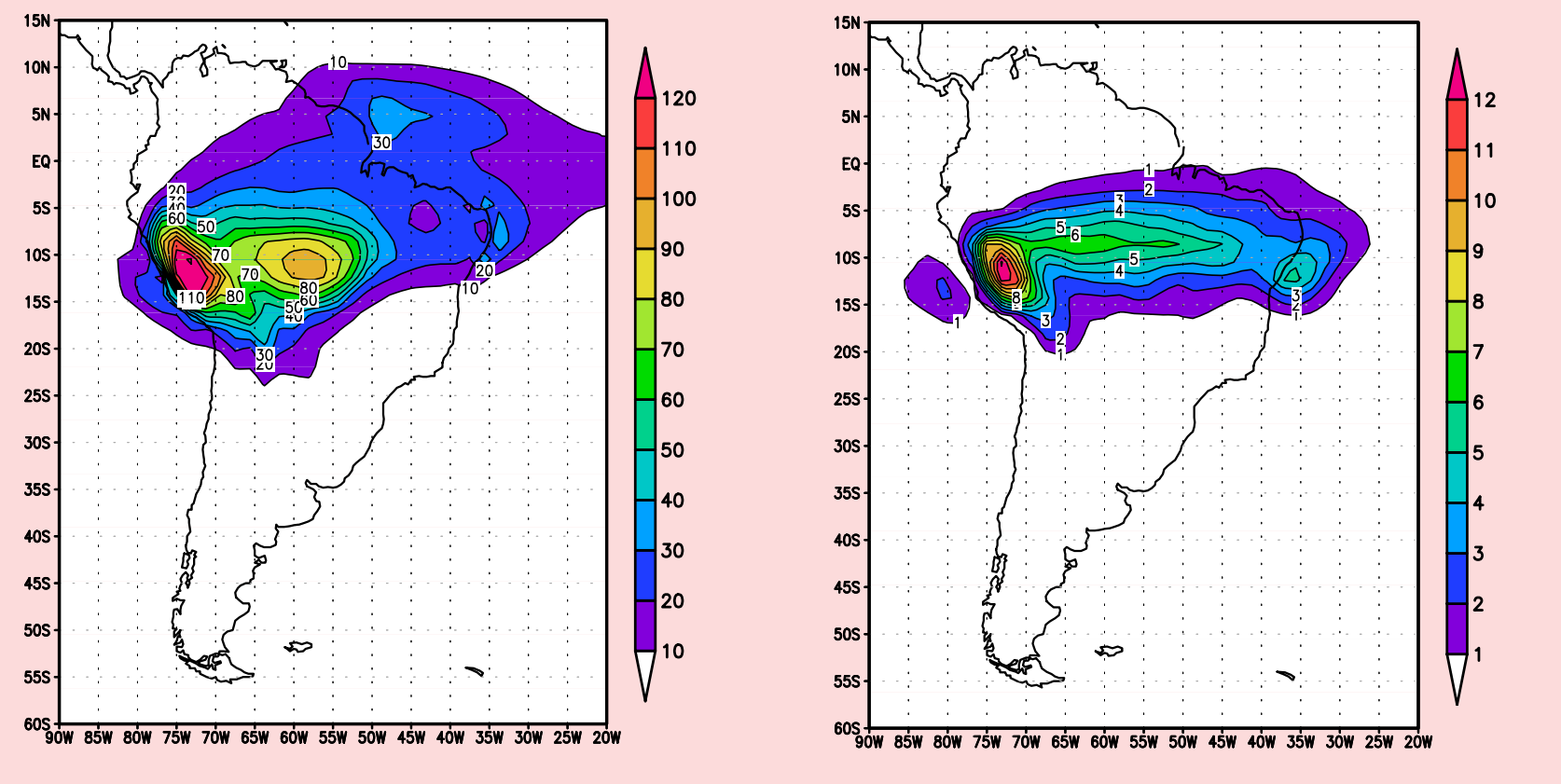

Figure 3: January (left) and July (right) evaporative source(mm) for 12S 72W.

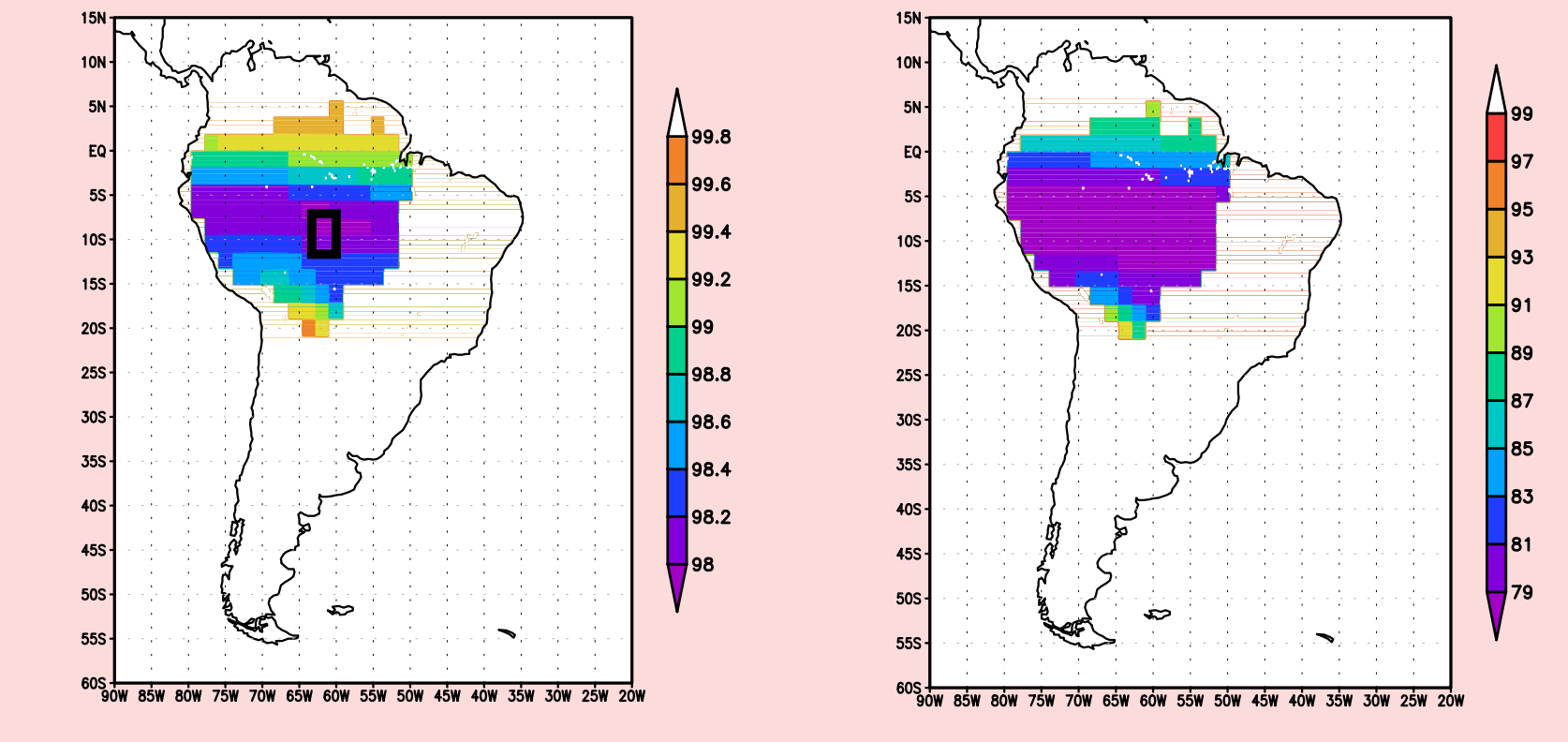

Figure 4: Percent change in Amazon Basin precipitation as a result of deforesting the region (left) 7S–12S and 63W–60W (black box), and (right) total deforestation.

Summary of Statistical Precipitation

- Dirmeyer et al [2] describes a model-data fusion technique that produces evaporative source maps for each grid point on a T42 map
- The evaporative source shows where the precipitation that falls at a given location originally evaporated from (figure 3)
- We use these maps as an influence function to calculate changes in remote precip as land cover change shifts the surface water balance (figure 4)
- Assumes no changes in atmospheric circulation or local convectivity

Boundary Layer Impacts of Changing Land Cover

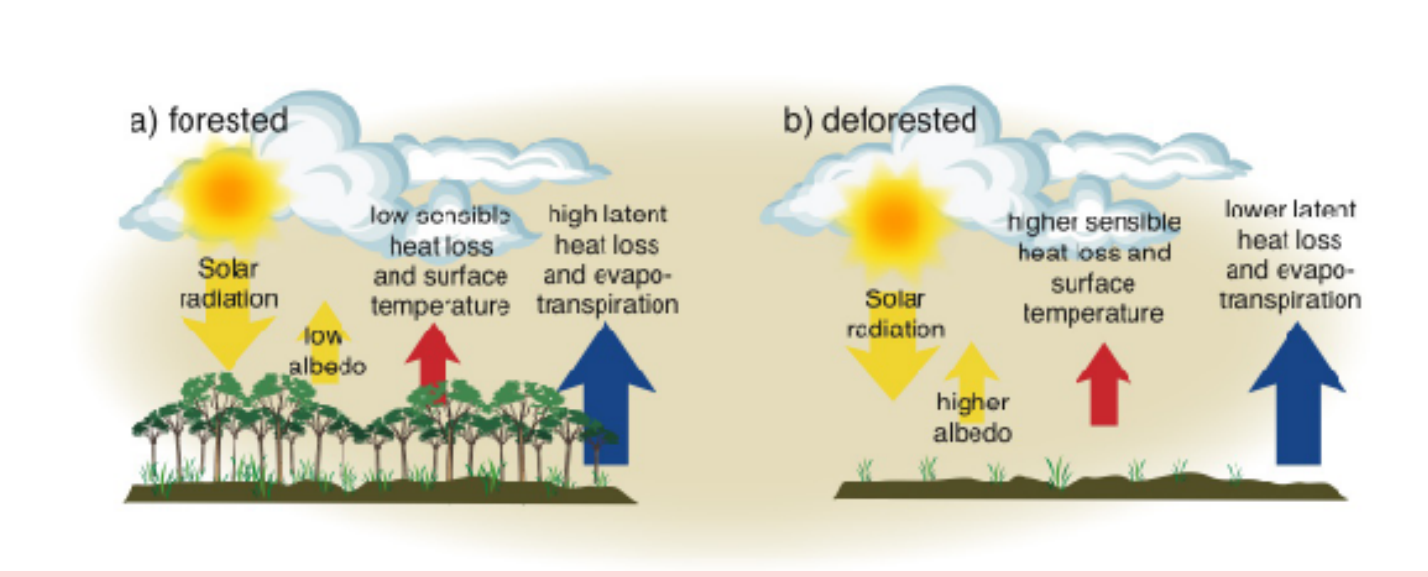

Figure 5: Schematic of the shift in surface energy balance that occurs as tropical forest regions become deforested (from J Foley personal communication).

Figure 5 describes the commonly accepted impact of deforestation on the surface energy balance in tropical rainforests. As a first test, for our vegetation-boundary layer model we tested how boundary layer parameters respond to deforestation in the Amazon region.

Associated with the expected increase in surface SHF and decrease in LHF shown in Figure 5, we expected the following boundary layer response over tropical rainforest:

+ Mean Potential Temperature

+ Maximum Boundary Layer Height

- Boundary Layer Relative Humidity

Figure 6 is our modeled response to deforestation.

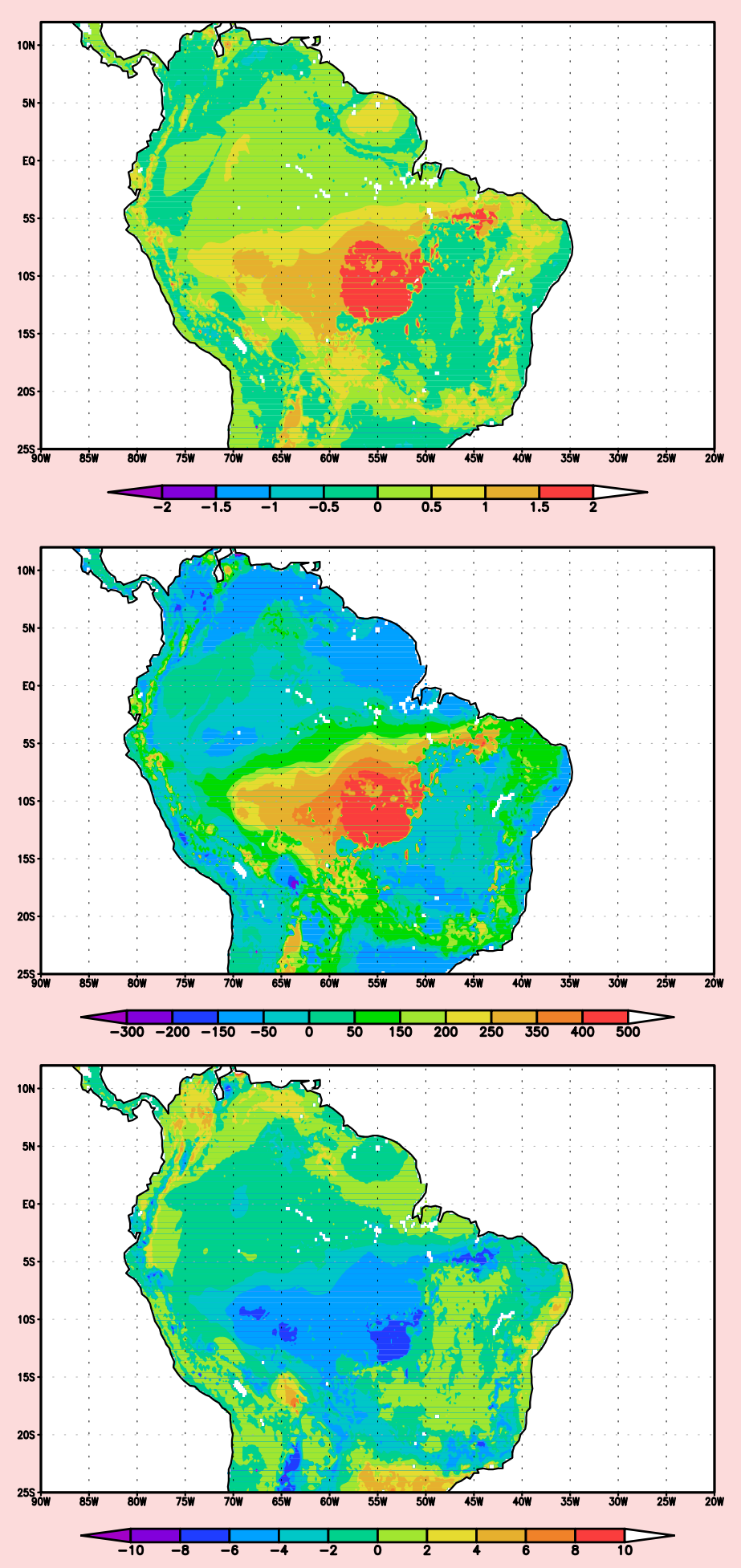

Figure 6: Difference in boundary layer potential temperature(K) (Top), daily maximum boundary layer height(m) (Middle) and relative humidity(%) (bottom) between deforested and potential vegetation runs for the Amazon region.

A Simple Fire Parameterization Application

[5] describes a simple fire estimation parameterization. This parameterization is given by:

$$N_{fire} = F(I_n + I_a) f_{ns}$$

F = Flammability (depends on vapor pressure and biomass)

I_n = Natural Ignition Sources (derived from OTD lightning strike data)

I_a = Human Ignition Sources (based on pop. dens.)

f_{ns} = Fraction Suppressed Fires (distance to pop. centers)

A comparison of observed fires to modeled index is shown in figures 10 and 11.

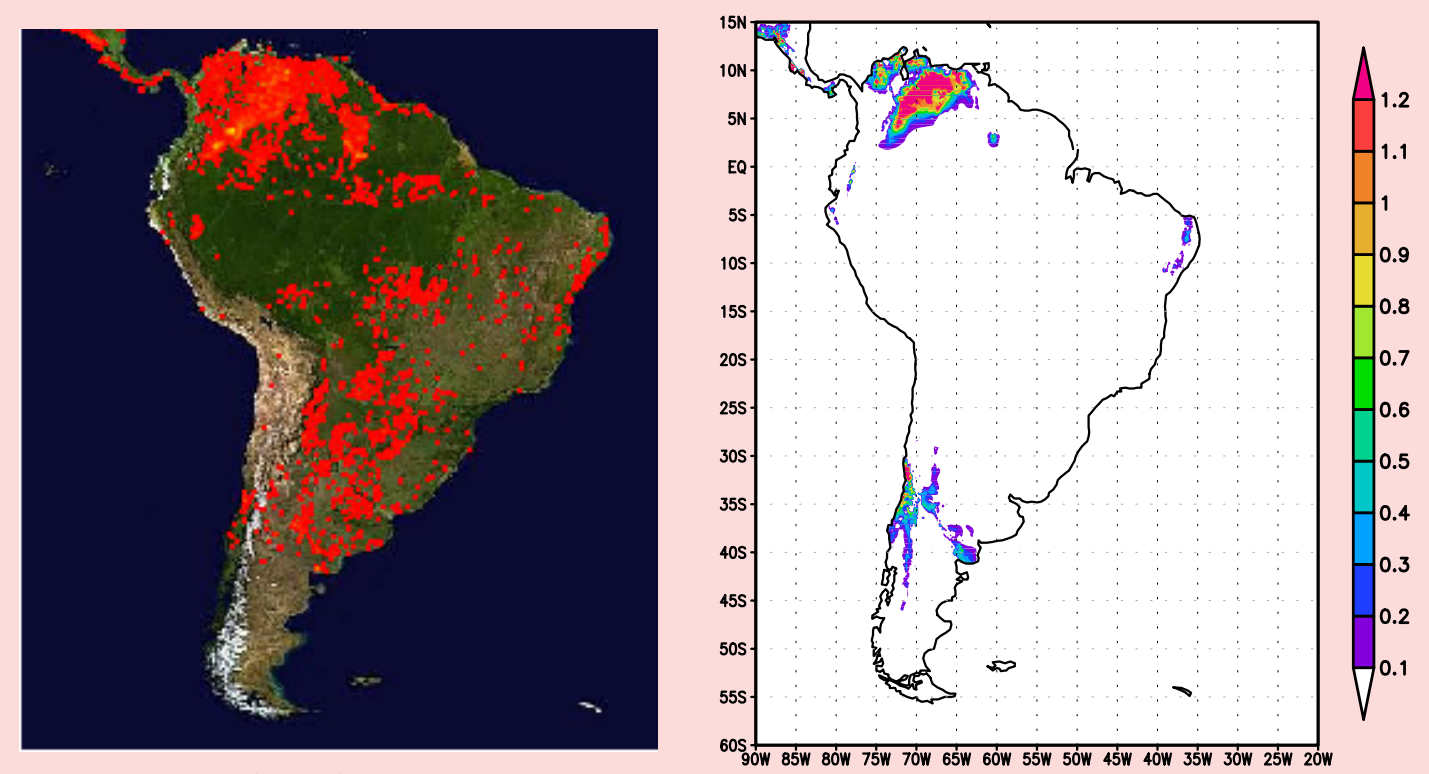

Figure 10: (Left) MODIS image of January fire from 2003 from [6]. (Right) Modeled January fire index from [5].

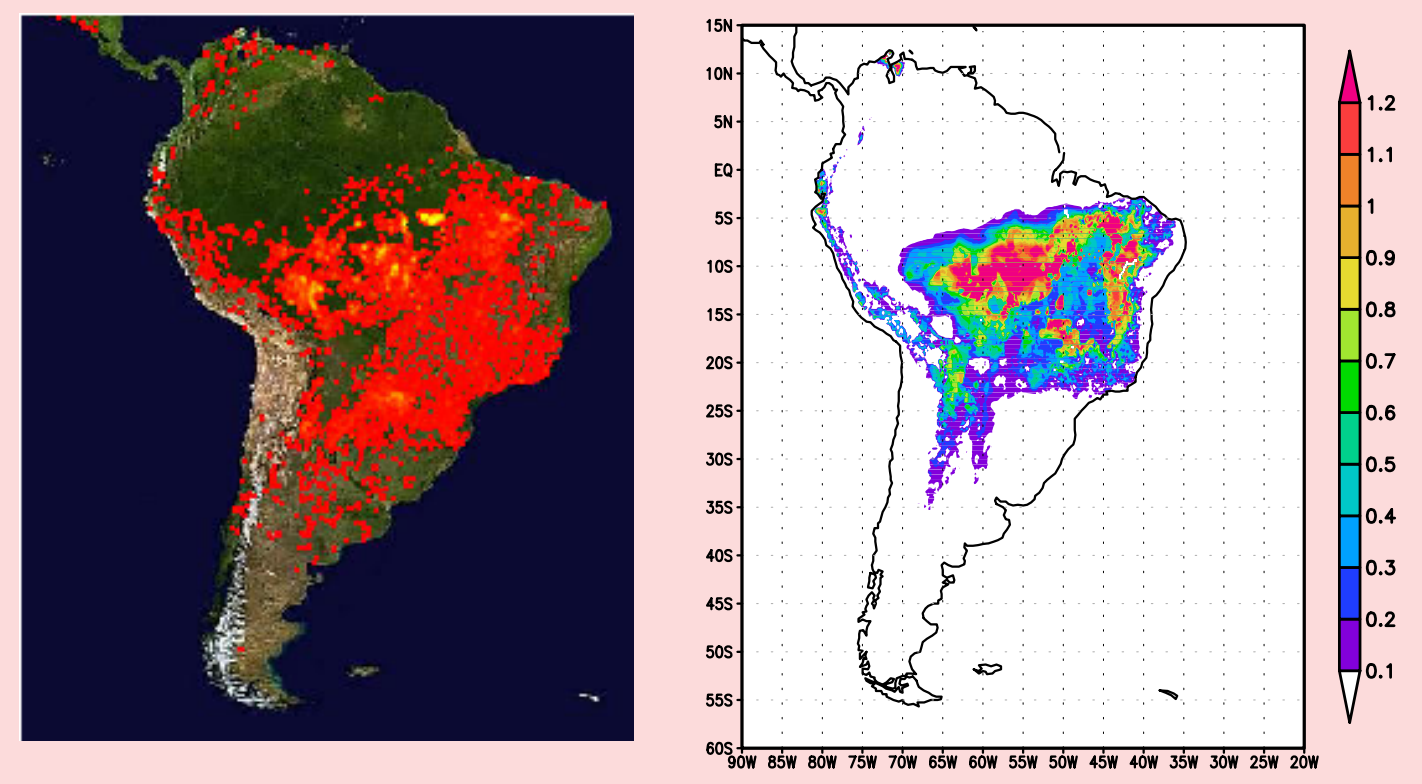

Figure 11: (Left) MODIS image of July fire from 2003 from [6]. (Right) Modeled July fire index from [5].

Initial Comparison of Surface Energy Balance and Boundary Layer Properties to Observations

Shown below is an initial comparison of our veg-boundary layer model to observations from the pre-LBA ABRACOS experiment describe in [3]. We used observations from a paired site near Ji-Parana where observations were taken at deforested and forested areas in close proximity. In this case, the observations and model results are from July 1993, which falls in the Amazon's dry season.

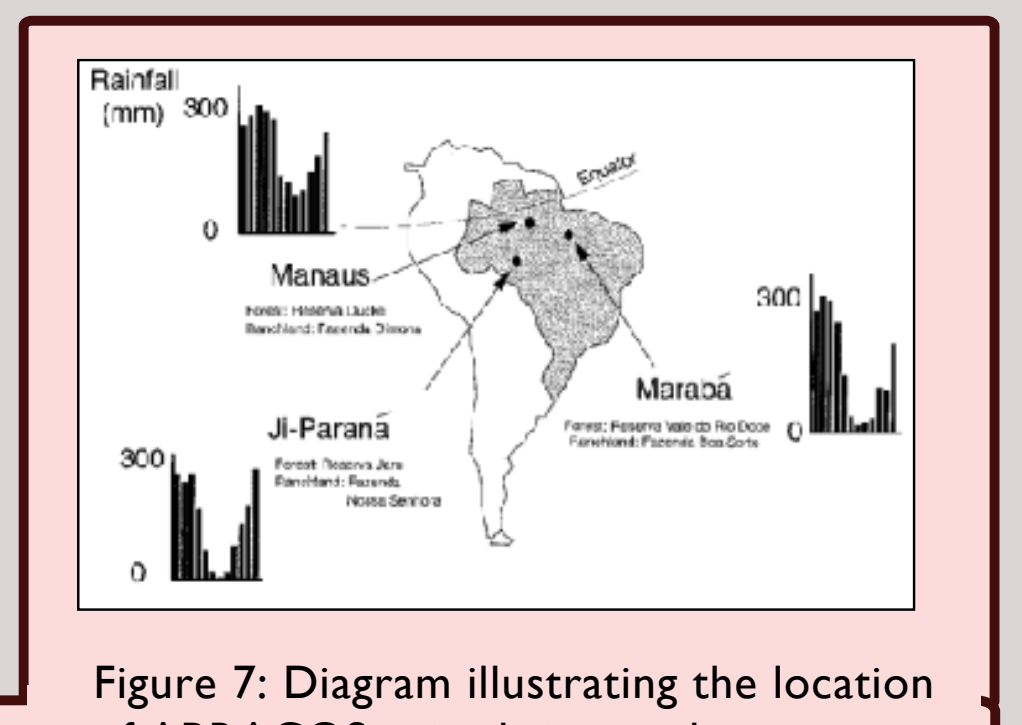

Figure 7: Diagram illustrating the location of ABRACOS paired sites and mean monthly rainfall. From figure 1 in [3]

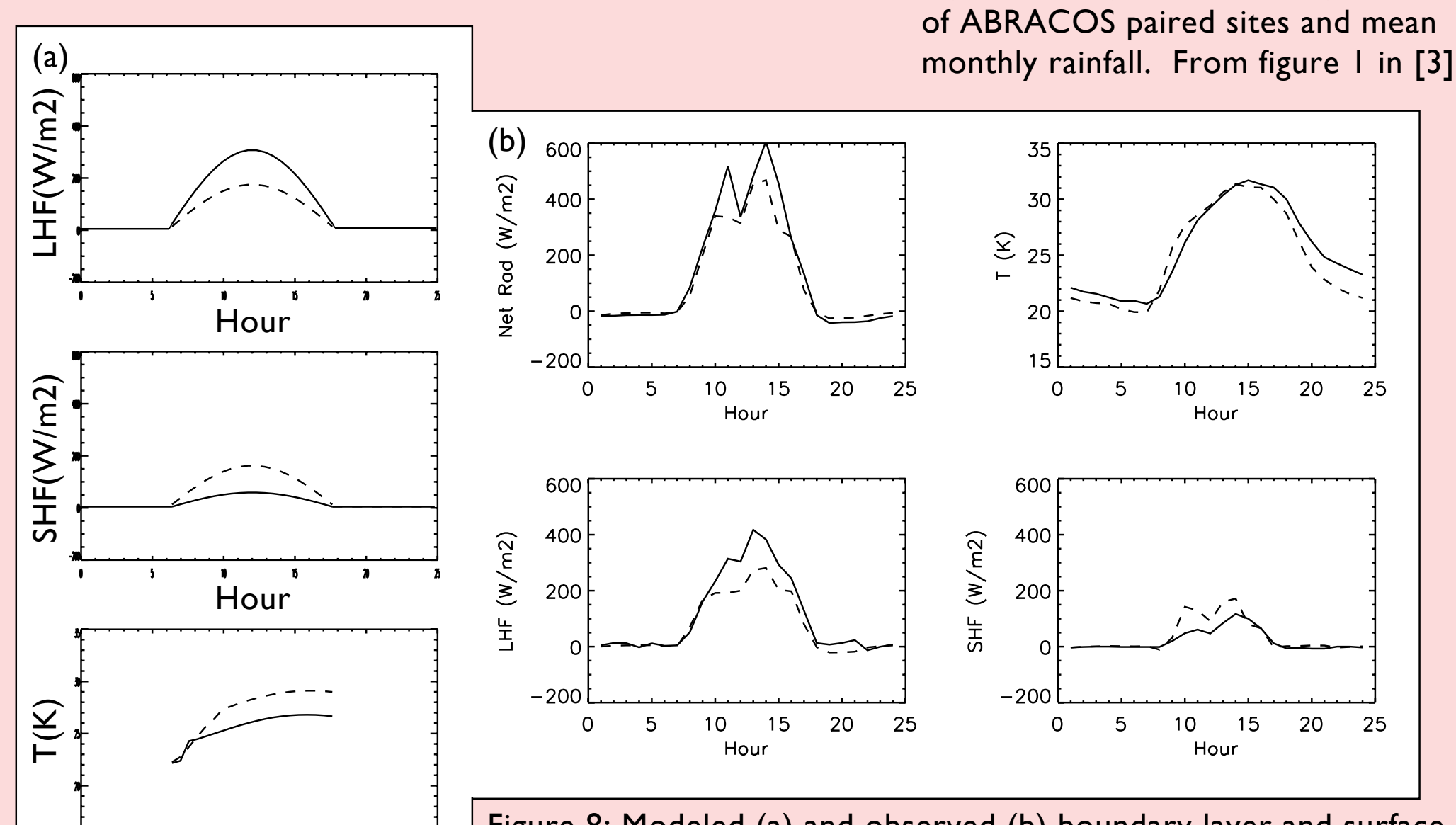

Figure 8: Modeled (a) and observed (b) boundary layer and surface properties for a typical July day (observed is July 3, 1993) near Ji-Parana. Solid(dashed) lines indicate modeled (a) or observed (b) results from a forested(deforested) location.

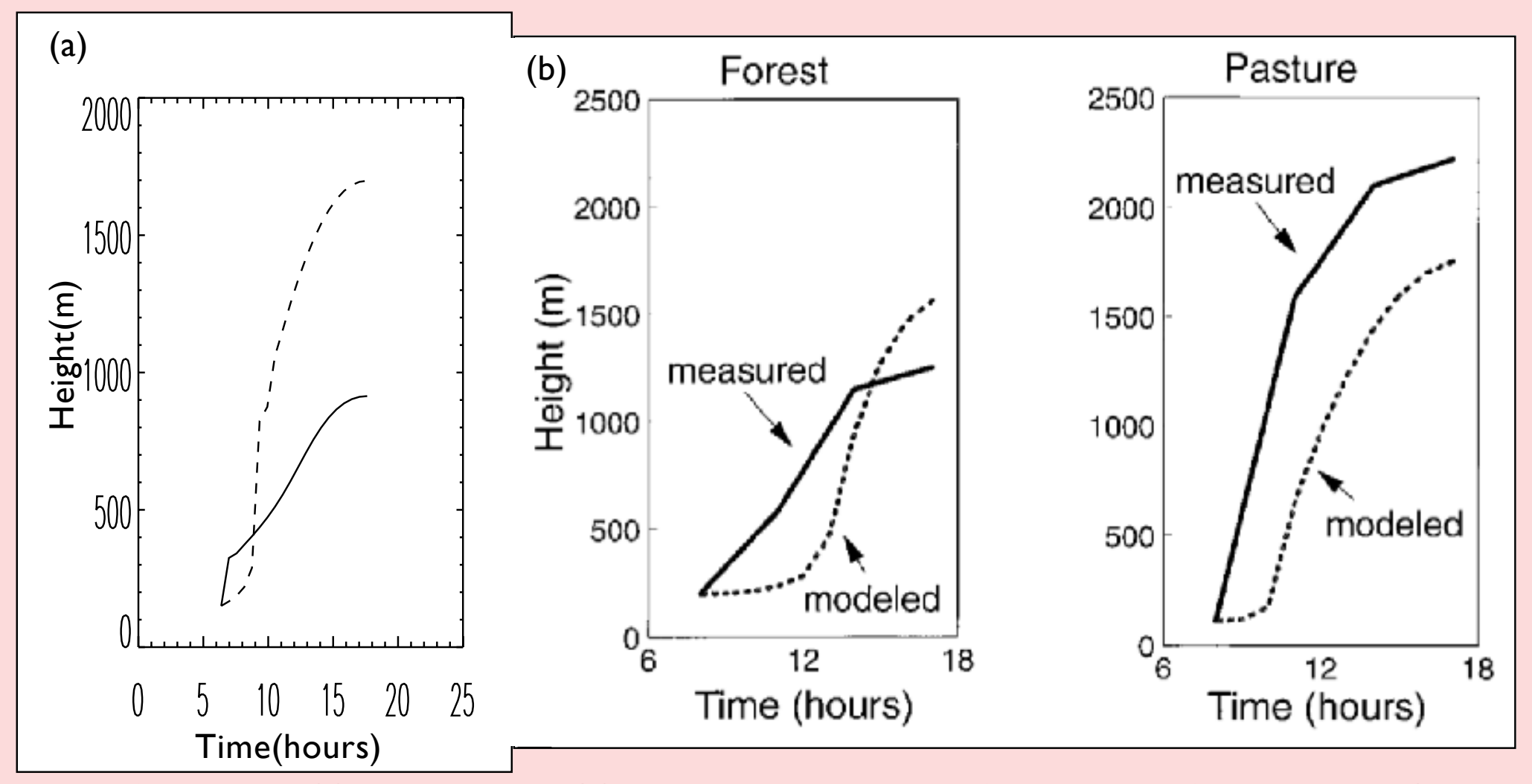

Figure 9: Modeled (a) and observed (b) boundary layer heights for a tropical forest location(solid line) and deforested location(dashed). (b) is figure 4 from [3].

Future Work

Building off of the work presented here, we have a series of tasks that we plan to carry out. Some of the key tasks include the following:

- Analyzing observations from the BOREAS and FIFE field campaigns, as well as Wisconsin flux towers to expand our model validation to higher latitude biomes.
- Integrating precipitation data from locations beyond the Amazon basin.
- Comparing deforestation scenarios in our model to similar scenarios using GCMs to test the robustness of the boundary layer and statistical precipitation models.
- Expand the applications of our model. In particular, we are looking at applications where an ensemble of high resolution scenarios are necessary, making

References

[1] J. A. Foley et al., 2005 Science, 309, 570.
[2] P. A. Dirmeyer and K. L. Brubaker, 1999 J. of Geophys. Res. 104, 19383-19397
[3] J. H. C. Gash and C. A. Nobre, 1997 BAMS 78, 823-830
[4] C. P. Kim and D. Entekhabi, 1998 Boundary-Layer Met. 88, 1-21
[5] O. Pechony and D. T. Shindell, 2009 JGR 114, D16115
[6] Images courtesy of NASA MODIS webpage: http://rapidfire.sci.gsfc.nasa.gov/firemaps