IMPACT OF INTERACTIVE VEGETATION ON PREDICTIONS OF THE NORTH AMERICAN MONSOON

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ABSTRACT

Under GCIP support, the Regional Atmospheric Modeling System (RAMS) and CENTURY Ecological Model have been coupled and the resulting coupled model successfully applied in the central U.S. to study regional-scale, two-way interactions between the atmosphere and vegetation. In this proposal, we will extend the use of that dynamically coupled RAMS/CENTURY model to the southwestern U.S. and Mexico to examine how land-atmosphere interactions influence the spatial and temporal variability of the North American Monsoon (NAM). The proposed work is motivated by recognition of the difficulties in numerically simulating the NAM. One significant feature of the NAM is its sudden onset and the accompanying rapid greenness of vegetation cover. Atmospheric processes, including mesoscale circulations and the formation of clouds and precipitating systems, can be highly dependent on surface heat and moisture fluxes which are, in turn, strongly influenced by the presence of live and dead vegetation, snow cover, and soil-moisture storage. Realistic representation of the vegetation's response (i.e., the change in live biomass) to atmospheric and hydrologic influences is currently lacking in the land-surface parameterizations used in the NAM numerical studies. Thus, we proposed to use our state-of-the-art atmosphere-vegetation two-way interactive modeling system (the coupled RAMS/CENTURY model) that is capable of realistically representing the biospheric responses to atmospheric and hydrologic conditions to improve the climate modeling of NAM at seasonal-to-interannual time scales. Our model results will be compared and evaluated against observational data in three years selected as having "average", "wet", and "dry" NAM precipitation. Studies will also include investigation of how the simulation of interactive vegetation influences the relative importance of local versus advected moisture sources, and the relative importance for prediction of adjacent sea surface temperatures (SST) versus the land-surface memory processes.

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A. Project Description

A1. Statement of the Problem

Representing the strong seasonal and interannual variability of the North American Monsoon (NAM) system and variations in its complex spatial pattern is a major challenge to the numerical modeling community (Adams and Comrie, 1997). The unique NAM convective environment is tied not only to particular synoptic patterns and to various sub synoptic features but also to complex topography. However, apparently identical synoptic situations can produce completely different spatial and temporal patterns of monsoon onset. Indeed, the forecasting skill scores for summertime severe storm events of the Southwestern U.S. have been exceptionally low in comparison with those for other regions of the continental United States (Maddox et al., 1995).

One significant feature of the NAM is its sudden onset and the accompanied rapid greening of vegetation cover. Atmospheric processes, including mesoscale circulations and the formation of clouds and precipitating systems, can be highly dependent on surface heat and moisture fluxes, which are largely determined by live and dead vegetation, snow cover, and soil-moisture storage. Vegetation plays a major role in determining the surface energy partition and the removal of moisture from the soil by transpiration. Realistic representation of the vegetation's response (i.e., the change in live biomass) to atmospheric and hydrologic influences is currently lacking in the land-surface parameterizations used in the NAM numerical studies. Assimilating satellite observations is one possible way to provide more realistic representation of (current) vegetation growth in model simulations. However, such an approach will inevitably create inconsistencies between the space-time distribution of rainfall calculated by the model and the assimilated vegetation biomass growth pattern. Although data assimilation is an excellent approach for studying model mechanisms and for model initialization, it is clearly not appropriate in the context of freestanding, long-term climate predictions.

Incorporating interactive vegetation into a land-surface model is a fairly new endeavor, but research in this area has already provided important insight. Claussen (1995), for instance, used an interactively coupled global atmosphere-biome model to assess the dynamics of deserts and drought in the Sahel. He found that the comparison of atmospheric states associated with these equilibria corroborates Charney's (1975) hypothesis that deserts may, in part, be self-inducing through albedo enhancement. Ji (1995) developed a climate-vegetation interaction model (AVIM) to simulate the seasonal variations of biomass, carbon dioxide, energy, and water fluxes for temperate forest ecosystems in northeastern China. Foley et al. (1998) directly coupled the GENESIS (version 2) GCM and IBIS (version 1) Dynamic Global Vegetation Model through a common treatment of land-surface and ecophysiological processes. They found that the atmospheric portion of the model correctly simulates the basic zonal distribution of temperature and precipitation with several important regional biases, but that the biogeographic vegetation model was able to capture the general placement of forests and grasslands reasonably well. An interactive canopy model (Dickinson et al., 1998) has been added to the Biosphere-Atmosphere Transfer Scheme (BATS: Dickinson et al. 1986, 1993) to describe the seasonal evolution in leaf area needed in atmospheric models, and to estimate carbon fluxes and net primary productivity: this scheme differs from that used in other studies by focusing on short time-scale leaf dynamics. Tsvetsinskaya (1998) introduced daily crop growth and development functions into BATS and coupled it to the National Center for Atmospheric Research Regional Climate Model (NCAR RegCM) to simulate the effect of seasonal crop development and growth on the atmosphere-land-surface heat, moisture, and momentum exchange. She found that the coupled model was in better agreement with observations than the earlier non-interactive mode. All these early attempts demonstrate that atmospheric scientists are now beginning to realize the importance of including two-way feedbacks between the atmosphere and biosphere in meteorological models. In some cases, the use of an interactive vegetation model did improve the numerical prediction.

Over the last two years, under GCIP support[1], a coupled RAMS and CENTURY modeling system has been developed and implemented (Lu et al., 1999a), in which both atmospheric variables (air temperatures, precipitation and relative humidity, etc.) and ecosystem variables (LAI, vegetation transmissivity, etc.) are prognostic variables in the linked system. The vegetation's response to weekly, seasonal, and interannual variations in the simulated atmosphere is itself simulated and fed back to the atmospheric model. The resulting two-way interactive model provides a sophisticated representation of the coupled atmosphere-land system that includes relevant aspects of the hydrological cycle. This model has been successfully applied in the central U.S. to study the two-way interactions between the atmosphere and land surface at seasonal-to-interannual time scales (Lu, 1999).

We believe that atmospheric, terrestrial biospheric, and surface hydrometeorological processes are highly interactive and are best represented as a coupled system in predictive models. Accordingly, the underlying hypothesis that motivates this proposal is:

> ***"Including a realistic representation of coupled atmospheric, terrestrial biospheric, and surface hydrometeorological processes in a predictive model will give at least an incremental and perhaps substantial improvement in numerical weather forecasting and climate predictions, and will give improved interpretation of such predictions in terms of their regional biospheric response."***

A2. Proposed Work

A2.1 Goal and Research Questions

The importance of linking atmospheric, vegetation, and hydrological processes together into a unified system in monsoon studies is highlighted in Figure 1, which illustrates the seasonal change of vegetation in Southwest U.S. and Mexico, and in Figure 2, which shows the interannual variability of atmospheric forcing versus Normalized Difference Vegetation Index (NDVI). Vegetation responds strongly to atmospheric temperature, precipitation, and soil moisture. In turn, the type and quantity of vegetation strongly influences runoff, evaporation, transpiration, surface heat flux, and, consequently, the air temperature and development of precipitation systems.

Our overarching research goal in this proposal is to investigate if and how introducing a description of interactive vegetation growth into a regional coupled model influences the modeled spatial and temporal variability of the NAM. To achieve this goal, we propose to use the state-of-the-art regional two-way interactive atmosphere-vegetation RAMS/CENTURY model to represent the biospheric response to atmospheric and hydrologic conditions, and we will address the following questions.

1. With appropriate re-specification of parameters, is the biogeochemistry CENTURY model able to realistically simulate the vegetation growth for the southwestern U.S.
2. In a year with average rainfall, does including interactive vegetation in the coupled SVAT-climate system (ClimRAMS) improve the simulation of precipitation and

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[1] Coupling Atmospheric Ecologic, and Hydrologic Processes in a Regional Climate Model, PIs R.A. Pielke Sr. and G.E. Liston, NOAA/NASA, Nov. 1, 1997 - Oct. 31, 2000, $358,171

temperature in the NAM region?

3. In the NAM region, in a year with average rainfall, how does including interactive vegetation in the coupled SVAT-climate system (ClimRAMS) influence the relative contribution to precipitation of advected moisture relative to that from local evapotranspiration?
4. Is the coupled ClimRAMS/DayCENT model capable of simulating the interannual variability of NAM?
5. How does the simulation of interactive vegetation influence the relative importance of adjacent sea surface temperature (SST) and land-memory processes including soil moisture, vegetation characteristics, and snow cover effects?

A2.2. Models

The following three models will be used in numerical experiments we will undertake.

A2.2.1 Climate Version of RAMS (ClimRAMS)

The Regional Atmospheric Modeling System (RAMS) is a three-dimensional, nonhydrostatic, general-purpose atmospheric simulation modeling system consisting of equations of motion, heat, moisture, and mass continuity in a terrain-following coordinate system (Pielke et al., 1992). The RAMS was developed at Colorado State University primarily to facilitate research into mesoscale and regional, cloud, and land-surface atmospheric phenomena and interactions (Pielke 1974; Tripoli and Cotton 1982; Tremback et al., 1985; Pielke et al., 1992; Nicholls et al.,1995; Walko et al., 1995a). The climate version of RAMS, ClimRAMS (Liston and Pielke, 1999), to be used in this study was developed from RAMS Version 3b by the addition of several features designed to allow single- to multi-year integrations. These changes included: (1) prescribing daily sea-surface temperatures and vegetation parameters throughout each year; (2) the addition of a collection of routines which simulates grid-scale snow accumulation, snow melt, and their effects on surface hydrology and surface energy exchanges; (3) the implementation of the "dump-bucket" parameterization scheme (Rhea, 1978; Cotton et al., 1995) to account for large-scale precipitation; and (4) the Mahrer and Pielke (1977) short-wave and long-wave radiation model is used in conjunction with the scheme presented by Thompson (1993) to account for the presence of clouds.

A2.2.2 Daily Time Step CENTURY (DayCENT)

CENTURY is a biogeochemistry model that was originally designed to simulate the long-term dynamics of carbon (C), nitrogen (N), phosphorous (P), and sulfur (S) in different plant-soil systems (Parton et al., 1987, 1988, 1993, 1994a,b, 1995, 1996). The grassland, agriculture crop, forest, and savanna ecosystems have different plant production submodels that are linked to a common soil organic matter submodel (SOM). The SOM simulates the flow of C, N, P, and S through plant litter and the different inorganic and organic pools in the soil. The plant production models assume that plant production is controlled by moisture and temperature, and that plant production rates decrease if nutrient supplies are insufficient. Natural events (fire, grazing, etc.) and management practice (irrigation, fertilization, cultivation, harvest, etc.) are simulated through scheduling.

DayCENT (Parton et al., 1998; Kelly et al., 1999; Lu et al., 1999b) was developed from version 4 of CENTURY (Parton, 1996) to allow more temporal resolution in the prediction of biomass growth. It uses a daily time step for the water and nutrient cycles, and the above-ground and below-ground biomasses are updated weekly.

A2.2.3 The Coupled ClimRAMS/DayCENT Model

The coupled RAMS/CENTURY modeling system was developed to study regional-scale two-way interactions between the atmosphere and biosphere. Both atmospheric forcing variables and ecological parameters (LAI, etc.) are prognostic variables in the linked system. The atmospheric and ecosystem models exchange information on a weekly time step. CENTURY receives as input the previous weeks daily air temperature, precipitation, radiation, wind speed, and relative humidity simulated by RAMS. At the end of each week CENTURY in turn produces output variables, including leaf area index and vegetation transmissivity, which are returned to RAMS. In this way, the simulated vegetation responds to seasonal changes in the atmospheric variables at weekly intervals, and this response is fed back to the atmospheric/land-surface hydrology model.

This coupled model has been used to simulate the two-way biosphere and atmosphere feedbacks from 1 January through 31 December in 1988, 1989, and 1993, these being, respectively, dry, average, and wet years in the central U.S. Validation of the atmospheric portion of the model has been made by comparing with more than 3,800 meteorological station observations across the modeled domain and, for the ecological component of the model, by comparison with NDVI data sets from AVHRR. A series of sensitivity experiments also have been conducted to highlight interactions and feedbacks between atmospheric and land-surface processes. The coupled model's atmospheric lateral boundary conditions were artificially perturbed to create dry and wet springs, and the model's ability to represent seasonal and interannual variations in both climate and biomass was examined. The results show that seasonal and interannual variations in the phonology of the vegetation strongly influences regional climate patterns through its control on land-surface water and energy exchanges. These earlier studies show that the coupled model captures the key aspects of weekly, seasonal, and interannual feedbacks between the atmosphere and ecological systems, and they demonstrate their model's usefulness as a research tool for studying complex interactions between the atmosphere, biosphere, and hydrosphere.

In the current configuration of the coupled modeling system, RAMS and CENTURY use their own soil submodels, and this may cause inconsistencies in the coupled model's hydrological cycle. However, developing a common hydrological cycle in the coupled model is a difficult task because other components of both RAMS and CENTURY are highly interwoven. We do not intend addressing this need as part of this proposal. Nonetheless, we believe that CENTURY's simulation of the biospheric response is much more realistic than assuming the alternative RAMS prescription, and that this coupled model in its present form can be used to carry out worthwhile studies of the effect of interactive vegetation in the NAM system.

A2.3 <u>Study Area</u>

Our target area is Southwest U.S., Mexico, and the adjacent oceans. The model domain and grid configuration is illustrated in Figure 3. The (100 km) coarse grid includes a larger area of the Gulf of Mexico and the tropical Pacific Ocean in order to better simulate the effect of moisture sources and better to investigate the relative importance of SST versus land-surface processes in NAM circulation. The (20 km) finer grid is to allow better resolution of the spatial distributions of the NAM and improved topographic representation.

A2.4 Observational and Model-Derived Data

A2.4.1 Surface Climate Observations

Validating ClimRAMS, driving CENTURY off-line, and investigating atmosphere-vegetation inter-relationships all require a surface meteorological observational data set that has the spatial and temporal coverage for the domain and time span of interest. First-order Summary-of-the-Day (SOD) meteorological-station observational data from National Climatic Data Center (NCDC), which has the global daily precipitation, snow fall, snow depth, maximum screen-height air temperature (T_{max}), and minimum screen-height air temperature (T_{min}), is ideal for this purpose. There are approximately 3,800 SOD stations distributed across the United States. Data from 1982 to 1996 has been obtained for previous coupled RAMS/CENTURY study (Lu et al. 1999a). New stations and time periods of interest will be selected for the current study.

A2*.4.2 AVHRR NDVI Data*

The Pathfinder Advanced Very High Resolution Radiometers (AVHRR) monthly and 10-day composite Normalized Difference Vegetation Index (NDVI) data set for North America at 8 km resolution will be used in this study. The data will be aggregated from the original 8 km by 8 km pixel on to a 20 km by 20 km grid. The NDVI spatial pattern will then be compared with the temperature and precipitation spatial distribution in time-averaged fashion to investigate the spatial correlation between the atmospheric forcing and the biospheric response. Meanwhile, we will evaluate the spatial-average to highlight the NDVI seasonality. As part of the DayCENT validation process, NDVI will be converted to LAI and then compared to DayCENT-simulated LAI (Lu, 1999). The NDVI-to-LAI conversion algorithm will follow Sellers et al. (1996).

A2.4.3 Re-analysis Data

Atmospheric lateral boundary conditions are needed for this study, in the form of horizontal wind components, relative humidity, air temperature, and geopotential height, at pressure levels on a 2.5Eby 2.5E global grid. These data are readily available from the National Centers for Environmental Prediction (NCEP) in the form of six-hourly atmospheric reanalysis products (Kalnay et al. 1995). Previous RAMS climate simulations (Liston and Pielke, 1999; Lu 1999) have demonstrated that, when using six-hourly NCEP reanalysis data to define the atmospheric lateral boundary conditions at approximately the outer boundaries of the simulation conterminous United States, the models that will be used in this study can successfully transfer the information they contain into the interior of the domain. In those previous studies, the models were able to simulate both spatial distributions and their temporal evolution throughout the year. The variables are linearly interpolated in time to each model time step and the lateral boundaries of the coarsest grid are nudged to the analyzed values following the flow-relaxation scheme of Davies (1976; 1983). Here the prognostic variables are forced in a margin zone to relax towards the NCEP values on a time scale that varies with distance from the lateral boundaries. The atmospheric fields used for initialization will also be taken from the NCEP reanalysis data.

A2.5 Numerical Experiment Design

In general, we plan to carry out 1-year runs starting January 1. Following the practice established in Lu's previous, similar modeling studies, the initial soil moisture distribution will be generated by first defining a spatially-constant soil moisture content over the domain (40% of total water capacity), and then running the model for the previous year to allow time for the soil moisture to reach equilibrium. The soil moisture distribution on the last day of this "spin-up" simulation will then used as the initial conditions for the year of the model study. In most cases we will carry out an ensemble of 6 (if time allows 10) runs, with the same soil moisture initialization but perturbed atmospheric variables, to allow statistical tests of the significance of any observed differences. For conciseness in the following, when we use the upper case RUN, we are referring to a 6-member (perhaps 10-member) ensemble of separate runs.

We will carry out the following numerical experiments to address the questions listed in Section A2.1.

Question 1. ***"With appropriate re-specification of parameters, is the biogeochemistry CENTURY model able to realistically simulate the vegetation growth for the southwestern U.S.?"***

Since the mid-1980s, the CENTURY model has been developed, modified, and applied to simulate various ecosystem dynamics over a wide range of spatial and temporal scales (Parton et al., 1987, 1988, 1993, 1994a,b, 1995, 1996; Ojima et al., 1993, 1994; Parton and Rasmussen, 1994; Parton 1996). When coupled with ClimRAMS, DayCENT-simulated LAI for the central U.S. shows remarkable agreement with NDVI-derived LAI from satellite observation (Lu, 1999). To address Question 1, DayCENT (with parameters appropriate to the study region) will be driven by observed atmospheric forcings derived from the SOD data set for each grid cell of the fine-grid domain (Figure 3) from 1 January 1982 to 31 December 1998. The DayCENT-simulated LAI will then be compared to NDVI-derived LAI. To further study the sensitivity of DayCENT to changes in atmospheric forcings, six perturbation runs will also be made with T_{max} and T_{min} increased and decreased 2°C, and precipitation increased or decreased 25%, from their original values.

Question 2. ***"In the NAM region, in a year with average rainfall, does including interactive vegetation in the coupled SVAT-climate system (ClimRAMS) improve the simulation of precipitation and temperature in the NAM region?"***

To answer this question, two RUNs will be made using NCEP global re-analysis products to define the models' initial and boundary conditions. The SOD data set will be used as the basis for selecting an "average" NAM precipitation year for this suite of numerical experiments. First, a ClimRAMS RUN will be made with RAMS prescribed LAI curves that are related to time of year and vegetation cover type. Then, using the same initial and boundary conditions, a coupled ClimRAMS/DayCENT RUN will be performed. The outputs from the two RUNs will be analyzed and compared with the observed (SOD) data sets.

Question 3. ***"In the NAM region, in a year with average rainfall, how does including interactive vegetation in the coupled SVAT-climate system (ClimRAMS) influence the relative contribution to precipitation of advected moisture relative to that from local evapotranspiration?"***

Prior to the two RUNs described in the context of Question 2, we will modify ClimRAMS/DayCENT to allow tracking of the source of vapor in the atmosphere. To answer Question 3, we will analyze the output from these two RUNs with an emphasis on diagnosing any change in spatial and temporal patterns in the relative contribution to precipitation of advected moisture relative to that from local evapotranspiration.

Question 4. ***"Is the coupled ClimRAMS/DayCENT model capable of simulating the interannual variability of NAM?"***

Computational resources will limit our ability to perform long-term simulations with the current model configurations. Hence, to investigate the coupled model's sensitivity to interannual climate variations, as an alternative approach we will perform simulations one year at a time for both average and anomalous years instead of running continuous multi-year simulations. First, the SOD data set will be used to determine characteristically "dry" and "wet" NAM years, an "average" year having been already identified in the context of addressing question (2). Then a RUN will be made with the coupled model for these two extreme years and the results compared against observational data sets (SOD). The coupled model's ability of representing NAM's interannual variability in both atmosphere and biomass (NDVI-derived LAI) will be examined.

Question 5. ***"How does the simulation of interactive vegetation influence the relative importance of adjacent sea surface temperature (SST) and land-memory processes including soil moisture, vegetation characteristic and snow cover effects?"***

A series of perturbation experiments will be performed to address this question. We will duplicate the average, dry, and wet year RUNs with RUNs in which the sea surface temperatures are arbitrarily changed by ± 2°C in the Gulf Of California. We will analyze these RUNs to seek insight into if, how, and why including interactive vegetation alters the response of the NAM system to modified sea surface temperatures in adjacent oceanic areas.

A2.6 Work Plan and Timing of Activities

This proposal involves four tasks defined as follows.

Task 1: **Test the adequacy of CENTURY in the NAM region**

Task 1.1: Carry out an offline CENTURY run to answer Question 1
Task 1.2: Adjust parameters as necessary to improve the simulation
Task 1.3: Publish results of Task 1

Task 2: **Understand the impact of interactive vegetation on model runs in an "average" year**

Task 2.1: Introduce "moisture source labeling" code into ClimRAMS/DayCENT
Task 2.2: Define average, wet, and dry monsoon years from SOD data.
Task 2.3: Carry out RUNs of ClimRAMS and ClimRAMS/DayCENT for the average
Task 2.4: Analyze above RUNS and compare with data to answer Question 2
Task 2.5: Publish results of Task 2.4
Task 2.6: Analyze the RUNS from 2.3 to answer Question 3
Task 2.7: Publish results of Task 2.6

Task 3: **<u>Understand the impact of interactive vegetation on model runs in "wet" and "dry" years</u>**

Task 3.1: Carry out RUNs of ClimRAMS/DayCENT for the dry and wet years

Task 3.2: Analyze above runs and compare with data to answer Question 4

Task 3.3: Write paper on results of Task 3.2

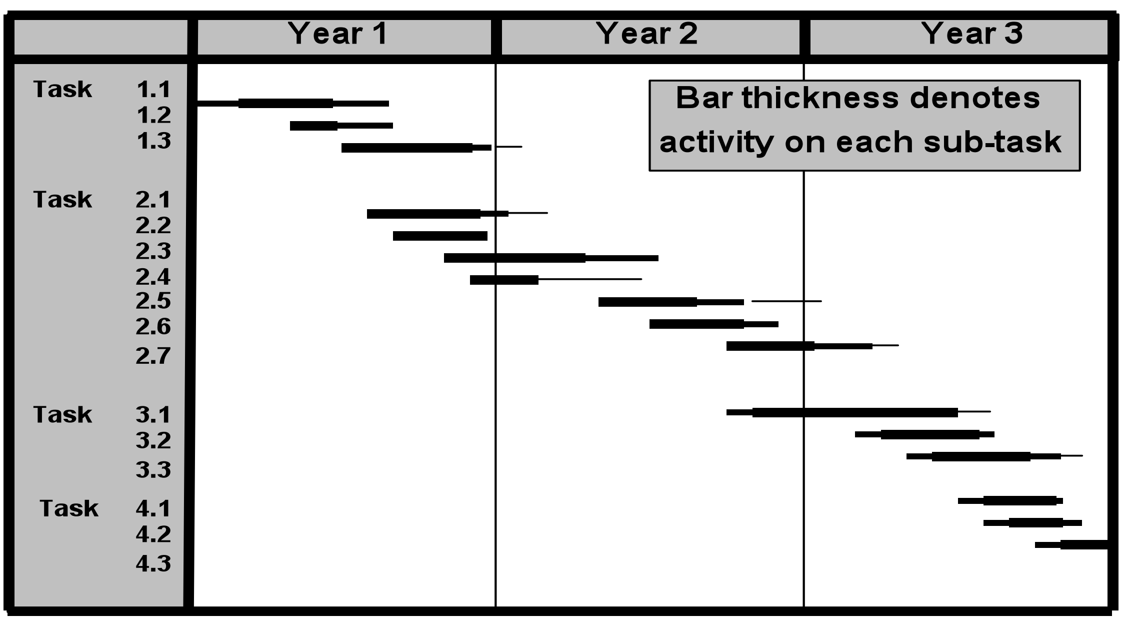
Task 4: **<u>Make an initial investigation of the impact of interactive vegetation on the relative importance for NAM of the land-surface and sea surface temperatures in the Gulf of California</u>**

Task 4.1: Duplicate the "average", "wet" and "dry" RUNs with RUNs in which the sea surface temperatures are arbitrarily changed by ± 2°C in the Gulf of California.

Task 4.2: Analyze above runs to explore Question 5.

Task 4.3: Publish the results of Task 4.2

The proposed timing and relative intensity of activity in the above tasks is illustrated in the following diagram.



A2.7 Management Plan and Responsibilities

Although this project will be carried out by scientists in two different universities, in practice the management of the project is simplified by the fact that all the activities to be undertaken will be carried out by the two PIs (Shuttleworth and Lu) themselves. Dr. Lu will carry primary responsibility for all aspects of this research related to developing, implementing and applying the CENTURY, ClimRAMS, and ClimRAMS/DayCENT models, and for making comparisons between modeled and observational data fields. This work will be carried out at the Colorado State University. Dr. Shuttleworth will be responsible for the overall scientific management of the project, and for supervising and monitoring the research activity over the lifetime of the project. He will also be actively involved in the analysis and interpretation of the results of the modeling studies carried out under all the Tasks. A great deal of the interaction associated with carrying out this function will be by electronic exchange of results and discussion, however the individual budgets for the two universities allow for exchange visits between Tucson and Fort Collins to facilitate the research.

A3. Facilities and Equipment

This project will make heavy demands on computer resources both for model runs and data analysis. Consequently, in the first year, we are requesting resources under this proposal to purchase an additional system for use in the proposed research.

A4. Relevance to This CLIVAR/PACS-GEWEX/GCIP Initiative

The modeling effort that will be undertaken under this proposal directly addresses the objectives of the NOAA Joint CLIVAR/PACS–GEWEX/GCIP North American Warm Season Precipitation Initiative (NAWSPI). Specifically, we seek ***"to develop a better understanding and more realistic simulation of the interaction of SST-forced atmospheric circulation anomalies and land-surface processes in shaping seasonal mean warm season precipitation patterns and their seasonal-to-interannual variability".*** Our focus is on the interaction between SST-forced atmospheric circulation anomalies and interactive vegetation within the coupled ocean-atmosphere-land system. We believe that interactive vegetation is a land-surface "memory" that merits investigation in NAWSPI and we believe that, within the overall suite of proposals supported by NAWSPI, we have the most appropriate skills to address this component of the NAM system. Thus, by providing state-of-the-art modeling in the area of modeling interactive vegetation, we expect to contribute research that, when combined with parallel projects in the overall program, will help ***"to determine the sources of predictability for seasonal-to-interannual precipitation anomalies"***, and ***"to determine and test hypotheses with the most potential for improving seasonal-to-interannual prediction."***

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