I. Past NSF Results (publications from these efforts are marked with asterisks in the References)

Previous NSF Results from Dr. Russell Monson: "Biocomplexity: Carbonshed Studies of Carbon Sequestration in Complex Terrain" (EAR 0321918, $1,999,830, 2004–2009). With this funding we: (1) established the Airborne Carbon in the Mountains Experiment (ACME 2004 and ACME 2007) (Sun et al. 2010), which were the first and second efforts to measure carbon exchange in mountainous terrain using airborne techniques, (2) developed the SIPNET data-assimilation model for use in evaluating eddy covariance flux measurements (Sacks et al. 2006, 2007, Moore et al. 2008), and (3) developed a multi-tower approach to measuring advective CO_2 fluxes in complex terrain (Sun et al. 2007, Yi et al. 2008).

Previous NSF Results from Drs. Connie Woodhouse, Steven Leavitt and Christopher Castro: "An Investigation of North American Monsoon Variability using Instrumental and Tree-Ring Data" (0823090, $607,829, 2008-2011). This grant is still in force. We are developing the first tree-ring network, utilizing existing and new collections, to study long-term North American monsoon (NAM) variability in the US Southwest. We are using partial-width indices (early-wood and late-wood), in combination with stable-carbon isotope measurements obtained from Douglas-fir and Ponderosa pine, to reconstruct and examine temporal variability of monsoon season precipitation, spatial patterns of the NAM in southern Arizona and New Mexico, and its relation to widespread droughts in western North America (Leavitt et al. 2010).

Previous NSF Results from Dr. Xubin Zeng: "Land-Atmosphere-Ocean-Ice Interface Processes in the NCAR CCSM (ATM-0634762, $349,433, 2006–2009). We accomplished the following aims related to earth-system processes: (a) we developed the revised form of the Richards equation for soil moisture that can be applied to both unsaturated and saturated zones (Zeng & Decker 2009); (b) we embedded the revised Richards equation in the NCAR Community Land Model (CLM 3.5),and demonstrated improved prediction of ground evaporation using satellite and *in situ* data (Decker & Zeng 2009, Sakaguchi & Zeng 2009); (c) we assessed the impact of the ocean skin temperature diurnal cycle on predictions from several global modeling platforms (Brunke et al. 2008); and (d) we removed the daytime cold bias of surface temperature over arid regions in NCEP global and regional weather forecasts.

Previous NSF Results from Dr. Debra Peters: "Jornada Basin LTER V: Linkages in Semi-arid Landscapes." (DEB 0618210, $4.92 million, 2006-2012). The Jornada Basin LTER program has been funded continuously since 1982 with a long-term focus on desertification. Peters is the current Lead-PI for the project. Included in her most recent contributions to the project are: (a) coordination of a special issue on cross-scale interactions in Ecosystems (Peters et al. 2007); (b) coordination of a special issue in Frontiers in Ecology and the Environment that expands connectivity ideas to the continental scale (Peters et al. 2008); (c) leader of the EcoTrends Project since its inception (http://www.ecotrends.info), including submission of a synthesis book and two journal articles based on this project. Since 2006, Peters was author or co-author on 28 papers, 26 book chapters and 1 book related to LTER research.

II. Introduction

We propose to study a set of climate-biosphere interactions in the western United States and northern Mexico that function with synchrony entrained to the North American Monsoon System (NAMS). The timing and extent of precipitation in this region is determined by a complex set of interactions involving large-scale atmospheric teleconnections, local land-sea thermal contrasts, and land surface feedbacks that determine interannual, interdecadal and spatial dynamics in winter and summer precipitation. We propose to confront the complexities of these interactions by developing a coupled land-atmosphere Regional Climate Model (RCM) capable of replicating climatological features and variability of the NAMS, and using the model to address hypotheses concerning climate-biosphere interactions. Coupled land-atmosphere climate modeling at the scale we propose (~1 km) has not been achieved previously, and our ability to do so will allow us to resolve local convective activity and accurately represent pulsed moisture inputs at the scale that is most meaningful to ecological processes in this system. In one application of the model we will study connections among precipitation, patterns in net primary production (NPP) in the native vegetation, the spread of invasive species, and regional synchronization of wildfire regimes. In a second application we will develop the tree-ring record in pinyon-juniper forests to reconstruct the spatiotemporal distribution of winter and summer rain and use it to validate the RCM's prediction of precipitation distribution. Finally, we will initiate development of a tree-ring growth model linked to NPP and driven by the RCM. Eventually, we aim to use this new model to apply model-data assimilation techniques capable of assimilating dendrochronological data streams and reconstructing paleoclimate regimes for this macrosystem. The overarching question that we will address is: ***what are the forcings, both external and internal, that provide spatial coherency and temporal synchrony to the system and how do those forcings influence the spatial and temporal propagation of ecological perturbations within the system?*** We have assembled a multidisciplinary research group with expertise in meteorology, climatology, hydrology, ecology and dendrochronology from both the US and Mexico. We propose to assemble six teams of post-docs and graduate students to form the 'spokes' of a well-connected research effort that effectively links all of these perspectives and defines the principal components and interactions of the system across multiple spatiotemporal scales.

When completed, our studies will not only provide insight into the mechanisms underlying macrosystem organization, they will provide the research community with a combination of tools and knowledge from which future activities can be launched and sensor placement honed as large-scale ecology continues to develop as a national priority. The National Ecological Observatory Network (NEON) will establish four core sites and several relocatable sites within or at the boundaries of the NAMS domain. One of the core NEON sites will be located at the center of the domain, one will be located at the northwestern boundary, and two will be located at the northeastern boundary. The boundary sites are crucial to understanding the forces that provide coherency to the domain, as it is at the boundaries where such forces tend to dissipate. Furthermore, it is at the boundaries where the NAMS macrosystem intersects with other distinct bioclimatic regimes, and where the effects of natural variability or unnatural perturbations in such regimes may be transmitted from one macrosystem to another. For example, in one recent study led by a member of our research team, it was shown that ~15% of the total summer rainfall in the Great Plains can be attributed to moisture transported from the adjacent NAMS domain, but that this contribution disappears during years with drought (Dominguez et al. 2009). This is one example of how the boundary NEON sites will provide insight into inter-domain process dynamics.

III. Building on the North American Monsoon Experiment (NAME)

The proposed study is timely given the foundations lain by the recently-completed North American Monsoon Experiment (NAME). NAME was a ten-year (2000-2010), internationally coordinated research program that included a multidisciplinary team of researchers (see special issue of Journal of Arid Environments, Volume 74, May 2010). The stated aim of NAME was: "*to promote a better understanding and more realistic simulation of the evolution of the North American monsoon system and its variability*." The accomplishments from NAME will provide a foundation and direction during the initial phases of our research (Box 1). The current effort will be distinguished from that for NAME, however, in that *ecology will be established as a focus equal to that of climatology*.

Box 1. Major accomplishments from NAME that can be used as a foundation from which to launch the current proposal.

1. Identification of Pacific SST as a major forcing element determining spatiotemporal variability in NAMS activity (Castro et al. 2001, 2007).

2. Comprehensive model assessment, including downscaled GCM projections revealing deficiencies in representation of the land surface as a forcing on NAMS propagation.

3. Detailed heat budgeting and linkage to SST dynamics in the Gulf of California (Lavin et al. 2009).

4. Development of remotely-sensed products for use in the NAMS domain, including SST, precipitation, land cover, surface albedo and soil moisture from passive microwave (see special issue of Remote Sensing of the Environment dedicated to NAME, Volume 112, February 2008).

5. Ongoing flux tower measurements in NAMS landscapes from northern Mexico and southern Arizona (e.g., Mèndez-Barroso and Vivoni 2010).

6. Establishment of a large binational and multidisciplinary science team.

IV. Background

IV.A. The spatial and temporal domains of the North American Monsoon System (NAMS)

The NAMS is initiated each year in late spring following heating of the Sierra Madre Occidental Mountains in northwestern Mexico and the Mexican Plateau (Douglas et al. 1993, Adams & Comrie 1997, Higgins et al. 1997). Continental heating in these regions creates a land-sea thermal contrast that facilitates the movement of moisture inland from the surrounding bodies of water. Upper-level moisture comes from the Gulf of Mexico and the eastern Pacific, with low-level moisture from the Gulf of California. Monsoon moisture can be transported potentially as far north as the Great Salt Lake (Fig. 1). Individual thunderstorms are initiated from local convective activity forced by rapid heating above elevated terrain, provided there is sufficient upper-level moisture and atmospheric instability. The inland transport of upper-level moisture is governed by the evolution and positioning of a subtropical high, or monsoon ridge, which is positioned to the north and northeast of this region during the summer. Monsoon 'burst' periods of intense thunderstorms are associated with synoptic-scale phenomena that vary on an intra-seasonal timescale, such as easterly waves, inverted troughs, and moisture surges from the Gulf of California. The NAMS persists into early autumn, when the subtropical ridge shifts southward. A previous wavelet study by Nolin and Hall-McKim (2006) found that the processes that control precipitation events during the NAMS operate at synoptic scales of 2-8 days (such as those associated with 'burst' periods) and >8 days (such as those associated with tropical cyclones). Winter precipitation in this domain is also forced by Pacific SST, including the oscillatory phases of El Niño Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO). Winter precipitation decreases in amount and ecological influence from the northwestern boundary of the domain, eastward. Winter precipitation events are not influenced by the higher frequency processes that emerge from analysis of summer rain events; being correlated instead with longer term climate modes (Nolin & Hall-McKim 2006).

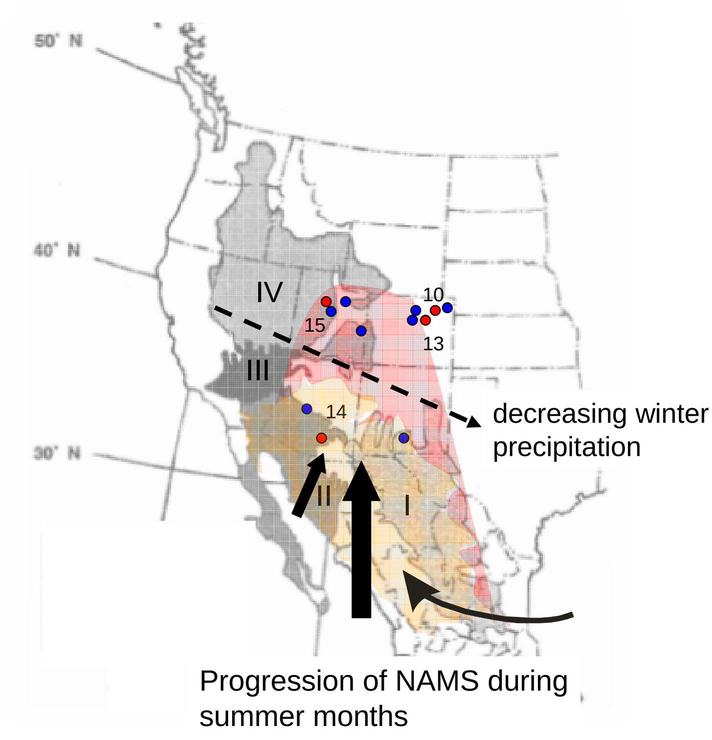

Figure 1. Map showing the spatial extent of the NAMS in relation to the four major desert systems (I, II, III, IV) in Western North America and the core (red) and relocatable (blue) sites proposed for NEON Domains 10, 13, 14 and 15. The bold arrows show paths of moisture transport that originate in the Gulf of California and Gulf of Mexico. The tan shaded area indicates the domain of major ecoregions within the NAMS (Gutzler 2000). The pink shaded area indicates the likely total NAMS extent, with the northern limit defined according to paleoclimate evidence of summertime maize agriculture during the Medieval Climate Anomaly (Coltrain & Leavitt 2002).

IV.B. Spatiotemporal teleconnections within the NAMS

Compared to other regional monsoon systems, the NAMS is 'weakly forced'; meaning that its formation and propagation are susceptible to multiple influences, including SST dynamics, antecedent winter precipitation, recycling of summer precipitation, and regional snow melt dynamics. The principal forcing is due to dynamics in Pacific SST, particularly those associated with ENSO and PDO. The influences of these SST anomalies in Western North America are highly predictable with regard to winter precipitation, stream flow, and plant phenology (Piechota & Dracup 1996, Piechota et al. 1997). The decadal-scale modes alone can account for 20-50% of precipitation variability in the western US (Cayan et al. 1998), and they can amplify influences by ENSO (Gershunov & Barnett 1998, Castro et al. 2007).

During oscillatory periods with warm SST anomalies, winter precipitation in the southwestern US is generally enhanced, including higher-than-normal snowfall in the southern Rockies (Higgins et al. 1998, Higgins & Shi 2000) and greening of vegetation at lower elevations in the arid regions of northern Mexico and the western US (Potter et al. 2008). These wintertime changes in the land surface have the potential to impose a 'memory effect' on the timing and intensity of subsequent summer rain (Kim 2002, Grimm et al. 2007). Increases in surface albedo at higher elevations due to deeper and longer-lasting snowpacks have the potential to slow surface warming, delay the onset of the NAMS and weaken its intensity (Gutzler & Preston 1997). Similarly, anomalously high rates of latent heat exchange from landscapes at lower elevations can delay warming during the late spring, thus delaying the onset of the NAMS (Grantz et al. 2007). Small (2001) used a regional climate model to show that summer snowmelt in the southern Rockies forced a negative feedback on the atmosphere, causing reduced summer rain, whereas summer evapotranspiration from landscapes at lower elevations forced a positive feedback on the atmosphere, enhancing rain. Dominguez et al. (2009) showed that the recycling of precipitation within the NAMS can be as high as 25%, depending on year and location. The recycling of precipitation can be viewed as an 'internal engine', providing stronger convective potential and influencing the extent of northward propagation. 'Cool' anomalies in Pacific SST also have a direct influence on atmospheric teleconnections, but the interseasonal precipitation relationships are opposite to those that occur during 'warm' anomalies. During cool phases of ENSO and the PDO, winter precipitation in the western US is generally below average, but the subtropical ridge is displaced further north during the early summer (Castro et al. 2001, 2007), which amplifies convective activity in the southwestern US. Cooler SST in the eastern Pacific also favors the more frequent occurrence and northward tracking of summertime upper-level disturbances that cause periodic bursts of monsoon rainfall (Bieda et al. 2009). Thus, analyses of observational data have shown that wet (dry) winters tend to be followed by dry (wet) monsoons, and this anti-correlation may be entirely due to remote Pacific SST forcing. The anti-correlation between winter and summer precipitation is reflected in regional patterns of NPP. Jenerette et al. (2010) analyzed satellite-derived peak greenness and growth in the Sonoran Desert for 2000-2007 and found that summer maximum growth was negatively affected by antecedent winter precipitation.

Past patterns of northward propagation of the NAMS can also be determined through paleoclimate proxy data. For example, stable isotope evidence from Fremont burial sites in Utah has shown that maize agriculture, tied to NAMS precipitation, spread as far north as the Great Salt Lake during the 'Medieval' Climate Anomaly (950-1250 AD) (Coltrain & Leavitt 2002). At approximately 1150 AD, as this extended anomaly weakened, Fremont dietary habits shifted from maize agriculture to foraging, potentially in response to southward retreat of the NAMS. (It is possible that now, in the Anthropocene, warming associated with increased mean atmospheric CO_2 concentrations will force a shift northward in the NAMS, once again establishing a prominent summer moisture regime across most of Utah.)

IV.C. Modeling NAMS climatology and vegetation processes

We propose to use four modeling platforms within an integrated framework to study spatiotemporal variability in NAMS climatology, the influence of that variability on land-surface processes, and coupled feedbacks to the climate. (1) The regional climate model that we will use is the Advanced Research version of the Weather Research and Forecasting (WRF) model (Skamarock et al. 2005). (2) The principal land surface model that we will use is the NCAR Community Land Model (CLM) version 4.0 (Oleson et al. 2010). (3) The surface hydrology model that we will use to redistribute precipitation across the landscape and better simulate the tendency for productivity to be highest along drainage channels in the local topography (see Bradley & Mustard 2006, Moran et al. 2009) is the CATchment HYdrological (CATHY) surface/subsurface model (Camporese et al. 2010). (4) The vegetation dynamics model that we will embed within CLM4 and use to specifically simulate establishment and growth in invasive grasses in the NAMS domain is ECOTONE (Peters 2002). These four models currently exist as stand-alone research platforms, and/or they are used in applications different than for what we propose. Thus, a major activity early in our research will be to combine these models for use as an integrated research system (Fig. 2).

We propose to integrate these models to form two different scale-dependent simulation systems. The first would involve coupling between WRF and CLM4, without ECOTONE or CATHY. This system would be capable of domain-wide simulations of NAMS activity and its coupling to land surface processes. In the case of these simulations, the land surface will be represented in a manner similar to that in the global version of CLM4, but with modification to account for restricted plant and soil types, and improved representation of the regional fire cycle (referred to here as Regional CLM4, or RegCLM4) (see Zeng et al. 2008). The second system would combine RegCLM4 with CATHY and ECOTONE (in newly formulated 'regional configurations, RegECOTONE, RegCATHY), and will be used to probe smaller scale (30 m) interactions among topography, hydrology and invasive species spread. The outcomes of dynamic runs with this second model system, within small grids nested in larger grids, can then be spatially averaged to provide up-scaled scenarios of invasive species spread, and scenarios from which land forcing feedbacks on regional weather patterns can be explored using the first model system (WRF-RegCLM4).

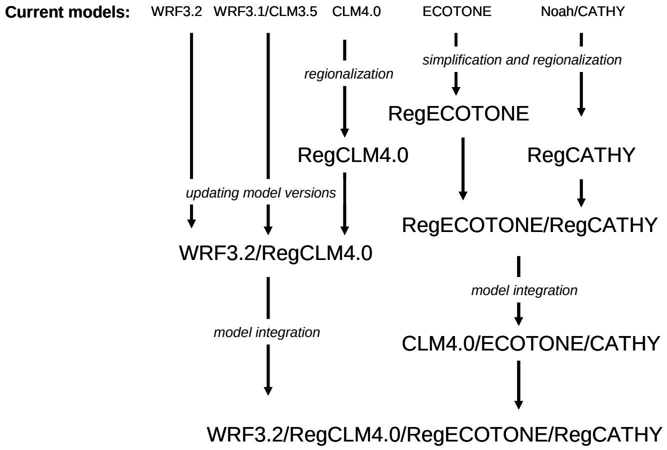

Figure 2. Scheme showing the process we will take to develop the modeling platform for the proposed studies. Current versions of the models are shown across the top row. We use the designation 'Reg' to indicate modification of the model for use in regional mode (e.g., RegECOTONE and RegCATHY).

The Weather Research and Forecasting (WRF) model is a numerical system capable of simulating weather and atmospheric dynamics for both research and operational applications. The ARW version of WRF includes parameterizations for moist atmospheric convection, a tunable surface energy balance, and the capability for nested horizontal domains of variable resolution (Skamarock et al. 2005). The version of WRF that we currently use is capable of producing quasi-operational forecasts for the southwestern US at grid spacing of 1.8 km by dynamically downscaling coarser global and regional model data. During the initial stages of model modification we will include new features consisting of Lin microphysics (Lin et al. 1983) with the Kain-Fritsch cumulus parameterization (Kain & Fritsch 1993, 2004). We will also make connections between WRF and the Dynamic Recycling Model (Dominguez et al. 2006), for purposes of evaluating spatially-explicit patterns of precipitation recycling. The DRM model includes a Lagrangian transport scheme that will be used to track the transport of recycled precipitation across the spatial extent of the domain, and inputs of recycled moisture into each grid cell will be used to adjust the WRF model, potentially amplifying convective activity. RCM simulations with WRF will utilize a recently developed spectral nudging capability to maintain the variability of large-scale circulation features. We will establish boundary climate conditions using North American Regional Re-analysis (NARR) products. This approach has already been applied to a dynamical downscaling of WRF for a contiguous US-Mexico domain at 32 km grid spacing, nearly identical to that in Castro et al. (2007) for simulations with the Regional Atmospheric Modeling System (RAMS). Thus, the boundary forcings required for this domain already exist for the period 1979-2009 at the University of Arizona.

We currently run WRF in coupled configuration with the Noah land surface model. As an initial activity, we will swap the Noah model for CLM4. The advantage of switching to CLM4 includes the potential for sub-grid variation in plant functional types (PFTs) and soil types, improved representation of hydrological processes, coupling of the C and N biogeochemical cycles, and introduction of wildfire activity. In CLM4, a gridded system can be established with vegetation represented by fifteen possible PFTs. The vegetation of each grid cell can be established in one of two ways: either driven from bare ground to stable PFT communities using the dynamic vegetation model within CLM4, or prescribed using satellite data. CLM4 has recently been modified (by Xubin Zeng, a Co-I on this proposal) to accommodate shrubs and grasses from the western US as additional PFTs (Zeng et al. 2008).

ECOTONE was originally developed to describe vegetation dynamics at the grassland-shrubland boundary in southwestern New Mexico (Peters 2002, 2010). ECOTONE simulates vegetation dynamics on a small plot (1-10 m^2) at an annual time step; soil water dynamics are simulated daily using a multi-layer soil water model, and aggregated to provide seasonal information about plant growth. Inputs include daily precipitation and temperature, soil texture by depth, and species-specific parameters that determine responses to climate. The model output is annual biomass increment (growth) for individual plants. Recruitment and mortality are described by stochastic elements (e.g., seed dispersal, local disturbance), but growth is deterministic based on root distribution and activity, and the ability of roots to capture water and nitrogen within a competitive context. Resources are distributed to each plant based on the proportion of active roots in each depth relative to total root biomass of all plants. The ultimate biomass increment (growth) is taken as the minimum between the water- or nitrogen-based increments, which in turn are determined by parameterized water- and nitrogen-use efficiencies (g biomass g^{-1} water or nitrogen used). Because ECOTONE has stochastic elements, replicate plots with the same input parameters are simulated to produce a mean response. Variation in the output can be used as a measure of uncertainty. Larger areas, such as grids from other models, can be simulated by assuming that the average response occurs throughout a grid cell. We will conduct tests to determine the number of replicate plots needed to represent grids of varying spatial extents in different parts of the domain.

CATHY is a soil hydrology model for simulating 3-d subsurface flow in variably saturated porous media (Paniconi & Wood 1993) and surface flow across hillslopes and in drainage-channel networks (Camporese et al. 2010). CATHY couples a finite element solver for the Richards equation and a finite difference solver for the diffusion wave equation. The Richards equation is solved numerically in space using tetrahedral control volumes, and with a weighted finite difference scheme for time integration. For simulation of surface redistribution, hillslope and channel flow are combined to form a drainage catchment and estimate surface storage. CATHY has a pre-processor to derive topographic representations from Digital Elevation Models (DEMs).

Some progress in working with these models and some initial couplings among the models have already been made within our research group. Professor Jiming Jin (Utah State Univ and a Co-I on this proposal), has conducted studies to link WRF with an earlier version of CLM (ver. 3.5) in order to study mountain snow water equivalent dynamics in the northwestern US. Professor Jin's projections using this modeling platform generally performed better at predicting snow depth, snow water equivalent, and rate of snow melt when compared to the coupling between WRF and other models (Fig. 3). Professor Guo Yue Niu (University of Arizona and a Co-I on this proposal) has coupled CATHY to the Noah land surface model for the purposes of examining topographic re-distribution of water and its effect on ecosystem-atmosphere CO_2 and H_2O exchange in native and invasive grass communities in a semiarid catchment in Southeastern Arizona. His work revealed that water redistribution by lateral overland flow and re-infiltration produces wetter soils in lowland areas along drainage channels and thus provides grasses with favorable conditions for growth during drought years and dry-down periods after the NAM (Niu et al., in review). A conceptual representation of how these models will interact to provide full surface-atmosphere coupling is shown in Figure 4. The colored images presented in this figure with regard to soil moisture distribution and leaf area index are actual simulations for the Walnut Gulch Experimental Watershed in Arizona using an invasive C_4 grass (*Eragrostis lehmanniana*) that has spread across the site.

We intend to use the resources of this proposal to initiate a community modeling process that will act as a seed from which broader efforts to establish novel regional climate models will germinate. WRF has been, and continues to be, developed as a community-based model within NCAR and NOAA; it currently has over 4,000 registered users. However, the coupling of WRF to CLM to provide a regional modeling platform has only been attempted in isolated research applications, such as the one described above by Professor Jiming Jin at Utah State University. We intend to leverage the resources of this grant to bring the co-development of these models into a broader community forum by working with the current WRF support staff at NCAR (see letter of collaboration by Jimy Dudhia, NCAR, in Supplementary Documents section). The community effort will provide the earth-system modeling community with a process for accessing model code that has been tested and verified, as well as access to support staff who can help users troubleshoot model components and design new configurations for regional modeling activities. Community modeling efforts are one of the most effective means of promoting international cooperation and generating broad scientific consensus on some of the most important issues facing humanity, including, for example, continuing IPCC analysis activities. The process that we will develop represents a significant value-added component of the research proposed here. We are requesting a 5% FTE for WRF support staff for the initial two years of the project.

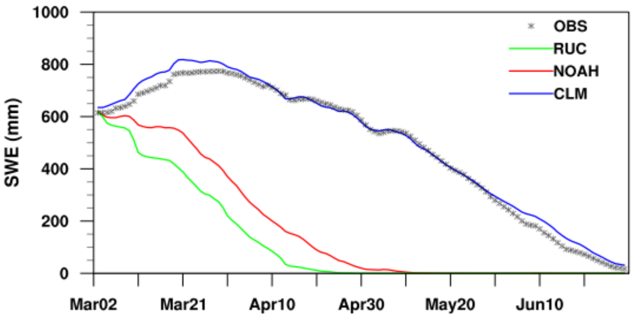

Figure 3. Snow water equivalent observations (from snow telemetry) compared to three land surface models for the Columbia River Basin for the period March-June 2002. (Jin et al., ms. in review).

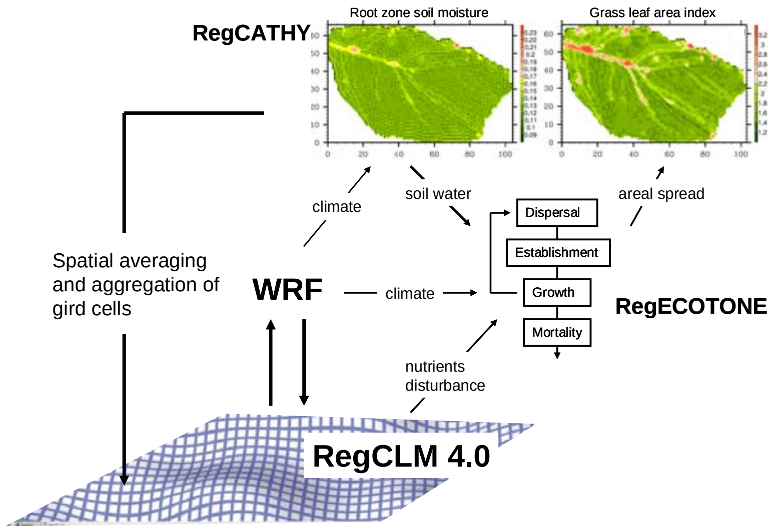

Figure 4. Model interactions proposed for the land-atmosphere simulations. WRF and RegCLM will drive inputs for the RegCATHY and RegECOTONE models which will be deployed at the sub-grid scale for selected regions of the NAMS domain. The simulated areal spread of invasive grasses will then be entered back into RegCLM through spatial averaging and aggregation to obtain regional perspectives on the land forcing back on WRF climate predictions.

IV.D. Use of tree rings and stable isotopes to discern mechanisms of regional synchronization

One of the tools that have proven useful to establishing patterns of climatic coherence within the western US has been the dendrochronological and stable isotope analyses of tree rings (Leavitt & Long 1989, Pendall 2000, Roden & Ehleringer 2007). In many woody species of the NAMS macrosystem, dimorphic annual rings, reflecting less dense 'early-wood' or denser 'late-wood', can be used to distinguish cambial activity during periods supported by winter precipitation or summer precipitation, respectively (Fig. 5, Meko & Baisan 2001, Stahle et al. 2009). 'False rings', which appear as even denser wood separating the early- and late-wood rings, can be related to cambial activity during the dry, pre-monsoon period. Recent analyses of early- and late-wood rings in Douglas-fir and Ponderosa pine extending back over 2,000 years in Western New Mexico have revealed evidence for synchronized failure of winter and summer rains during the multi-decadal, severe droughts of the 8th and 17th Centuries (Stahle et al. 2009). Trees differ in the degree to which early- and late-wood is differentiated, and with regard to the presence or absence of 'false rings'. In this proposed study we will focus on climate reconstructions from pinyon pine (*Pinus edulis*) tree rings which have been shown to have distinct early- and late-wood rings in populations from different sites in the western US, with populations from the NAMS domain exhibiting distinct 'false rings' as well (Leavitt & Long 1989, Pendall 2000). Furthermore, the widths and isotope ratios of early- and late-wood rings in pinyon pine have been shown to be sensitive to variations in drought among sites and years (Leavitt & Long 1989, Pendall 2000, Newberry 2010). We chose to focus on pinyon pine because the pinyon-juniper woodland type sits at the boundary between desert grasslands and montane forests in the NAMS domain; thus, representing a critical zone across which climate and fire regimes are passed along elevational gradients.

In addition to tree-ring width, the ^{13}C/^{12}C, ^{2}H/^{1}H or ^{18}O/^{16}O ratios in the cellulose of tree rings can be used to reconstruct responses to past climate regimes. Roden and Ehleringer (2007) compared the celluosic δ^{18}O signal extracted from the tree rings of Ponderosa pine from sites in Oregon (outside the NAMS domain) and Arizona (inside the NAMS domain). They found a significant correlation between the δ^{18}O of tree ring cellulose and the fraction of precipitation at a site that is due to summer rain. They also discovered that interannual dynamics in atmospheric humidity (driving differences in the leaf-to-air vapor pressure difference) can be detected in the δ^{18}O signal. Using the δ^{13}C record of pinyon pine rings, Coltrain and Leavitt (2002) inferred the intersection of two hydroclimate regimes at the northern boundary of the NAMS macrosystem, one supported by winter precipitation and one supported by both winter and summer precipitation (Fig. 6). During the 1930-1934 North American droughts, the δ^{13}C ratio of trees near the northern extent of the region revealed northwesterly expansion into the NAMS domain. Those parts of the macrosystem supplied by summer rain appeared to be less affected by these droughts, likely because of the aforementioned out-of-phase relationship in interannual variability of winter and summer rainfall associated with Pacific SST forcing. Pendall (2000) showed that the δD ratio of early- and late-wood cellulose in pinyon pine trees from populations within or without the NAMS domain reflected relative differences in the amounts of winter versus summer rain and relative humidity during ENSO variation.

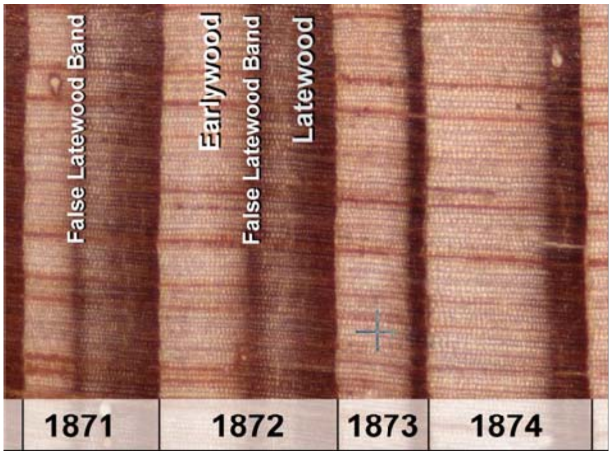

Figure 5. Douglas fir tree rings from southwestern New Mexico showing variability in the widths of early (light) and late (dark) rings, and the presence of 'false rings', produced in the dry pre-monsoon season. The relative widths of early and late wood can be used as a proxy to reconstruct winter versus summer moisture. From Leavitt et al. 2010.

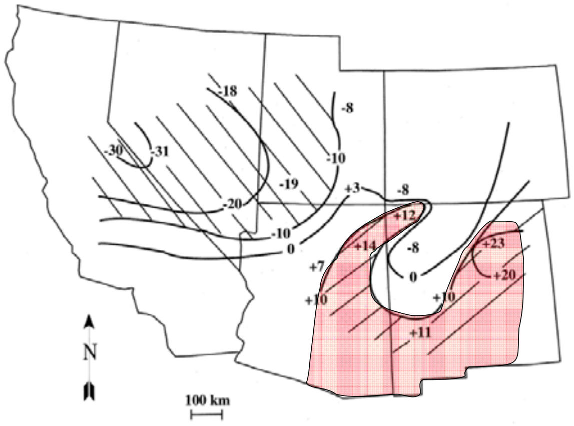

Figure 6. Drought contours for 1930-1934 derived from tree-ring $\delta^{13}C$ ratios in pinyon pine. Positive anomalies reflect above-average moisture whereas negative anomalies reflect below-average moisture. The contours reflect two distinct hydro-domains, with the approximate extent of the NAMS domain shown in red shading. This type of analysis demonstrates the use of tree isotope chronologies to map macrosystem boundaries and levels of coherency within domains. (Coltrain & Leavitt 2002).

We propose to use observations of $\delta^{13}C$, $\delta^{18}O$ and δD in early- and late-wood rings as proxies to assess the available soil moisture (precipitation) ($\delta^{18}O$ and δD), atmospheric humidity ($\delta^{18}O$ and δD), and photosynthetic water-use efficiency ($\delta^{13}C$) during wood cellulose production. We have requested funds to analyze 5,000 samples during the five-year tenure of the grant. In theory, this would allow us to analyze both early- and late-wood for a 100 yr record on 250 trees from across the domain if binned by decades, or a 50 yr record for 250 trees if binned by pentads. In practice, we think we can improve on this estimate. For the ring width studies, we aim to sample 10 trees from 50 sites across the domain. We will use the ring-width studies to inform us about which rings, or bins of rings, might be most interesting with regard to isotope analysis. Using this approach, we hope to sample a 100-yr span from trees at all 50 sites. We will focus on rings or groups of rings that, based on width, appear to reflect oscillatory phases in Pacific SST, anomalies in the timing of snowmelt of the southern Rockies, or known major drought anomalies from the past century.

In addition to the development of new tree-core collections associated with pinyon pine, we will be able to leverage a major effort that is underway to expand our knowledge of past NAMS activity through analysis of tree-ring patterns in Douglas-fir and Ponderosa pine (Leavitt et al. 2010). Connie Woodhouse and Steve Leavitt (Co-Is on this proposal) are in the final year of an NSF grant aimed at developing chronologies of NAMS activities from analysis of the late-wood rings in Douglas-fir and Ponderosa pine collected in mountainous regions of southern Arizona and western New Mexico. A map of these sites is shown later in this proposal (Fig. 9). Furthermore, an extensive tree-ring climate reconstruction exists for the Sierra Madre Mountains and Plateau region of northwestern Mexico (where the NAMS originates each year) due to collaborations among researchers at the Instituto Nacional de Investigaciones Forestales in Mexico and the University of Arkansas. With the development of all of these activities, we are now entering a phase of unprecedented access to historical knowledge about past bioclimatic couplings within the NAMS macrosystem.

V. Conceptual organization of the proposed studies

We have developed questions and hypotheses concerning the processes that control the extent and nature of the NAMS macrosystem according to the conceptual linkages shown in Figure 7. Some of the key interactions depicted in this diagram are: (1) the potential for SST in different ocean regions to control both winter and summer precipitation variability, (2) the potential for antecedent winter precipitation to influence summer precipitation, (3) the potential for future climate change to influence productivity patterns through changes in the strength and frequency of Pacific SST forcing, (4) the potential for the spread of invasive species to influence climate through altered land forcings on the atmosphere, and (5) the potential for the spread of invasive species to influence wildfire frequencies and fire connectivity within the NAMS domain.

The oceanic sources of NAMS moisture have been the subject of active debates for over fifty years (Adams & Comrie 1997). There is general consensus that most of the moisture originates from the Gulf of California (Stensrud et al. 1995, 1997, Fawcett et al. 2002), and this flow is most sensitive to the local land-sea thermal contrast. One of the larger uncertainties that remain is the importance of the atmospheric teleconnections associated with oscillations in eastern Pacific SST. Furthermore, we have recently become aware that the recycling of summer precipitation has a major role in sustaining convective activity within the NAMS and determining the patterns of propagation across the domain (Dominguez et al. 2009). These climate interactions, involving different SST teleconnections and precipitation recycling, have not been studied previously due to the lack of an adequate modeling system.

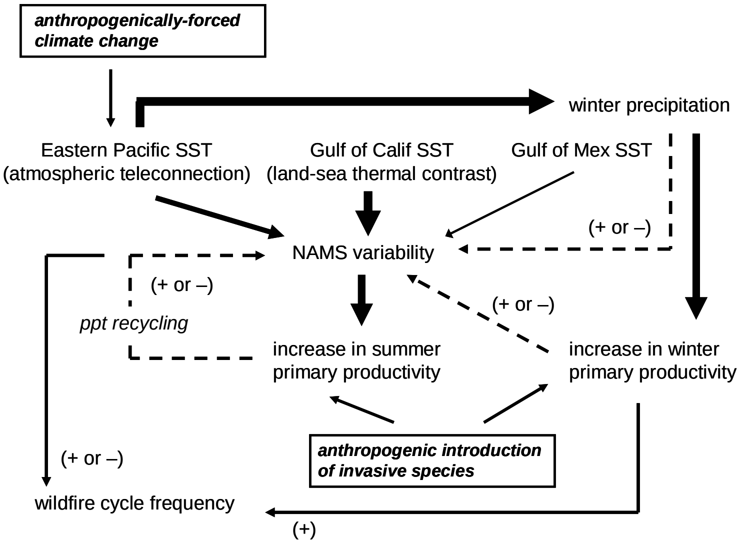

Figure 7. The principal bioclimatic interactions that provide coherency and synchronization within the NAMS domain.

The regional spread of invasive species has the potential to directly influence wildfire frequency (Whisenant 1990, D'Antonio & Vitousek 1992), and indirectly influence climate by altering surface albedo and surface energy partitioning. In this proposal we focus on the spread of invasive grasses. Currently, the spread of winter-annual invasive grasses is most threatening to alterations in regional fire regimes during El Niño years, when winter productivity and associated fuel loads are high. The fire frequency in higher elevation woodlands is most often increased during La Niña years, with associated dry winters. The continued spread of invasive grasses threatens to alter those relations by establishing connectivity in the fuel loads of lower elevation desert grasslands and higher elevation woodlands. The spread of summer-active C_4 grasses in northern Sonora, Mexico and southern Arizona could amplify these changes by expanding the margins of connectivity in these normally disparate fire regimes (Arriaga et al. 2004)

VI. Specific questions and hypotheses to be addressed in the proposed studies

We offer three sets of questions and separate hypotheses to be tested within the context of each question.

1. What are the external and internal forcings that organize the system into a coherent climatic domain and how do they interact with one another?

H1. Changes in atmospheric dynamics. Dynamics in SST in the Gulf of California, the eastern Pacific and the Gulf of Mexico have the potential to force changes in the amount and distribution of summer and winter precipitation, but the system is most sensitive to SST in the eastern Pacific.

H2. Precipitation recycling. Recycling of summer precipitation increases moisture availability in the northeastern part of the domain (see Dominguez et al. 2009), and this process exerts a major control over the annual northward extent of NAMS propagation. A negative feedback exists on the recycling of precipitation in the eastern part of the domain due to late snowmelt in the southern Rocky Mountains.

H3. NAMS behavior in the paleoclimate record. Based on dendrochronological evidence: (1) the use of winter versus summer precipitation by pinyon pine trees shifts in response to SST oscillations, with the variance in this shift increasing from south to north; (2) shifts in the shape and extent of the NAMS domain (patterns of coherency) are most evident at the transition from cool to warm climate phases.

2. ***Does the spread of invasive species have the potential to disrupt regional climate patterns (by affecting energy partitioning at the land surface) and thus disrupt the forces that provide coherency to the system, and if so, which parts of the domain are most sensitive to disruption?***

H4. Invasions and land-atmosphere feedbacks. During periods with anomalously high Pacific SST the spread of winter-active invasive grasses in the western part of the domain increases surface cooling longer into the spring, resulting in a delayed and weakened NAMS.

H5. Topographic influences. Heterogeneous elevation, slope, aspect, and associated water redistribution within the macrosystem affect the spread of invasive grasses, producing a local topographic control that modifies the domain-wide forcing by SST anomalies discussed in H4.

3. Will the combination of climate change and spread of invasive species change the frequency of wildfires and patterns of connectivity in wildfire regimes across the domain and how will that perturbation disrupt those forcings that induce synchrony in regional ecological processes?

H6. Invasive species and wildfire connectivity. Increases in the spread of winter-active invasive grasses in the western part of the domain and summer-active invasive grasses in the central part of the domain will increase the dry fuel load of lower elevation ecosystems, increase synchrony in the wildfire regimes across elevation gradients, and generally increase the frequency of wildfire across the domain.

H7. Paleoclimate and fire. Dendrochronological phases with high fire frequency coincide with domain-wide spatiotemporal patterns of winter and summer precipitation that are deduced, from modeling with the land-atmosphere RCM, to be correlated with anomalies in Pacific SST that favor high winter precipitation (fuel build-up at lower elevations) and low summer precipitation (dry fuel at higher elevations).

In addition to addressing these hypotheses, we will leverage the funds of this grant to initiate development of a new modeling platform that will permit us to take climate reconstructions from the tree-ring record into a new era of understanding. Cambial growth models are reaching a level of sophistication by which they can be coupled to mechanistic carbon assimilation models and regional climate models, and used to inform paleo-climate reconstructions with new perspectives on plant physiology-climate interactions (see Downes et al. 2009). We aim to initiate development of such a model. We will design the model to be simple enough to permit the assimilation of tree-ring records, and through inverse parameterization, determine the principal ecophysiological and climatological states that most influenced NPP in the NAMS domain during past climate phases.

VII. Testing the Hypotheses

In order to test the hypotheses associated with Question 1, we will develop and deploy the coupled WRF-CLM regional modeling platform using the entire NAMS domain (covering the tan and pink regions shown in Figure 1). We will begin our modeling explorations with low-frequency variability (daily to monthly) evaluated for the 20th and 21st Centuries, focusing on how large-scale atmospheric teleconnection responses are represented and how regional-scale climate responses are manifest in surface temperature, general patterns of precipitation and associated greening in the native vegetation. We will then move to description of higher frequency events (hour to daily) in selected portions of the domain, and then across the domain as a whole. As we move to these higher-frequency events we will be able to evaluate weather variability at scales that resolve localized convective activity, and thus best capture the evolution of individual monsoon thunderstorms. We will test H1 by exploring variance in the distribution of winter and summer precipitation across the NAMS domain in response to natural modes of variation in SST in the Gulf of California, Gulf of Mexico and eastern Pacific, as well as artificially forced combinations of SST in these various bodies of water. A variety of statistical tools (discussed below) will be used to develop spatial and temporal covariance matrices from model outputs. We will test H2 by exploring spatiotemporal patterns of precipitation recycling in response to natural modes of variation in SST, and we will force the modeling exercise by entering artificial, but realistic, rates of precipitation recycling in specified grids of the domain to determine spatially-explicit sensitivity to precipitation recycling in the extent and pattern of northward NAMS propagation. In order to test H3, we will apply Empirical Orthogonal Function (EOF) and Rotated Empirical Orthogonal Function (REOF) analyses to the tree-ring data (widths and stable isotope composition) to derive the principal components that define covariance between space and time across the NAMS domain. The principal components will be then be regressed against time-dependent climate anomalies (e.g., in SST, timing of snow melt). We will search for patterns in the distribution of nodes of convergence and divergence between the principal components defining tree ring patterns and modeled precipitation, to determine spatial (e.g., north-south) and temporal (e.g., different SST phases) trends with regard to winter versus summer precipitation use by pinyon pine.

We will test the hypotheses associated with Question 2 using the coupled WRF-CLM model, but this time in a configuration that includes ECOTONE and CATHY. We will test H4 by modeling the spread of winter-active invasive grasses in the western part of the NAMS domain, assessing the effect of that spread on spatial and seasonal patterns of predicted evapotranspiration (from the CLM component), and assessing alterations to the whole-domain distribution of winter and summer rain (from the WRF component). Once again, we will look for shifts in the nodes of spatial and temporal coherency and synchronization given different distribution scenarios in the spread of invasive grasses. In order to test H5 we will use runs with the coupled CATHY-ECOTONE models for isolated grid cells in both the western (invasive winter-active grasses) and central (invasive summer-active grasses) portions of the NAMS domain. We will examine the rates and spatial distributions of spreads in these invasive grasses as a function of specific features of the topographic relief (e.g., slope, aspect). We will use 'Smart Interpolation', a regression-based topographic analysis (Willmott & Matsuura 1995; described in more detail below), and in this case, applied to different combinations of landscapes and climate regimes.

In order to address the hypotheses associated with Question 3, we will develop a modeling framework for predicting wildfire frequency across the domain. We will develop new ways to link 'ignition probability' to 'fire damage (area burned)' within the existing wildfire component of CLM4 (see Kloster et al. 2010). Gill et al. (2010) used a pasture production model to predict grass production and the distribution of live and dead biomass in Australia as inputs to the Grassland Fire Danger Index (GFDI) model and thus predict the probability of fire on any single date at any single site. We propose to use the ECOTONE model in much the same way, but to focus on invasive grasses in the western US. The ECOTONE model provides estimates of biomass production, recruitment and mortality for grasses and shrubs. We will use the model to provide direct inputs to the GFDI Model in selected grids of the NAMS domain at different times of the year in order to predict fire danger probability. Using these grids, we will overlay time-dependent maps of fire danger with the geographic distribution of daily fire starts from the National Fire Occurrence Database and the Monitoring Trends in Burn Severity database to determine probabilities of wildfire in the grass-invaded grids (Bartlein et al. 2008). Maps of live fuel moisture will be constructed for grasslands and woodlands in the NAMS domain using the National Fuel Moisture Database that is a component of the Real-Time Observation Monitor and Analysis Network (a consortium effort between the US Forest Service, the Department of the Interior and the National Weather Service). We will test H6 by using the coupled WRF-CLM-ECOTONE-CATHY models to estimate fire frequencies for pinyon-juniper woodlands located in specified grid domains that border desert grasslands, and test for the influence of the spread of invasive grasses on fire frequency in both systems. We will test the sensitivity of this relation to different locations in the NAMS domain and during different climate regimes. We will test H7 by comparing the modeling results from H6 against reconstructed fire regimes from the tree ring record using analyses of fire scars. In this latter analysis we will search for relationships between fire frequency and distributions of winter and summer precipitation after cross-correlation between fire scar chronologies and climate chronologies constructed from the early- and late-wood ring analyses.

VIII. Specific Research Approaches

VIII.A. Model Development. An initial challenge will be to combine and integrate the four main modeling platforms. The structure of WRF is flexible and accommodating of new physical schemes, model code, and novel links among variables. CLM4 was originally developed for use in global configuration, and its architecture is different from that of regional models like WRF. To merge CLM4 and WRF, a considerable amount of coding work will be needed, including removing the time manager system of CLM4 and changing the sub-grid configuration. In addition, an interface between the two models will need to be built to enable exchanges of momentum, heat, water and radiation. Finally, we will need to modify CLM to operate with a more restricted set of surface properties specific for the NAMS domain. As discussed previously, we have previous experience in coupling WRF with CLM3.5. Given this experience, we believe that we can accomplish the coupling in a timely manner. We will revise ECOTONE to handle the specific case of establishment, growth and death of invasive grasses. We will draw upon existing data sets on the spread and demography of invasive grasses in different parts of the NAMS domain. We have identified four likely sources for such data: (1) the USGS Canyonlands Experimental Range in Western

Utah (Jayne Belnap, Director), (2) the USGS Santa Rita Experimental Range in Arizona (administered through the University of Arizona), (3) the Onaqui-Benmore site in Utah and eight other sagebrush sites administered under the SageStep Program (Jim McIver, Director), and (4) the Sevilleta LTER site in New Mexico (Scott Collins, Director). We have contacted the Directors of these sites and received permission to work with them, if funded, to identify data sets that would be of use to the further development of ECOTONE (see letters from Belnap, McIver and Collins). In coupling the CATHY, ECOTONE and CLM4 models, the hydrological schemes of ECOTONE including the 1-d soil moisture solver, will be removed. The slow ecological processes represented in ECOTONE and CLM4 will be coupled with CATHY's fast hydrological processes by averaging the output from CATHY to longer time intervals. The coupled models will be developed to update phenology once per model day and compute photosynthesis, respiration, and stomatal conductance per CLM time step. We will design CATHY to transfer its 3-d soil moisture solved at 198 nodes to ECOTONE's grid cells, and in turn, average ECOTONE's output in terms of daily plant growth across space to accommodate the grid structure of CLM4. Feedbacks from ECOTONE back to CATHY will occur through root growth and subsequent transpiration.

VIII.B. Model validation and estimation of uncertainties. We have described the various data sets available for validation activities in the Data Management and Access Plan. Briefly, we will validate the climate modeling through comparisons of time- and space-dependent patterns in model output and observations. For example, we will ask: does the model produce a diurnal pattern of convective activity within specified portions of the NAMS domain that is consistent with weather-process observations? We will test the model against observations of lower frequency processes, such as regional stream flow and changes in soil moisture, using combinations of satellite products and sensor networks from within the domain. For example, we will follow the approach of Lizárraga-Celaya et al. (2010) in using remotely-sensed MODIS products to derive seasonal maps of surface temperature, leaf area index and surface greening, and examine spatial distributions in the error between the observations and model output. We will also test modeled processes in the CLM4 model against patterns of CO_2, H_2O and energy exchange from a distributed set of eddy flux towers that were deployed during the NAME experiment, and a new set of flux towers distributed across southern Arizona (see letter of collaboration from Russ Scott in Supporting Documents). We will examine ways to validate spatially-averaged soil moisture predictions made by CATHY (embedded within CLM4) using the NCAR high-resolution land data assimilation system (HRLDAS) (Chen et al. 2007). HRLDAS utilizes Noah (in uncoupled mode) as its land surface model and the precipitation inputs to HRLDAS are independent of those for the CLM4 and CATHY runs (the NCEP Stage IV data originates from multi-sensor products from NWS Forecast Centers).

We will develop ways to validate predicted patterns of invasive grass spread using Landsat data. Landsat Thematic Mapper imagery has been used in past studies to map the spread of cheatgrass across landscapes in the northwestern US (Peterson 2005, Bradley & Mustard 2005). The early-season growth of invasive bromes and their amplified response to winter precipitation provide clear signals by which to map their spread. We will have access to historic information and maps on the spread of both cheat grass and red brome (Salo 2005, Bradley & Mustard 2006) from which we will isolate regions with available satellite images and assess annual rates and patterns of spread. We will also have access to the modeled spread of buffelgrass invasions in northern Sonora Mexico and southern Arizona (Arriaga et al. 2004, Rogstad 2008), from which we can guide similar analyses using satellite imagery.

Uncertainties in modeling activities will be assessed through multiple realizations of model runs for specified, but limited, time periods, and for specified, but limited, portions of the NAMS domain. In these different realizations we will vary parameterization schemes (e.g., for transport processes in the climate model, PFT-specific growth rates in the vegetation models, soil structural features in the hydrology model) within limits derived from previous knowledge to provide estimates of model sensitivities to various process components both at the level of overall model output and for the output of specific sub-processes. Uncertainties will be estimated as statistical variance among separate realizations in these sensitivity runs.

VIII.C. Assessing patterns of coherence and synchronization. As discussed above, we will use variants of principal components analysis (EOF and REOF) to assess and prioritize the variables that best explain covariance in model projections and observed tree-ring patterns from across the domain. We will use this activity to not only validate model projections, but to identify nodes of convergence and divergence. Additional approaches that we will use to identify nodes of synchrony include: (1) the Mann-Park multivariate frequency-domain (MFD) approach (Mann & Park 1993, Mann & Lees 1996), which is commonly used in weather forecasting (Rajagopalan et al. 1998). The products of this analysis include a local fractional variance (LFV) spectrum from which spatiotemporal modes can be identified and formal confidence intervals can be calculated. (2) a non-linear classification technique known as the self-organizing map (SOM) (Kohonen 1995, Cavazos et al. 2002). The SOM approach has been used to extract low-dimensional nodes of coherency from high-dimensional observation streams, especially where non-linear dependencies exist (Rodriguez-Iturbe et al. 1998). The SOM approach reflects an adaptational learning process in which multidimensional input vectors are mapped non-linearly onto two dimensional maps of convergence nodes. (3) 'Smart interpolation' (Willmott & Matsuura 1995, Willmott & Robeson 1995), a type of spatial kriging, but with more explicit consideration of topography using digital elevation maps. Data for specific locations are regressed against terrain variables, such as elevation or slope aspect, and the residuals of the regressions are kriged and added back to the regressions to produce a mapped product. Comrie and Broyles (2002) used this approach to create maps of synchronized cells within southern Arizona using precipitation data from a long-term rain-gauge network. Spatially-explicit maps of synchronization among grid cells and regions of the NAMS domain, and identification of oscillatory modes within time series developed from the climate modeling and tree-ring data, will be principal products of this research effort.

VIII.D. Initiation of a new tree ring growth model. We will leverage the opportunities provided by this grant to initiate a new modeling activity that would allow us to couple tree-ring climate reconstructions to the processes driving net primary production. The ultimate determinant of tree ring production reflects both climate and physiology (Vaganov et al. 2006). If we could construct a model that also reflects the climate-physiology relation, conditioned to the tree-ring record, we could use it to predict climate parameters. Recent models have been developed, including the CAMBIUM-CABALA model, that link tree ring growth to tree growth (Downes et al. 2009). We aim to push this type of modeling a step further and develop a system capable of accommodating tree ring observations as an assimilated data stream in order to estimate key physiological and climate parameters through inverse parameter estimation (Fig. 8).

We will develop an integrated modeling system using the CAMBIUM tree-ring growth model and the Deducing Emergent Structure and Physiology Of Trees (DESPOT) model; a model that determines CO_2 and H_2O fluxes on the basis of resource optimization (Buckley & Roberts 2006). The DESPOT model is driven by 44 physiological parameters, which is comparable in its simplicity to other process models we have used in past model-data assimilation studies (e.g., Sacks et al. 2006, 2007). We will initially run the model with climate forced by the WRF-CLM model for the NAMS domain, and use an inverse parameterization approach to 'optimize' the physiological parameter set, conditioned on the tree ring record for the past fifty years. We will then run the model again, but this time we will treat the climate parameters as unknowns to be optimized, and use the previously-optimized physiological parameters as knowns. This would allow us to estimate climate variables and their relation to winter and summer precipitation for periods prior to that used in the fifty-year initialization. We recognize that there are challenges to accomplishing this aim. For example, we will need to reconcile the seasonal and daily time-scale mismatch between model projections and tree-ring growth. We will explore ways to rectify this mismatch, both empirically (through stable isotope analyses on radial slices taken from individual tree rings) and through modeling (by averaging climate projections at the growing season scale). However, if we are successful with this effort, it could be transformational in that it would provide a new tool by which regional climate regimes can be reconstructed from tree-ring data through a physiologically-informed process.

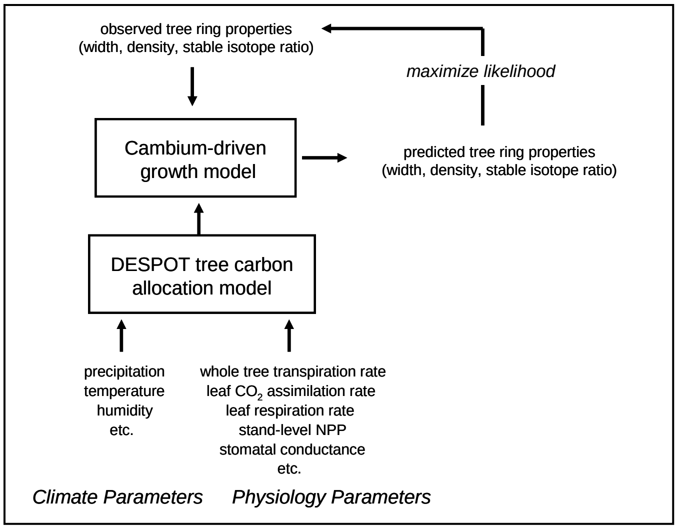

Fig. 8. Model-data assimilation scheme in which the tree-ring record is used to condition a model linking climate parameters to tree physiology.

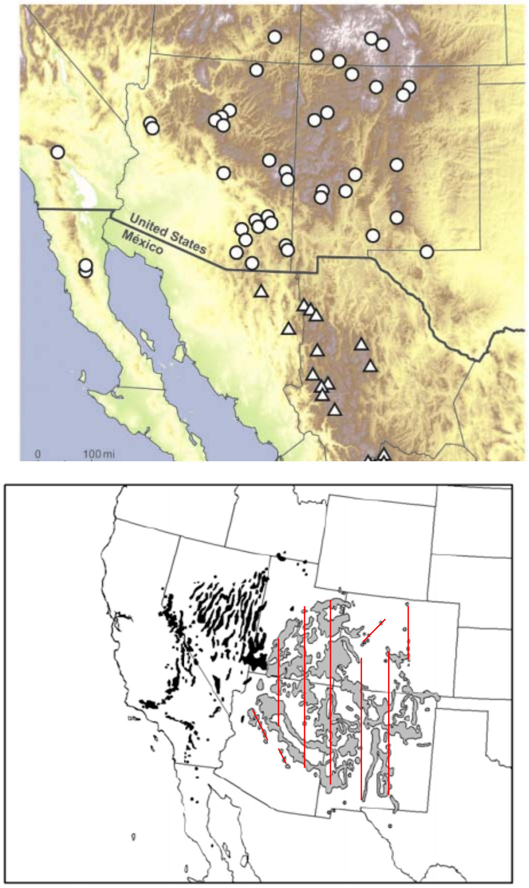

Figure 9. Upper figure. The monsoon-sensitive tree ring network being developed jointly by researchers at the University of Arizona (circles) and Instituto Nacional de Investigaciones Forestales, Agrícolas, y Pecuarias (INIFAP) in Mexico and Univ of Arkansas (triangles). **Lower figure.** Distributions of *P. monophylla* (black) and *P. edulis* (grey) in the Great Basin Desert and Colorado Plateau. From West (2006). The red lines mark proposed transects for developing the *P. edulis* tree ring archive.

VIII.E. Developing the tree ring record

We will develop tree-ring chronologies from pinyon-juniper (p-j) woodlands within the NAMS domain. In p-j woodlands of the southwestern US, *Pinus edulis* is the dominant pinyon species in areas with summer rain and *Pinus monophylla* dominates in areas with winter rain (Fig. 9) (Cole et al. 2008). We will focus on chronologies from *P. edulis*, as its range crosses the northern and eastern boundaries of the domain. (Juniper is not included because in the western US it tends to have multiple intra-annual rings that render accurate dating intractable.) We have marked proposed sampling transects as red lines in Figure 9. This sampling protocol will allow us to best address Hypothesis #3, "*that the relative use of winter versus summer precipitation for growth in pinyon pine has shifted over the past two centuries, with the variance in this shift increasing from south to north in the NAMS domain…".* As discussed previously, we will also have access to tree-ring records from Douglas-fir and Ponderosa pine from southern Arizona and western New Mexico, and from areas that extend into the Sierra Madre Mountains and Central Plateau of Mexico. These rings have been collected as part of ongoing research at the University of Arizona, University of Arkansas, and Instituto Nacional de Investigaciones Forestales in Mexico (Fig. 9, upper figure). We will leverage these activities by drawing on this tree ring record for additional analyses where justified.

We will generally follow the methods of Meko and Baisan (2001) and Stahle et al. (2009) for developing early-wood (EW) and late-wood (LW) records. Cores will be polished and cross-dated following Douglass (1941) and dated rings will be measured to 0.001 mm. Cross-checking of dating accuracy will be conducted using the program, COFECHA (Holmes 1983). Width chronologies for both EW and LW will be calculated from the means of normalized, detrended (to control for tree size and age) widths using the ARSTAN and CHRONOL programs (Cook 1985, Cook & Holmes 1986). For detrending we will use the spline method (Stahle et al. 2009) and for removing autocorrelations between EW and LW we will use the regression normalization described by Meko & Baisan (2001). Fire scars will be identified, dated and cross-checked with collections from across the domain.

VIII.F. Stable isotope analyses of tree ring cellulose

Early-wood and late-wood cellulose will be extracted from excised rings after drying and grinding to a fine powder. Samples will be placed in filter bags and extracted in a Soxhlet apparatus using toluene:ethanol (2:1) followed by just ethanol as described previously (Leavitt & Danzer 1993, Roden and Ehleringer 2007). Samples will be bleached with a sodium chlorite:acetic acid solution, extracted further with NaOH and dried to obtain pure cellulose. For measurement of ^{18}O, samples will be loaded into silver capsules, converted to CO by pyrolysis and analyzed with a Finnigan MAT deltaPlus XL isotope ratio mass spectrometer at the Stable Isotope Ratio Facility for Environmental Research at the University of Utah (see letter from Jim Ehleringer in Supplementary Documents). ^{13}C content will be determined following combustion of cellulose using the same mass spectrometer. Deuterium content will be determined from cellulose nitrate after removing exchangeable hydrogen according to Pendall (2000).

IX. Research Group

We have assembled a multidisciplinary research group consisting of ecologists (Monson, Peters, Betancourt, Yepez), hydrologists (Dominguez, Gochis), climate modelers (Castro, Watts), land-surface modelers (Zeng, Niu, Jin), and dendrochronologists (Woodhouse, Leavitt, Swetnam). These researchers bring unique and deeply-developed experiences to the project. Monson studies ecosystem carbon and water budgets from an ecophysiological perspective. Peters has studied ecosystem dynamics, population dynamics and the processes controlling invasive species spread in southwestern US grasslands; she developed the ECOTONE vegetation dynamics model. Castro has had extensive regional climate modeling experience, first with the RAMS model, and more recently with the WRF model, which he has developed for dynamic downscaling within the NAMS domain. Dominguez is a hydrologist and is working closely with Castro to include the DRM model of precipitation re-cycling within WRF. Zeng, Niu and Jin have strong linkages to the NCAR CLM modeling group; Zeng and Niu contributed directly to the development of CLM 4.0; Niu has coupled the CATHY hydrology model with the Noah land surface model to explore catchment-scale hydrology; and Jin has conducted a coupling of WRF and CLM for studies of western US snow dynamics. Woodhouse and Leavitt have expertise in analyzing tree rings, including stable isotopes, with regard to paleo-climate reconstructions. Swetnam has been an international leader in the reconstruction of contemporary and paleo-fire histories, with special emphases in the western US. Julio Betancourt a paleo-climatologist and ecologist at the USGS Laboratory for Arid Land Studies will collaborate on aspects of paleo-climate reconstructions. Dave Gochis, a hydrologist from NCAR, will help develop the community modeling platform and will collaborate on the regional climate modeling. Jim Ehleringer will serve in an informal role as a collaborator on the tree ring stable isotope analyses (see letter in Supplementary Materials). ***A detailed timeline as to how and when we will achieve the proposal aims is presented in the project Management Plan.***

X. Collaboration with Colleagues from Mexico

We will work with two collaborators from Mexico, Enrico Yèpez who studies plant ecology in Sonora and in the dry, sub-tropical forests of the Sierra Madre Mountains where the NAMS develops each year, and Christopher Watts who is broadly trained in climate and land-surface modeling. We have requested funds to allow these colleagues to visit the US and work with us on ecological process modeling (Yèpez) and the land-atmosphere feedback modeling (Watts). Using these funds, both researchers will be able to visit for one month each year for research collaborations. Both researchers were actively involved in the NAME research campaigns and thus they not only bring a binational collaboration to the studies, but they help maintain the scientific continuity developed during that decade-long research program.

XI. Broader Impacts

We will carry out five principal activities aimed at Broader Impacts in science: **(1)** We will train six post-doctoral associates and seven graduate students. **(2)** We will create a Discovery Fellows program through the Laboratory of Tree Ring Research (LTRR) to hire six K-12 teachers each of four summers to work with us as we assemble a pinyon tree ring archive. The Discovery Fellows will be divided into pairs and will work on developing a tree ring chronology for two different sites within the NAMS domain. At least one Fellow each year will be recruited from the Navajo Nation in New Mexico (see letter from Steven Chischilly (Diné) in Supplementary Documents). **(3)** We will establish collaborative studies with two professors from universities in Mexico (Prof. Enrico Yépez, Instituto Tecnológico de Sonora, and Prof. Chris Watts, Universidad de Sonora, see letters in Supplementary Documents). We intend for these collaborations to extend to the level of graduate student interactions, and we will allow Yèpez and Watts to use some of the funds we have requested for their own travel to be used by their students, should the students wish to visit for collaborations. **(4)** We will initialize a new 'community modeling process' to develop the coupled WRF-CLM platform. We will work with existing NCAR WRF support staff (see letter by Jimy Dudhia in Supplementary Documents) to provide a portal for model access, documentation for model users, and flexible coding schemes for use with multiple applications and platforms. **(5)** We will create a public display describing our research on the summer monsoon and its relevance to past Native American groups and contemporary societies, and we will present the display at the Biosphere 2 Center (University of Arizona), which hosts ~75,000 visitors each year (see supporting letter from Dr. Travis Huxman, Director). The display will emphasize ***connectivity*** among land-atmosphere forcings and feedbacks, the role of historical shifts in the NAMS on agriculture and subsistence within Native American groups, and reliance of contemporary human societies on climate dynamics within the NAMS domain.