# Role of the Hydrologic Cycle in Vegetation Response to Climate Change: An Analysis Using VEMAP Phase 2 Model Experiments


## Abstract

This proposal describes research intended to: 1) examine the effects of historical shifts in climate on the interactions of the carbon and water cycles as simulated by the biogeochemical and dynamic global vegetation models of the Vegetation/Ecosystem Modeling and Analysis Project (VEMAP) Phase 2, and 2) investigate how alterations to future climate, as simulated through the end of the $21^{st}$ century, are predicted to impact those same cycles and interactions. A substantial portion of the hydrologic exchange between the soil and the atmosphere is through vegetation. Conversely, available soil moisture is a key driver in the distribution of vegetation. Nonetheless, our understanding of the role of vegetation in the hydrologic cycle remains rudimentary. I plan to analyze the interactions of vegetation, hydrology, and climate at a regional scale using a 0.5° latitude/longitude grid across the conterminous U.S. Questions I intend to investigate include: How does the water balance of a region, including surface runoff, change as a result of climate alterations, and to what extent do these changes influence vegetation dynamics or species' migration? What role does the structure and function of vegetation play in mediating those changes, and what are the potential feedbacks between the vegetation and hydrology? Do the interactions between ecological and hydrological processes vary across temperature and moisture gradients? The analyses will require the compilation of an historical database of streamflow and precipitation data and the implementation of novel methods such as the application of river routing algorithms. The analyses will specifically examine issues of spatial (e.g., biomes, watersheds) and temporal (e.g., seasonality, interannual)

variability. It is expected that the results of this study will lead to a better understanding of the coupling of vegetation and hydrology, and improved representation of dynamic vegetation in global climate models.

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## Introduction

A question central to current investigations in earth system science is how does vegetation interact with the physical processes of the hydrological cycle? The question lies at the heart of our attempts to understand the potential effects of changing climate patterns over decades to centuries on the distribution of vegetation and linked effects on surface hydrology and the atmosphere. Because our understanding of global biogeochemical cycles and vegetation dynamics, and their links to the hydrologic cycle and to the physical-climate system, is incomplete and observations are sparse, modeling is a tool that can be used to study the response of terrestrial ecosystems to changing climate.

### *Goals and Objectives*

Described in this document is a research plan that proposes to investigate the interactions of vegetation, hydrology, and climate at a regional scale using a 0.5° latitude/longitude grid across the conterminous U.S. My objectives are twofold. First, I intend to examine the effects of historical shifts in climate on the interactions of the carbon and water cycles as simulated by the constituent models of VEMAP Phase 2 (see http://neit.cgd.ucar.edu/vemap/ for details). Second, I will investigate how alterations to future climate, as simulated through the end of the 21$^{st}$ century, are predicted to impact those same cycles and interactions. The linkages between the carbon and water cycles at the regional scale have only recently been the subjects of research; hence, much work remains to improve our understanding of the feedbacks between coupled processes. In fact, current policy documents highlight the necessity for research on how vegetation influences the transfer of freshwater through the land surface on decadal to centennial timescales (National Research Council 1998; National Science and Technology Council 1999).

Vegetation plays an active role in regulating water, energy, and carbon dioxide ($CO_2$) fluxes, which makes it a key regulatory force in the Earth's hydrological cycle. Through the plant-soil system, $CO_2$ uptake and water evaporation are intrinsically coupled, leading to links and feedback between land surface and climate processes. Questions I plan to investigate include: How does the water balance of a region, including surface runoff, change as a result of climate alterations, and to what extent do these changes influence vegetation dynamics or species' migration? What role does vegetation structure and function play in mediating those changes, and what are the potential feedbacks between the vegetation and hydrology? Do the interactions between ecological and hydrological processes vary across temperature, moisture, and topo-edaphic gradients? Can we attribute climate-induced changes in hydrology and the water balance to specific formulations of either the dynamic global vegetation or biogeochemistry models?

VEMAP is uniquely positioned to address these questions as it is, in part, a model intercomparison project. By examining multiple models and their interactions while controlling for climate, I expect to be able to effectively isolate the links between vegetation and hydrology. In all likelihood some models will more accurately simulate historical biogeochemical and biogeographical processes than others will. Examination of the models' output from various climate change scenarios will provide crucial insight into the level of uncertainty surrounding future climate predictions and the effects on ecosystem function. Identification of formulations that make the models successful under historical conditions will aid in further refinement and development of future models that can be used to predict future climate change and its effects.

Background

*What is VEMAP?*

The Vegetation/Ecosystem Modeling and Analysis Project (VEMAP) is an ongoing, multi-institutional and multi-national effort to address the response of biogeochemistry and biogeography to climate change, increasing levels of atmospheric $CO_2$, and other forcings for the conterminous U.S. (VEMAP Members 1995). VEMAP's objectives include the intercomparison of biogeochemistry models simulating the cycles of carbon, nutrients, and water in terrestrial ecosystems, and dynamic global vegetation models (DGVMs) that simulate the changing dominance or distribution of various plant life forms over time. The main purposes of VEMAP are to: 1) assess the models' sensitivity to climate change and $CO_2$, 2) determine important similarities and differences among model processes and responses, and 3) quantify the uncertainty in modeled responses to changing climate and other drivers.

The completed Phase I of the project was narrowly structured to identify differences in model algorithms and their implementation by running three biogeochemical and three biogeography models with common boundary conditions and driving variables (i.e., a database of current climate, soils, vegetation, and climate change scenarios used as a common input data set to the models) (VEMAP Members 1995). Conditions under which models were simulated and results compared included contemporary conditions of atmospheric $CO_2$ and climate, doubled $CO_2$ and a range of other climate scenarios. The shortcomings of Phase 1 included instantaneous changes in climate and $CO_2$ and the short duration of the experiment (i.e., climate scenarios were run for one only year).

The second phase of VEMAP model intercomparison and analysis is underway. The objectives of Phase 2 are to compare the responses of the biogeochemical and the coupled biogeochemical-biogeographical models to historical (i.e., $20^{th}$ century) and projected transient forcings (i.e., $21^{st}$ century) across the conterminous U.S., including scenarios of changing climate and atmospheric $CO_2$ concentrations. For the historical simulations, a 99-year historical climate data set containing daily and monthly values is being used to force the models. The future climate scenarios are derived from three climate model experiments. The major accomplishment of Phase 2 will be the representation of dynamic changes in vegetation structure and function, the inclusion of realistic interannual variability, and the generation of sufficient data for analyzing ecosystem changes over decadal to centennial time scales.

Runoff (Hibbard et al. in preparation) and the water balance (Cienciala et al., in preparation) were investigated during Phase 1. The hydrologic analysis compared simulated runoff to gauged streamflow data for nine biomes (Hibbard et al. in preparation). The study reported that all participating models underestimated annual observed runoff across the entire U. S., though the results varied by biome. The proportion of the water budget dominated by specific processes (e.g., evapotranspiration or runoff) also varied among models. The analyses were hampered by insufficient runoff data in some geographic regions and an absence of surface water routing. The water balance study examined simulated actual evapotranspiration (AET) and found it to be similar among models. However, predictions of other hydrological variables differed significantly among models (e.g., evaporation, partitioning of AET into transpiration and evaporation, changes in available soil moisture). Because Phase 1 experiments simulated equilibrium or steady-state conditions under long-term climatologies, no long-term trends could be analyzed. Phase 2 presents an opportunity to expand the scope of inquiry on these and related topics.

*Linkages Between Ecology and Hydrology*

Local and regional scale hydrology integrates plant physiological processes (e.g.., evapotranspiration), radiative transfer (e.g., latent heat flux), precipitation, and soil physics. In fact, streamflow data are commonly used to validate the land-surface component of climate models (e.g., Bonan 1998, Lohmann 1999). Many components of local and regional water balances are strongly influenced by the dominant vegetation type, topography, and soil hydraulic characteristics. Feedback mechanisms among these characteristics and functions in the face of altered climate may induce the redistribution of vegetation due to soil moisture limitations (e.g., Stephenson 1990, Foley et al. 1998), nutrient deficiencies as a result of altered litter decomposition rates (e.g., Cotrufo and Ineson 1996), and constraints on net primary productivity (Pan et al. 1996).

Prior research on the effects of climate change on vegetation and hydrological properties has focused primarily on plant physiological responses and changes in soil moisture (e.g., Hatton et al. 1992; Jackson et al. 1998). Soil moisture storage is a component of the water balance with important consequences for the dynamics of ecosystems and for climate. Not only is soil moisture a driving force in the global energy budget through latent heat fluxes, it is also tightly coupled with soil microbial activity. Both soil microbial biomass and respiration are positively correlated with soil moisture (up to an optimum). Changes in soil moisture would be expected to produce feedbacks on climate change through physical processes mediated by vegetation and soil fauna.

Most of the studies to date linking the topics of vegetation and the water balance have involved modeling (e.g., Idso and Brazel 1984; Hatton et al. 1992; Neilson and Marks 1994; Kremer et al. 1996; Jackson et al. 1998). The results from these studies generally demonstrated that increased atmospheric $CO_2$ leads to decreased stomatal conductance, followed by increased available soil moisture, and a concomitant increase in leaf area. The limited scope of many of these simulations, in conjunction with differing methodologies, has hampered synthetic analyses of the issues. A recent paper examined the effects of climate change on the hydrologic regimes of continental Europe (Arnell 1999), but without explicit consideration of the role of vegetation.

Increasingly, the research community is turning to coupled land-surface-atmosphere-ocean models with dynamic modules to achieve the realism necessary for climate studies. Most of the studies to date have incorporated equilibrium vegetation models into climate change simulations (e.g., Neilson and Marks 1994, VEMAP Members 1995, Betts et al. 1997, Neilson and Drapek 1998; but see Foley et al. 1998 for an example of climate simulations with a DGVM). It is recognized that the next stage is to include dynamic representations of the terrestrial biosphere. In this context, VEMAP Phase 2 model experiments will provide a unique opportunity to assess the effects of climate change on the hydrologic cycle and the water balance of regions on a continental scale, and how vegetation dynamics mediate those responses.

## Methods

I am proposing two major analyses: 1) a comparison of simulated to observed streamflow and soil moisture for the historical period as a means of validating the hydrology of the VEMAP models, and 2) an examination of how changes in the water balance affects species' distributions over the entire simulation period, and vice versa. The synthesis of these analyses should result in an understanding of how the models' formulations contribute to the patterns analyzed.

VEMAP Phase 2 model runs will cover two discrete periods: (1) the baseline or historical period from 1895-1993, and (2) a period of altered climate inputs from 1994 through the end of the 21st century as derived from three climate model experiments: i) the Canadian Centre for Climate Modelling and Analysis (model = CGCM1); ii) the Hadley Centre for Climate Prediction and Research, U.K. (model = HADCM2); and iii) the National Center for Atmospheric Research, U.S. (model = CSM)). The nearly 100-year baseline period will allow for the examination of multi-decadal variations that may be of similar magnitude to the effects of climate change.

*Validation of Simulated Data for Historical Period*

Several sources of historical data are available for the purpose of validating simulated runoff. Dolph and Marks (1992) developed a comprehensive geographic database of historical runoff measurements for the conterminous U.S. The database is derived from monthly time-series runoff data spanning 1948 to 1988 from 1014 gauging sites. A second database was compiled by Slack and Landwehr (1992) using daily discharge records from more than 1500 streamgages. Another source of data is the Global River Discharge Database (Vörösmarty et al. 1998) derived from UNESCO river archives. For the conterminous U.S. there are nearly 90 sites included, and some records extend back through the early part of the 20th century. I will build an observed validation data set from these sources.

A parsimonious approach to the evaluation of streamflow will be to compare simulated, historical streamflow to observed data on a monthly, seasonal, and annual basis for selected watersheds representative of different geographic regions. These analyses will summarize the hydrological extremes of base flows, low flows, and peak flows, and the validation exercise will specifically include key climatological events such as the droughts of the 1920s/1930s and the 1950s.

A more sophisticated method of evaluation will include evaluating model behavior by comparing simulated to observed hydrographs. One method for making these comparisons is to apply cell-to-cell routing algorithms to precipitation and runoff data. A precipitation data set has been compiled for VEMAP Phase 2 (Kittel et al. 1997). Work on developing routing algorithms is currently in progress at The University of Texas at Austin (Bransetter and Famiglietti 1999; Olivera et al. 1999). Currently, routing of surface water is absent from all VEMAP models, that is, precipitation falls on a grid cell and any runoff generated within that grid cell remains in place. The application of routing will allow the transport of runoff between grid cells. It should be interesting to determine the importance of surface runoff routing to the accurate representation of surface hydrology by the models.

Soil moisture is a relevant parameter for assessing the impact of changes in the hydrologic cycle on vegetation as it integrates the effects of changes in precipitation, evapotranspiration, and runoff throughout the year. Unfortunately, soil moisture data for validation purposes are available on a limited basis only. Sources of soil moisture data include the Oklahoma mesonet, a 10-year database of monthly measurements for the state of Illinois (Hollinger and Isard 1994), and Long-term Ecological Research Station data. I will compare simulated soil moisture data to observed *in situ* data on a monthly basis where possible.

*Interactions Between the Water Balance and Species' Distributions*

The simultaneous examination of changes in the water balance and species' distributions will require analyses of processes occurring across a range of spatial and temporal scales. Climate changes might yield alterations in the seasonality of precipitation and runoff, and the timing of peak and low streamflows, with concomitant changes in soil moisture storage; changes in any of these parameters may have consequences for plant phenology and species' distributions. I will look at the magnitude and direction of changes in intra- and interannual variability of surface runoff and other components of the water balance while also looking for changes of similar magnitude in the distribution of dominant plant species. Analysis of water balance data by biome type as delineated by VEMAP will facilitate this investigation. The use of biomes provides a simplified approach to characterizing the linkage between vegetation and hydrology by narrowing the analysis to similar plant functional types.

The area of each biome under past, current, and future climates will be calculated. At each of the three time periods, one approach will be to calculate water available for plant use (roughly precipitation minus runoff) by biome and zonally across large-scale temperature, moisture, and topo-edaphic gradients to examine interactions among climate, physiological processes, and abiotic factors. Stephenson (1990) determined that the distribution of North American biomes was highly correlated with two water balance parameters, AET and deficit. Zonal analyses will be achieved by aggregating data at relatively coarse scales, that is, on the order of 10 degrees of latitude.

Another approach will be to assess the relative sensitivity of streamflow to climate-induced changes in precipitation and evapotranspiration. As noted above, elevated concentrations of $CO_2$ have been shown to directly influence evapotranspiration through reductions in stomatal conductance (Knapp et al. 1996). Models have suggested that this effect could lead to increases in streamflow (e.g., Idso and Brazel 1984). Changes in temperature and humidity, expressed as changes in evaporative demand, would be expected to affect evapotranspiration. We would also expect changes in evapotranspiration as a result of alterations to vegetation structure and function (i.e., changes in the areal extent of plant cover, in density of vegetative cover, and in species' distributions) due to either climate change and/or direct effects of $CO_2$ on plant growth. Following the methods of Wigley and Jones (1985), I will quantify the relative contributions of changes in precipitation and evapotranspiration to changes in runoff. I will also engage in off-line studies using several of the models to further explore how unique model formulations contribute to differential sensitivity. As noted above, there may be zonal influences on these relationships. We might expect to find, for example, differences between coastal and continental areas as the hydrologic cycle of coastal areas is typically driven by seasonal variability in rainfall and evaporation, while northern continental areas have a snow-driven hydrology and snow cover is highly sensitive to changes in temperature. These analyses should promote a mechanistic understanding of changes in species' distributions.

*Synthesis*

The analyses of the historical data simulations will provide a baseline for understanding how model formulations vary among the different DGVMs and biogeochemical models participating in VEMAP. Because future climate simulations are sensitivity experiments covering a future period, it will be impossible to validate their results. Nonetheless, findings from the historical climate experiments should foster qualitative assessments of the plausibility of the modeled outcomes under climate change. Moreover, the results of the climate change scenarios will, in all likelihood, provide a range of results. Again, identifying similarities and differences in results across the models will aid in understanding which physiological and physical processes may determine the physiognomy of future landscapes.

As in any project, VEMAP has its limitations. Vegetation changes cannot feed back to climatological processes. In this respect, the models run one-way. There are uncertainties associated with the simulations of regional climate changes from global climate models including uncertainties related to changes in the timing and seasonality of precipitation. There are also uncertainties in the downscaling of climate change scenarios from the climate model scale to the catchment scale. The models differ in their representation of hydrologic processes, and hence, will vary in their sensitivity to climate change. Finally, the inherent variability of climate model data differs from that of actual weather – with potentially serious implications for the transition between observed and simulated periods. One way in which these issues will be explored during data analysis is by examining variance characteristics in addition to measures of central tendency.

## Summary

I have outlined a research plan to examine the effects of historical shifts in climate on the interactions of the carbon and water cycles as simulated by the constituent models of VEMAP, and to investigate how alterations to future climate, as simulated through the end of the 21st century, are predicted to impact those same cycles and interactions. In particular, I intend to investigate questions concerning the role of hydrology in vegetation change, and the ways in which vegetation dynamics mediate hydrologic changes. This project should make a unique contribution by considering the links between vegetation and hydrology in conjunction with changing climate, by applying new methodologies to the analysis of streamflow data, and by expanding the period of time over which analyses have been performed. A recent report on trends in streamflow data for the conterminous U. S. (Lins and Slack 1999) suggests that these types of analyses are timely with respect to the questions being posed here and the availability of data to answer those questions. The investigation into the importance of runoff routing to the accurate representation of surface water hydrology in ecological models is also timely and important as many modelling groups, including VEMAP participants, are proposing to include routing in the next generation of models. The linkages between the carbon and water cycles have only recently been the subject of research; hence, much work remains to improve our understanding of these coupled processes. The experiments and analyses described herein should lead to better representation of dynamic vegetation in global climate models.

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