The VEMAP Integrated Database for Modelling United States Ecosystem/Vegetation Sensitivity to Climate Change

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The VEMAP integrated database for modelling United States ecosystem/vegetation sensitivity to climate change

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Abstract. For the Vegetation/Ecosystem Modelling and Analysis Project (VEMAP), we developed a model database of climate, soils and vegetation that was compatible with the requirements of three ecosystem physiology models and three vegetation life-form distribution models. A key constraint was temporal, spatial and physical consistency among data layers to provide these daily or monthly time step models with suitable common inputs for the purpose of model inter-comparison. The database is on a 0.5° latitude/longitude grid for the conterminous United States. The set has both daily and monthly representations of the same long-term climate. Daily temperature and precipitation were stochastically simulated with WGEN and daily solar radiation and humidity empirically estimated with CLIMSIM. We used orographically adjusted precipitation, surface temperature and surface windspeed monthly means to maintain consistency among these fields and with vegetation distribution. Vegetation classes were based on physiognomic and physiological properties that influence biogeochemical dynamics. Soils data include characteristics of the 1–4 dominant soils per cell to account for subgrid variability.

Key words. Climate, soils, integrated database, spatial interpolation, ecosystem physiological modelling, vegetation life-form distribution modelling, United States.

INTRODUCTION

Continental and global simulations of ecosystem physiology and vegetation distribution and their sensitivity to climate and CO_2 change have recently been evaluated in a number of modelling studies (e.g. Melillo *et al.*, 1993, Monserud, Tchebakova & Leemans, 1993; Neilson, 1993; Ojima *et al.*, 1993; Running & Nemani, 1991). Comparison of these results is restricted by the use of different driving-variable and boundary-condition datasets and different scenarios of altered forcing. In addition, with few exceptions (cf. Pastor & Post, 1988), studies have not evaluated the joint response of ecosystem nutrient cycling and biome redistribution to altered forcing across large domains.

The Vegetation/Ecosystem Modelling and Analysis Project (VEMAP) is a multi-institutional, international effort whose goal is to evaluate the sensitivity of terrestrial ecosystem and vegetation processes to altered climate forcing and elevated atmospheric CO_2. The project's objectives are (1) inter-comparison of the climate and CO_2 sensitivity of three ecosystem physiology models (plant production and soil biogeochemical process models) and three vegetation life-form distribution models (biome distribution models) and (2) the one-way linkage of vegetation distri-

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bution and ecosystem physiology models to evaluate the joint response of these processes to altered conditions. To accomplish these objectives, the models require common boundary conditions and driving variables so that differences in model results arise only from the models and their implementation rather than from differences in inputs. In addition, a consistent dataset was required for paired simulations with vegetation distribution and ecosystem physiology models.

The three biome distribution models in the VEMAP set are BIOME2 (Prentice *et al.*, 1992; Haxeltine, Prentice, Cresswell, 1995, DOLY (Woodward *et al.*, 1995), and MAPSS (Neilson, 1995). The three ecosystem physiology models are BIOME-BGC/GESSys (Running & Hunt, 1993), CENTURY (Parton *et al.*, 1987, 1994), and TEM (Melillo *et al.*, 1993; McGuire *et al.*, 1993). DOLY and BIOME-BGC are daily time step models, while the others run with monthly inputs.

In this paper, we describe briefly the VEMAP integrated model input database and its development. Access to the database is open to the modelling community via the internet on the World Wide Web site:

http://www.cgd.ucar.edu: 80/vemap/

or contact the corresponding author.

DATABASE REQUIREMENTS AND CONCEPTUAL FRAMEWORK

Current-climate driving variables required by the suite of models were both daily and monthly fields of minimum and maximum surface air temperature, precipitation, total incident solar radiation, surface air humidity and surface windspeed. Boundary conditions included soil properties (including texture and water holding capacity) and vegetation type. Altered climate scenarios were also needed for the same set of driving variables. The domain for the VEMAP simulations was the conterminous United States, using a 0.5° latitude/longitude interval grid.

Beyond supplying needed variables on a specified grid, additional requirements for the model inter-comparison dataset were (1) physical consistency among driving variables and boundary conditions as required for any standalone model run and (2) the need to match differing individual model requirements for the same variables in a manner that did not violate the conceptual basis of any of the models. Physical consistency among variables was achieved in the climate database by (1) using monthly mean data developed with spatial interpolation techniques that account for effects of topography on climate and (2) using covariance information and empirical relationships among related variables in the generation of daily data. Altered climate scenarios were also constrained to maintain some degree of physical consistency.

In the soils dataset, physical consistency was incorporated by representing a grid cell's soil by a set of dominant soil profiles, rather than by a simple cell average of properties. Because soil processes, such as soil water balance, are non-linearly related to soil texture and other soil parameters, simulations based on dominant soil profiles and their frequency distribution can account for soil dynamics that would be lost if averaged soil properties were used.

Matching model requirements was also a key constraint in the development of consistent daily and monthly climate datasets. Daily time step models require realistic daily variance structure and, as a result, daily 'normals' (e.g. 30-year averages by day of year) would not suffice. On the other hand, the monthly time step models generally require long-term monthly climatological data. Therefore, the daily climate dataset had to have daily variances and covariances characteristic of an actual weather record but maintain, on a monthly basis, the same climate as the long-term climatology. This was accomplished by (1) stochastically generating daily climates for each grid cell based on temporal statistical properties of nearby weather stations and (2) constraining the monthly means of the created daily record to match those of the cell's long-term climate. These processes are described in more detail in the next section. Matching model requirements also played a role in the classification of vegetation types. We based the vegetation classes on physiognomic and physiological characteristics that best corresponded to the conceptual perspectives of both classes of models.

DATASET DEVELOPMENT

Grid description

The VEMAP grid is a 0.5° latitude/longitude grid with cell centres at 0.5° and 1.0° points and covers the conterminous United States (Fig. 1). The dataset includes fields of cell latitude, longitude, elevation and area. Elevation was aggregated from 10-minute Navy Fleet Numeric Oceanographic Center (NFNOC, 1985) data (D. Kicklighter and A. D. McGuire, pers. comm.).

Climate variables

For the model inter-comparison, the common climate input dataset needed to be:

1. Spatially consistent, with climate data reflecting orographic effects.
2. Temporally consistent, with daily and monthly representations of the same long-term base climate.
3. Physically consistent, maintaining relationships among climate variables.

These requirements were met in a three-step process.

Step 1: topographically adjusted interpolation of monthly mean temperature, precipitation and windspeed. Monthly mean minimum and maximum temperatures from 4613 station normals (NCDC, 1992) were adiabatically adjusted to sea level using algorithms of Marks & Dozier (1992), interpolated to the grid, and then re-adjusted to grid elevations. Mean monthly precipitation was spatially aggregated from a 10-km gridded U.S. dataset

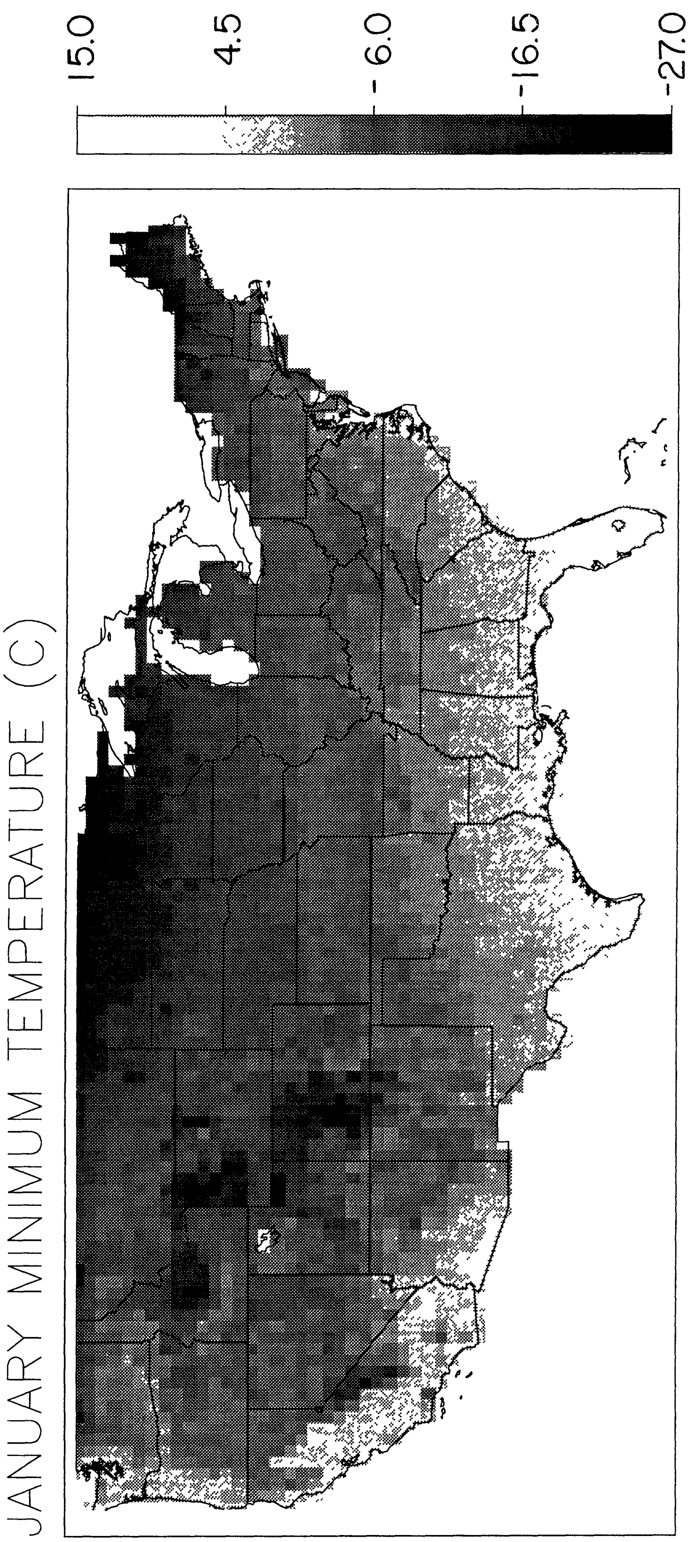

FIG. 1. VEMAP gridded mean January minimum temperature, spatially interpolated with adiabatic adjustment from surface station means.

TABLE 1. VEMAP vegetation classes, based on physiognomy (life-form, leaf seasonal duration and leaf shape) and, for grasslands, physiology (photosynthetic pathway).

Tundra	
1	Tundra
Forest	
2	Boreal coniferous forest (includes boreal transition & subalpine forests)
3	Maritime temperate coniferous forest
4	Continental temperate coniferous forest
5	Cool temperate mixed forest
6	Warm temperate/subtropical mixed forest
7	Temperate deciduous forest
8	Tropical deciduous forest
9	Tropical evergreen forest
Xeromorphic woodlands and forests	
10	Temperate mixed xeromorphic woodland
11	Temperate conifer xeromorphic woodland
12	Tropical thorn woodland
Savannas	
13	Temperate/subtropical deciduous savanna
14	Warm temperate/subtropical mixed savanna
15	Temperate conifer savanna
16	Tropical deciduous savanna
Grasslands	
17	C3 grasslands (includes short to tall C3 grasslands)
18	C4 grasslands (includes short to tall C4 grasslands)
Shrublands	
19	Mediterranean shrubland
20	Temperate arid shrubland
21	Subtropical arid shrubland

developed using PRISM (Daly, Neilson & Phillips, 1994). PRISM models precipitation distribution by (1) dividing the terrain into topographic facets of similar aspect, (2) developing precipitation–elevation regressions for each facet for a given region based on station data, and (3) using these regressions to spatially extrapolate station precipitation to cells that are on similar facets. Mean monthly windspeeds at 10 m height were derived from Marks (1990) based on DOE seasonal wind averages (Elliott *et al.*, 1986). The DOE winds were topographically corrected to account for greater windspeeds over regions with high terrain by Elliott *et al.* (1986).

Step 2: stochastic generation of daily temperature and precipitation data. We used a daily weather generator, a modified version of WGEN (Richardson, 1981; Richardson & Wright, 1984), to statistically simulate daily temperature and precipitation. Monthly means of daily values were matched to the long-term means. Parameterization of WGEN was based on daily records from 870 stations (Shea, 1984; Eddy, 1987). WGEN created records that realistically represent daily variances and temporal autocorrelation (e.g. persistence of dry and wet days) and maintain the physical relationship between daily precipitation and temperature. For example, days with precipitation tended to have higher minimum and lower maximum temperatures than days with no precipitation. These characteristics of the daily set are required for the daily-based models to adequately simulate water balance and ecological dynamics.

Step 3: empirical estimation of daily and monthly solar radiation and humidity. We used CLIMSIM (a simplified version of MT-CLIM for flat surfaces; Running, Nemani & Hungerford, 1987; Glassy & Running, 1994) to estimate daily total incident solar radiation, daily irradiance and surface humidity based on the daily minimum and maximum temperature and precipitation. The objective of this approach was to maintain physical relationships among temperature, precipitation, solar radiation and humidity on a daily basis. Monthly means of radiation and humidity were derived from the daily values. CLIMSIM determines daily solar radiative inputs based on latitude, elevation, diurnal range of temperature and occurrence of precipitation using algorithms of Gates (1981) and Bristow & Campbell (1984). Mean daily irradiance was also calculated based on day length. CLIMSIM estimates empirically daily vapour pressure and relative humidity by assuming that on a daily basis minimum temperatures reach the dew point. Because this is often not the case in arid regions, we adjusted daily humidity data downward so that the monthly means match those of Marks (1990).

Boundary conditions

Vegetation types were defined physiognomically in terms of dominant life-form and leaf characteristics (including leaf seasonal duration, shape and size) and, in the case of grasslands, physiologically with respect to dominance of species with C3 versus C4 photosynthetic pathway (Table 1). The physiognomic classification criteria were based on our understanding of vegetation characteristics that influence biogeochemical dynamics (cf. Running *et al.*, 1994). The U.S. distribution of these types was based on a 0.5° latitude/longitude gridded map of Küchler's (1964, 1975) potential natural vegetation (D. Kicklighter and A. D. McGuire, pers. comm.). These vegetation types represent a match between vegetation classes simulated by the biome distribution models and ecosystem types required as boundary conditions by the ecosystem physiology models.

Soil texture, depth and other properties were determined for dominant soil types based on Kern's (1994, 1995) 10-km gridded Soil Conservation Service national-level (NATSGO) database. To aggregate the Kern dataset spatially to the 0.5° grid, we used cluster analysis to group the 10-km subgrid elements into modal soil types. In this statistical approach, cell soil properties are represented by a set of 1–4 modal soil profiles, rather than by an 'average soil' that may not correspond to an actual soil in the region.

Climate scenarios

Climate scenarios for eight climate change experiments were included in the database. Seven of these experiments are from atmospheric general circulation models (GCMs) implemented with a simple 'mixed-layer' ocean representation that includes heat storage and vertical exchange of heat and moisture with the atmosphere. The experiments are $1 \times CO_2$ and $2 \times CO_2$ equilibrium runs and are archived at the National Center for Atmospheric Research (NCAR; Jenne, 1992). These runs are from the Canadian Climate Centre (CCC; Boer, McFarlane & Lazare, 1992), Goddard Institute for Space Studies (GISS; Hansen *et al.*, 1984), Geophysical Fluid Dynamics Laboratory (GFDL, including R15 4.5° × 7.5° grid runs with and without Q-flux corrections, and an R30 2.22° × 3.75° grid run; Manabe & Wetherald, 1987; Manabe & Wetherald in Mitchell *et al.*, 1990), Oregon State University (OSU; Schlesinger & Zhao, 1989), United Kingdom Meteorological Office (UKMO; Wilson & Mitchell, 1987). The CCC and GFDL R30 runs are among the high resolution GCM experiments reported in IPCC (1990). We also included in the VEMAP scenarios results for the conterminous United States from a nested regional climate model (RegCM, based on the Pennsylvania State University/NCAR mesoscale model MM4) by Giorgi, Brodeur & Bates (1994) driven by 1 × and $2 \times CO_2$ GCM runs (Thompson & Pollard, 1995a,b).

Changes in temperature were represented as differences and those for precipitation, solar radiation, vapour pressure (not available for the CCC run) and horizontal windspeed as change ratios. We determined differences for relative humidity based on the VEMAP base climate and climate changes for temperature, vapour pressure and surface pressure. We interpolated change fields spatially to the 0.5° grid using simple interpolation techniques. This provided smoothed change fields that could be applied to the VEMAP base climate to generate altered-climate inputs.

A key issue in the generation of altered climates based on climate model output is the strong possibility of physical inconsistences in the new climates. Change ratios from the NCAR archive have an imposed upper limit of 5.0, providing some constraint on these changes. In the creation of the new climates, additional checks were that (1) total incident solar radiation did not exceed potential solar input and (2) relative humidity stayed in the range from 0 to 100%.

SUMMARY

The VEMAP database is an integrated dataset for ecological modelling studies covering the conterminous United States. Physical consistency among climate drivers was accomplished by (1) spatial interpolation that incorporates topographic effects and (2) stochastic generation and empirical estimation of daily data that accounts for temporal variance structure and covariance among variables. Vegetation types were defined in a manner compatible with the needs of both ecosystem physiological and vegetation lifeform distribution models. We developed modal soil data to provide boundary conditions that more closely represent actual soils than would a coarse-grid average of soil properties. Together these methods assure the consistency among model inputs, and between inputs and model assumptions, required to adequately capture spatial patterns of ecological change.

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