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Effects of spatial and temporal climatic variability on terrestrial carbon and water fluxes in the Pacific Northwest, USA

Sinkyu Kang [a,*], Steven W. Running [b], John S. Kimball [b], Daniel B. Fagre [c], Andrew Michaelis [b], David L. Peterson [d], Jessica E. Halofsky [e], Sukyoung Hong [f]

[a] Department of Environmental Science, Kangwon National University, Chuncheon, Kangwon-do 200-701, Republic of Korea
[b] Numerical Terradynamic Simulation Group (NTSG), College of Forestry and Conservation, The University of Montana, Missoula, MT, USA
[c] USGS Northern Rocky Mountain Science Center, West Glacier, MT, USA
[d] U.S. Forest Service, Pacific Northwest Research Station, Seattle, WA, USA
[e] School of Forest Resources, University of Washington, Seattle, WA, USA
[f] Soil and Fertilizer Management Division, National Academy of Agricultural Science, Rural Development Administration, Suwon, Republic of Korea

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ABSTRACT

The Pacific Northwest (PNW) of the conterminous United States is characterized by large variations in climate and topography, and provides an ideal geographic domain for studying interactions between regional climate and vegetation dynamics. We examined vegetation carbon (C) and water dynamics along PNW climate and topographic gradients using a process-based biogeochemical model, BIOME-BGC, the algorithms of which form bases for a fully-prognostic treatment of carbon and nitrogen cycles in Land Community Model (CLM). Simulation experiments were used to (1) analyze spatial and temporal variability of terrestrial carbon (C) stocks and flux, (2) investigate primary climatic variables controlling the variability, and (3) predict effects of future climate projections on vegetation productivity and water flux variables including evapotranspiration and water supply. The model experiments focused on two 18-year (1980–1997 and 2088–2105) simulations using future climate predictions for A2 (+4.2 °C, −7% precipitation) and B2 (1.6 °C, +11% precipitation) emissions scenarios through year 2100. Our results show large west to east spatial variations in C and water fluxes and C stocks associated with regional topography and distance from coastal areas. Interannual variability of net primary productivity (NPP) and evapotranspiration (ET) are 57% and 33%, respectively, of the 18-year mean annual fluxes for 1980–1997. The annual NPP and ET are positively correlated with precipitation but inversely proportional to vapor pressure deficit; this suggests that modeled NPP and ET are predominantly water limited in the PNW. The A2 scenario results in higher NPP and ET of 23% and 10%, respectively, and 15% lower water outflow. The B2 scenario results in higher NPP and ET of 12% and 15%, respectively, and 2% lower water outflow, despite projected increases in precipitation. Simulation experiments indicate that most PNW ecosystems are water limited, and that annual water outflow will decrease under both drier (A2) and wetter (B2) scenarios. However, higher elevations with high snowpacks of long duration may buffer the loss of water resources in some areas, even if precipitation is lower.

1. Introduction

The functions of terrestrial ecosystems and climate are closely linked, and numerous studies have examined the influence of climatic variability and change on ecosystem function at the global or continental scale (e.g., Braswell et al., 1997; Kucharik et al., 2000; Bachelet et al., 2001, 2003; Cramer et al., 2001; Lucht et al., 2006). However, there is increasing interest in predictions of the effects of climatic variability and change at the regional scale (Fagre et al., 2003), because studies at this scale provide important information about ecosystem response to climatic variability and change that can be masked in coarser scale studies (Bachelet et al., 2001). It is also more feasible to implement mitigation and adaptation strategies at regional and sub-regional scales (e.g., Millar et al., 2007; Joyce et al., 2009).

It is particularly important to investigate effects of climatic variability and change in mountainous regions, because mountains support a high diversity of ecosystems, provide a wide range of

* Corresponding author. Tel.: +82 33 250 8578.
E-mail address: kangsk@kangwon.ac.kr (S. Kang).

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ecological services to human populations (Beniston and Fox, 1996), and are especially vulnerable to climate change (IPCC, 2007). Mountains accumulate larger amounts of precipitation, often in the form of snow, than surrounding lowlands and serve as "water towers" by supplying river systems and providing fresh water for humans. Increasing temperatures with climate change are expected to cause more precipitation falling as rain rather than snow (Mote, 2003), earlier snowmelt and snowmelt-driven streamflow (Stewart et al., 2005), and reduced spring snowpack (Mote, 2003; Mote et al., 2005; Barnett et al., 2008). For the mountainous regions of the western United States, snowmelt provides approximately 70% of annual streamflow (Mote et al., 2008). Both increased winter rain (as opposed to snow) and shifts to earlier spring snowmelt are expected to result in higher winter and spring streamflows and lower summer streamflows in snowmelt-dominated and transient (rain/snow) watersheds. This reduction in summer streamflow would have major implications for water supply, fisheries, wildlife, and agriculture, making increased understanding and regional predictions of changes in water flux with climate variability and change critical.

Increased temperatures and atmospheric CO_2 levels with climate change will also influence other plant and ecosystem processes, such as photosynthesis, water use efficiency, and biogeochemical cycling (Long, 1991; Amthor, 1995; Kirschbaum, 2004). Changes in these and other processes will influence vegetation dynamics, ecosystem productivity and carbon storage (Cao and Woodward, 1998; Cramer et al., 2001; IPCC, 2007). For example, increased atmospheric CO_2 concentrations could have a direct plant "fertilization" effect by increasing water use efficiency, thus increasing net primary production (NPP) (Idso, 1991; Kirschbaum, 2004). However, climate warming may also result in decreased soil moisture in mountainous regions of the western United States (Wetherald and Manabe, 2002; Manabe et al., 2004). Process-based models can help in understanding these complex interactions. By providing information on the influence of climatic variability and change on carbon stocks and fluxes, process-based models can also suggest how ecosystem processes, productivity, and services will be influenced by climate change.

Regional modeling studies using process-based models have been reported at various spatial scales from watershed to sub-continental scales. White et al. (1997a,b) and Baron et al. (2000) simulated current and future carbon and water fluxes in Rocky Mountain areas using RHESSys model (Tague and Band, 2004). Nemani et al. (2009) provided a case study investigating carbon and water fluxes under current and projected future climate conditions in Yosemite National Park in U.S.A. The sub-continental carbon and water fluxes were also simulated for East Asia (Ito, 2008), Canadian boreal forest (Kang et al., 2005), and tropical forests (Ichii et al., 2005). The regional modeling applications provide us new opportunity to enhance our understanding on carbon and water dynamics across climatic and topographic gradients at spatial scales that can be comparable with management practice units. Nevertheless, some research gaps exist for future enhancements of regional modeling schemes such as (1) incorporating high spatial resolution input data of climate and soil information, (2) investigating climatic and topographic controls on coupled carbon-water dynamics and, (3) considering historical disturbances, and (4) developing regional model validation dataset from both pristine and disturbed areas. Nemani et al. (2009) proposed a comprehensive regional modeling system to fill the research gaps. This study focus to address the above-mentioned first and second research gaps for the Pacific Northwest (PNW) region of the continental United States.

The PNW region is a biologically, topographically, and climatically diverse region that encompasses steep topographic and climatic gradient, with strong west-to-east temperature and precipitation variability within and across the Olympic, Cascade, and Rocky Mountains (Fig. 1). The large regional variations in climate and topography that characterize the PNW make it an ideal geographic region for studying interactions between regional climate and ecosystem function. In this study, we examined vegetation carbon and water dynamics along climatic and topographic gradients in the PNW using the process-based biogeochemical model, BIOME-BGC (White et al., 2000; Thornton et al., 2002). Simulation experiments were used to: (1) analyze spatial and temporal variability in carbon stocks and flux variables of carbon, (2) investigate the primary climatic variables controlling this variability, and (3) predict effects of different climate change scenarios on vegetation productivity and water flux variables, including evapotranspiration and water supply. Simulations were conducted for two 18-year periods (1980–1997, 2088–2105) and two different climate change scenarios (A2 and B2; Table 1).

2. Methods

Simulation experiments were designed to have two 18-year (1980–1997 and 2088–2105) simulations for the A2 and B2 emission scenarios (*sensu* IPCC, 2007). The A2 scenario is characterized by hotter and drier climate in the PNW (+4.2 °C, −7% precipitation) for the year 2100, and the B2 scenario is characterized by moderately warmer and wetter conditions (1.6 °C, +11% precipitation).

2.1. Study area description

The spatial domain for this study encompasses a 1000 km by 200 km portion of the PNW, spanning 12° (113–125 W) of longitude and 2° (47–49 N) of latitude, including portions of northern Washington, Idaho, and western Montana, USA (Fig. 1). The study domain encompasses Olympic, North Cascades and Glacier National Parks (NP), which include the major mountain environments of the PNW and extend along a general longitudinal transect from the Pacific coastal mountains to the Cascade Range and Rocky Mountains. These mountain ranges extend in a north-south direction roughly parallel to the Pacific coast and exert a major influence on regional climate and land cover variability.

Climatic diversity is largely a function of distance from the Pacific Ocean and physiographic relief, with relatively steep west-east temperature and moisture gradients across the major mountain ranges. The coastal mountains have a general maritime climate with extensive precipitation in the form of rain and snow on windward slopes driven by orographic uplift of moist cyclonic air masses moving predominantly west to east off the Pacific. Inland areas east of the Cascade Range and east-facing slopes of the major ranges exhibit a more continental climate with lower precipitation and higher seasonal temperature variability than coastal areas and west-facing slopes.

Natural vegetation patterns within the region correspond with the major PNW physiographic and climatic regimes. Lower elevations with moderate to high precipitation are dominated by coniferous forests, while semi-arid and arid inter-mountain areas consist of predominantly shrub-steppe vegetation cover. Upper elevation mountain areas consist of subalpine forest and alpine tundra. Deciduous tree species are found in all locations, primarily in riparian and disturbed areas, but comprise a small proportion of total forest cover. Lower elevation forests outside the national parks have been subject to logging over the past 50–120 years, and are still dominated by coniferous species, but of younger ages than in unlogged areas. Periodic disturbance by fire, insects, and wind contribute to a mosaic of age classes across the forested portion of the PNW.

The study domain is classified as 68% evergreen needleleaf forest (ENF), 16% grassland (including agricultural land), 9% shrubland, 7% deciduous broadleaf forest (DBF) (including mixed forest, MX), and 0.2% other biomes based on the MODIS land cover classification (Fig. 1). Both vegetation and surface meteorological variables have considerable spatial heterogeneity corresponding to topographic gradients ranging from sea level to 3207 m elevation. The 18-year mean daily air temperature and mean annual precipitation from 1980 to 1997 ranged from −5.4 to 11.5 °C and from 124 to 7081 mm y^{-1}, respectively, with cooler temperatures and higher precipitation at higher elevations. The rainfall fraction of total annual precipitation varies from 7 to 100% and is generally higher near the Pacific coast and at lower elevations. Interannual variability in average air temperatures for the domain is approximately ±2.7 °C, and variability in precipitation, vapor pressure deficit and solar radiation is ±592 mm, ±218 kPa, and ±0.7 MJ m^{-2} d^{-1}, respectively (Fig. 2a). Interannual variability in surface meteorology is relatively high compared to regional means for temperature (44%, mean = 6.1 °C), precipitation (50%, mean = 1183 mm y^{-1}), VPD (31%, mean = 699 Pa), and solar radiation (10%, mean = 7.5 MJ m^{-2} d^{-1}).