Water-vegetation interaction in Mediterranean climate zones under global warming

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Introduction

Though they cover a small fraction of the earth, lands with Mediterranean climates are biodiversity hot spots, and are also densely peopled. Here, we look at the regional impact of global warming in coupled-climate-model runs, emphasizing the interaction of changes in temperature, precipitation, soil moisture, heat fluxes, plant growth, and carbon partitioning between air and land.

Mediterranean climate is characterized by subtropical temperatures and summer drought. We operationally define Mediterranean zones, following the Köppen classification (e.g. Kottek et al. 2006), as those averaging less than 30 mm of rain in the driest summer month, provided this is less than 1/3 the average rainfall on the wettest winter month; mean temperatures above 10 °C on the warmest month and below 18 °C on the coldest month; and rainfall above the desert threshold. The model land grid cells meeting these criteria are colored in Figure 1 (red and pink). Here, we show model results averaged only over the Mediterranean-climate grid cells which are in the Mediterranean basin and adjacent southwest Asia (red in Figure 1); these account for most of the land area that is in the climate zone.

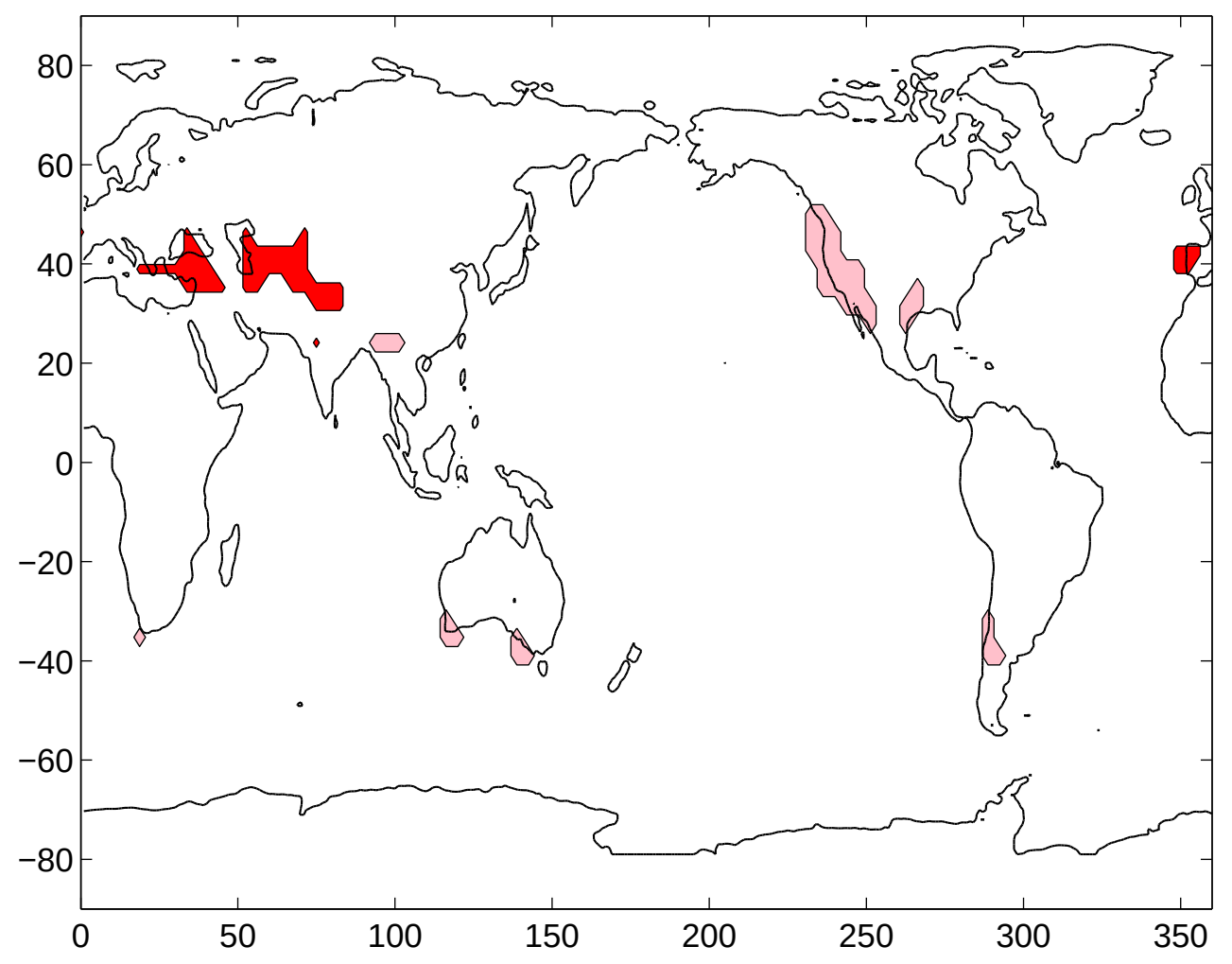

Figure 1. Mediterranean-climate regions.

The model runs, with the NCAR Climate System Model (CSM1.4), are part of a suite conducted for a study of carbon-climate coupling in the 21st century under prescribed carbon-emission scenarios (Fung et al., 2005; Doney et al. 2006). We show results, averaged over the Mediterranean region and over the entire land surface, from two such model runs, both for 1820-2100. Carbon emissions are from the SRES A2 ('business-as-usual') scenario. The two runs differ only in that one (color-coded green) includes enhancement of photosynthesis by CO_2 fertilization, whereas the other (color-coded brown) does not. Figure 2 sketches important feedbacks between the components of the coupled model.

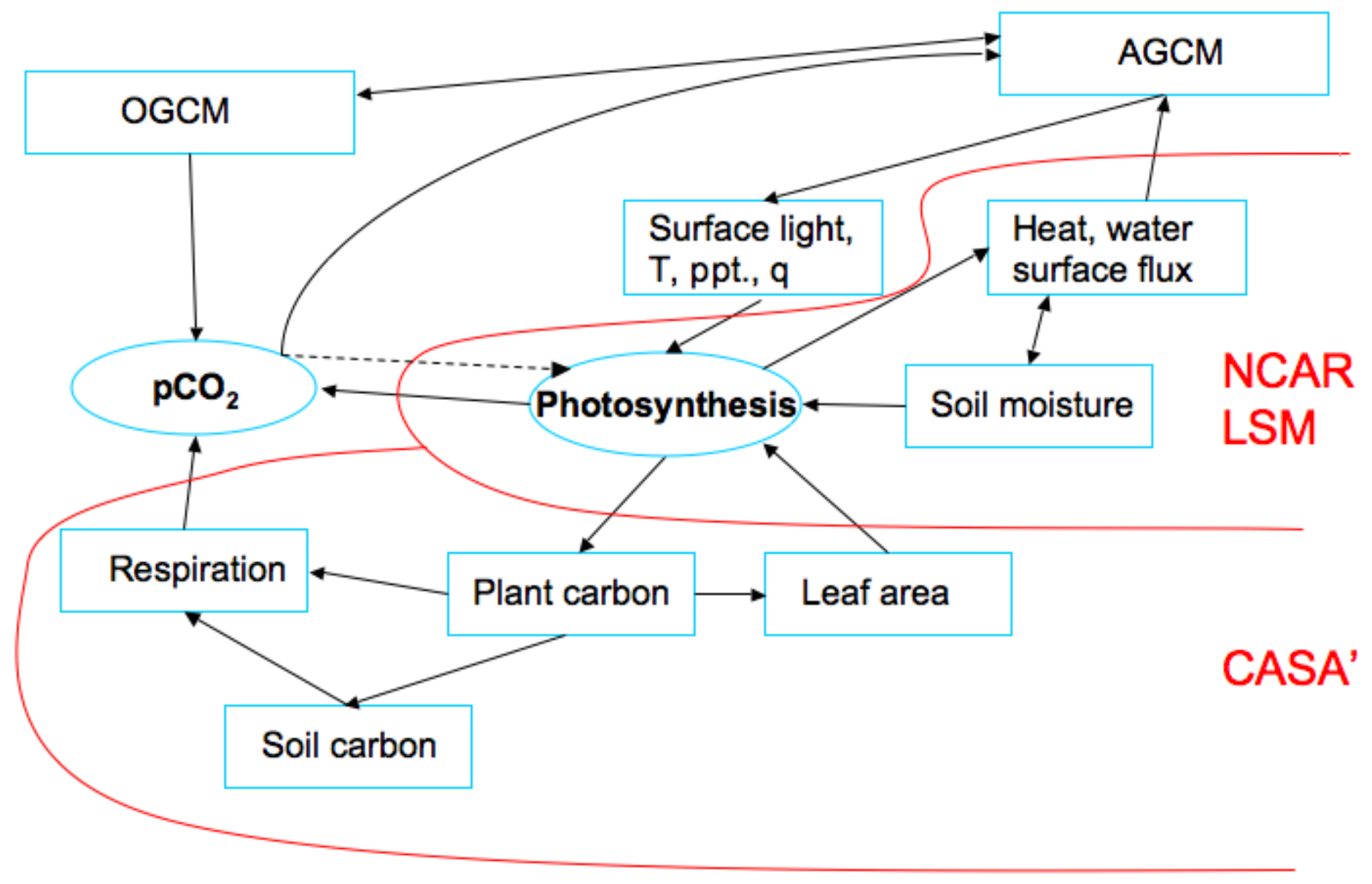

Figure 2. Schematic of feedbacks in the NCAR-CSM model runs, emphasizing the influences on photosynthesis and atmospheric pCO_2. pCO_2 directly influences photosynthesis (dashed arrow) only in the CO_2-fertilization run.

Temperature and precipitation

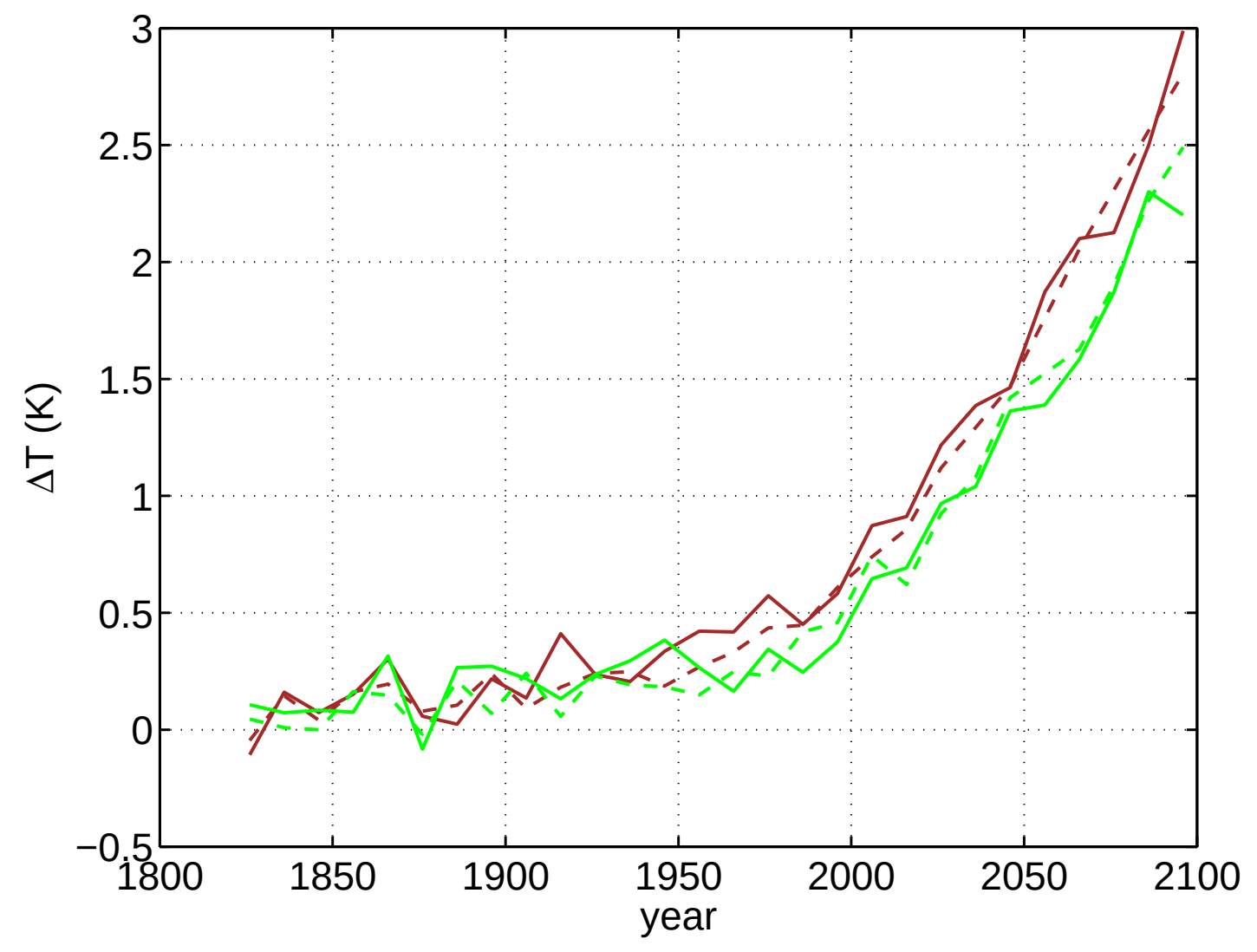

Figure 3. Decadal mean temperature departures from the preindustrial values for the Mediterranean region (solid lines) and for all land (dashed lines) (green: with CO_2-fertilization, brown: without; 10-year means).

Mediterranean temperature increases in tandem with the global land mean both without and with fertilization (Figure 3). Mediterranean precipitation does not change either with or without fertilization (Figure 4), although globally precipitation increases by 3-5%.

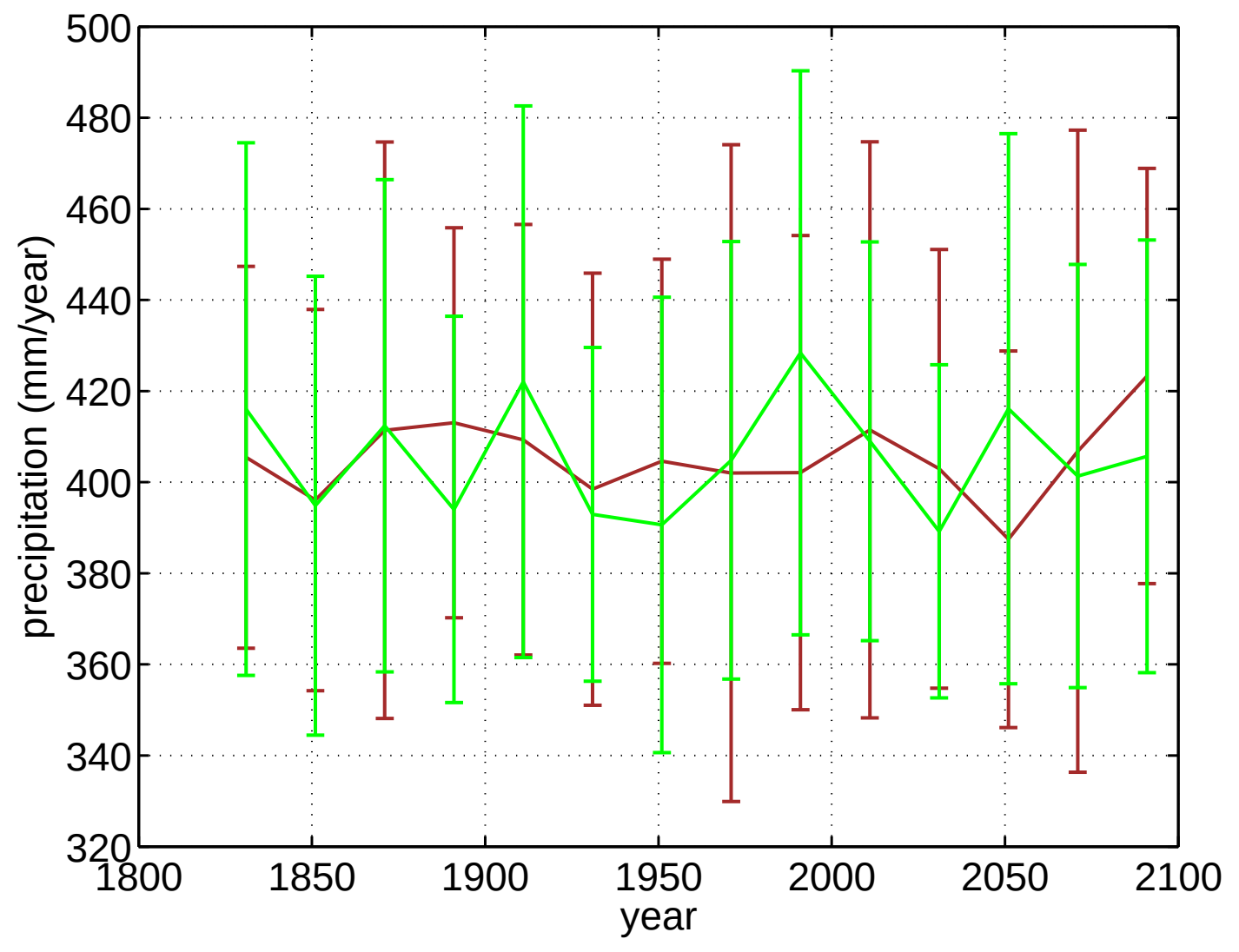

Figure 4. Precipitation for the Mediterranean region in NCAR-CSM model runs (green: with CO_2 fertilization, brown: without; 20-year means, with interannual standard deviations for each 20-year period).

Plant productivity

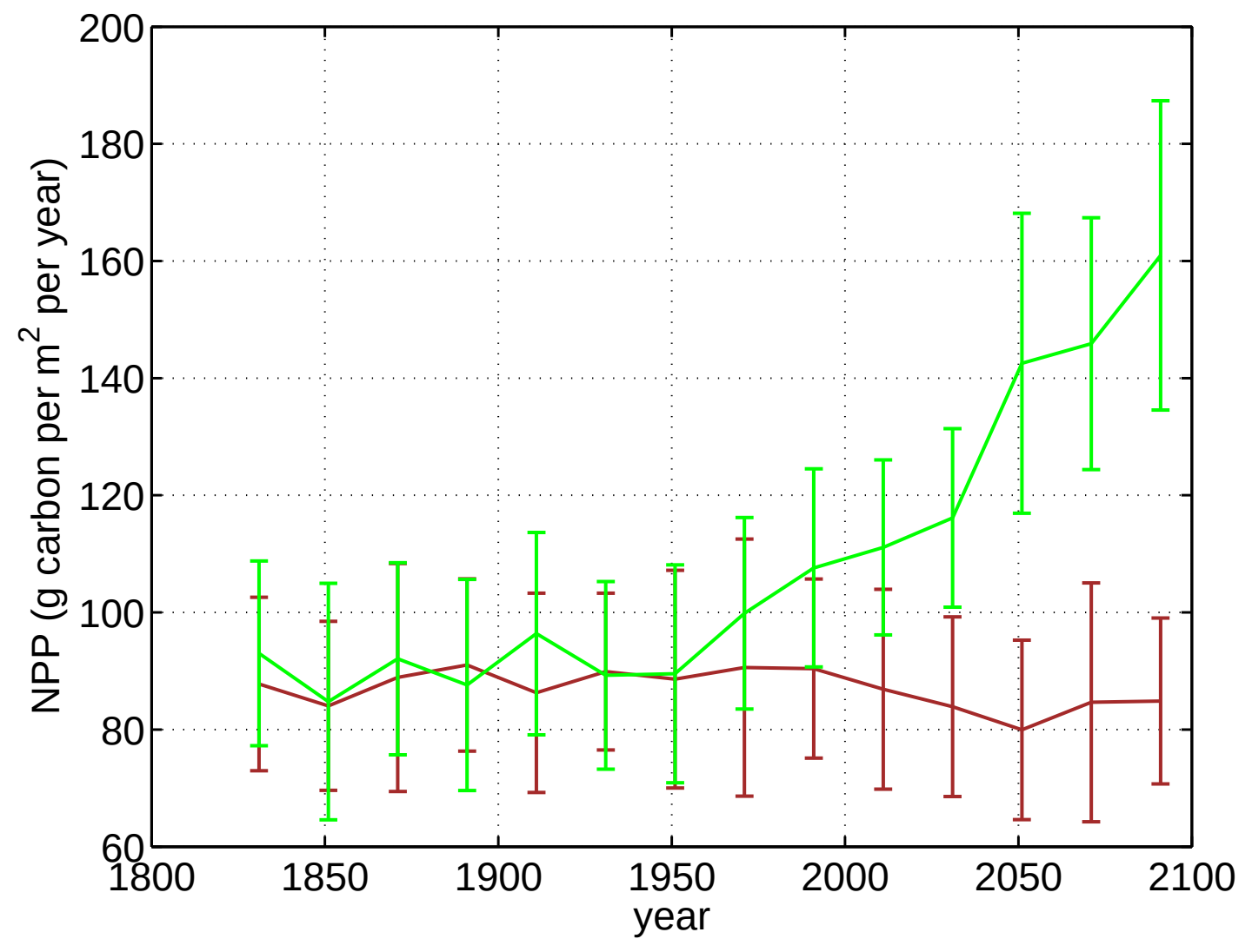

Figure 5. Net primary production for the Mediterranean region in NCAR-CSM model runs (green: with CO_2 fertilization, brown: without; 20-year means, with interannual standard deviations for each 20-year period).

Mediterranean plant net primary production (NPP) shows little change in the no-fertilization scenario, but increases dramatically with fertilization (Figure 5). Interannual variability (error bars in Figure 5) is large, driven largely by variability in precipitation. The impact of fertilization in increasing NPP is much larger in the Mediterranean (doubling by 2100) than globally (+40% by 2100) (Figure 6). CO_2 fertilization boosts plant water use efficiency, which has a particularly large impact on plant productivity in this water-limited regime. The increased NPP causes the region to turn into a carbon sink, whereas without fertilization it is a small carbon source (Figure 7).

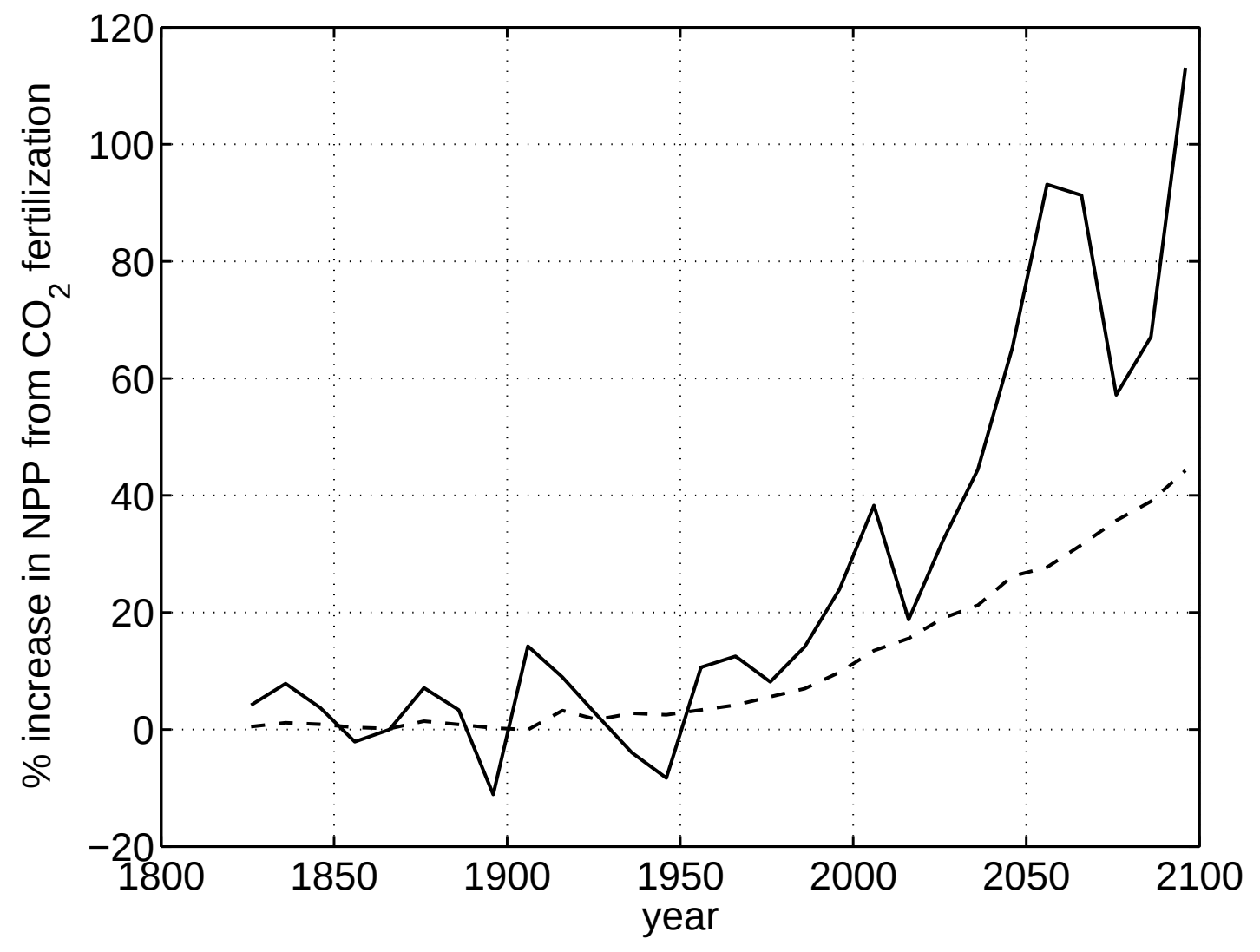

Figure 6. % difference in decadal NPP between the CO_2-fertilization and no-fertilization runs for the Mediterranean region (solid line) and globally (dashed line).

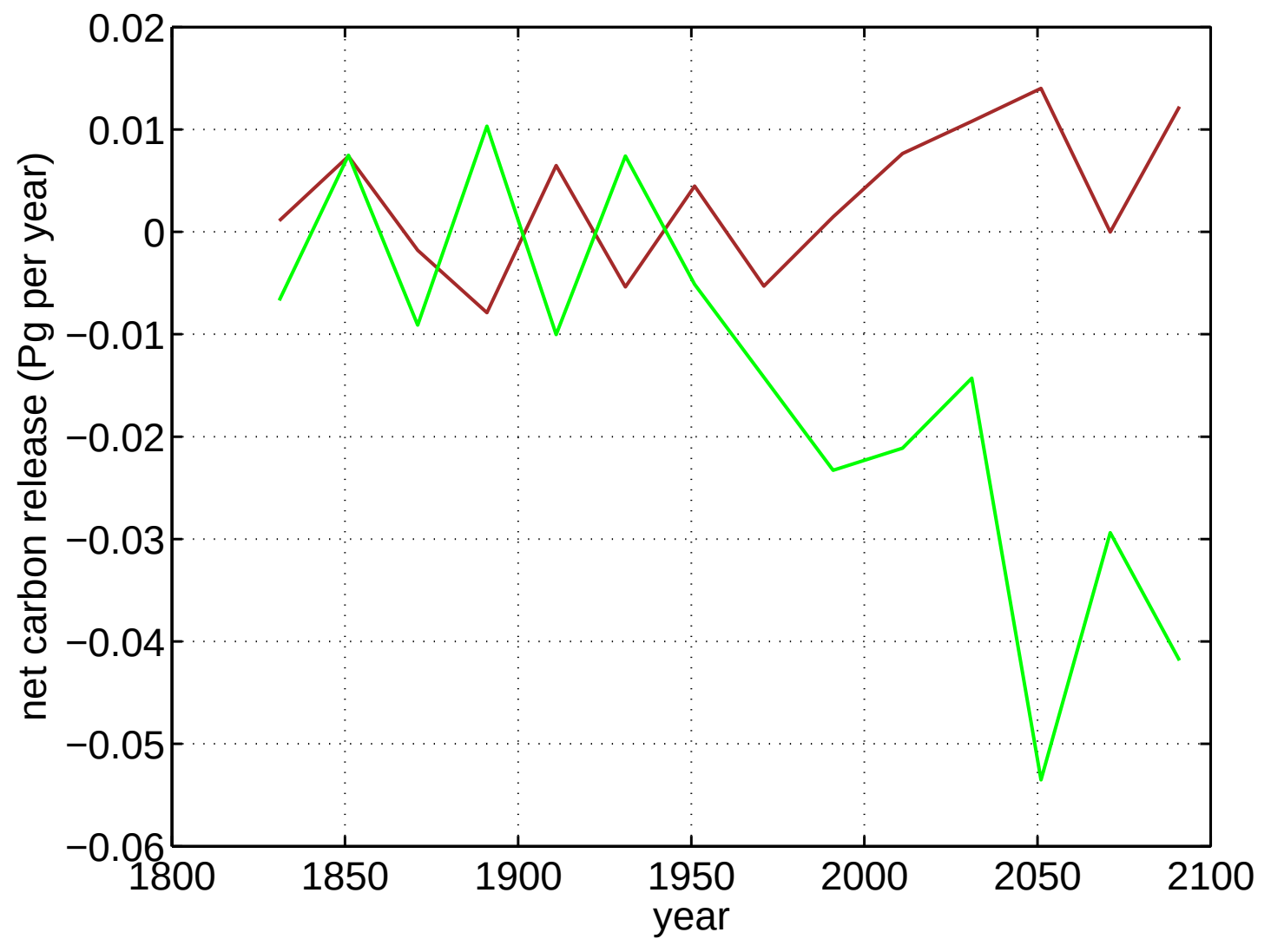

Figure 7. Net carbon flux for the Mediterranean region in NCAR-CSM model runs (green: with CO_2 fertilization, brown: without; 20-year means; negative values correspond to a land sink).

Soil moisture and evapotranspiration

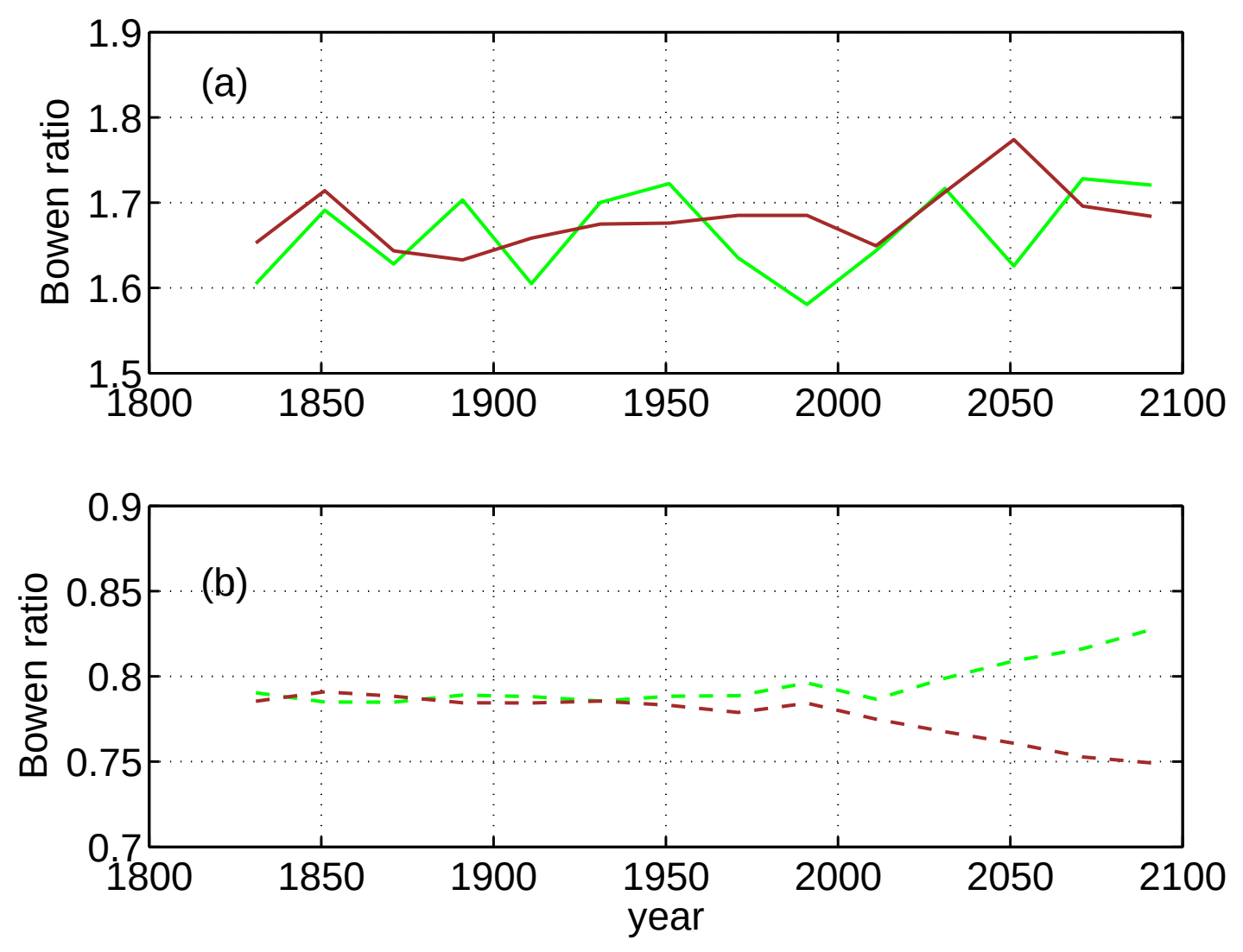

Figure 8. Bowen ratio for the Mediterranean region (**(a)**, solid lines) and for all land (**(b)**, dashed lines) (green: with CO_2 fertilization, brown: without; 20-year means).

Fertilization causes the Bowen ratio (of sensible to latent heat flux from the surface) to trend upward globally (Figure 8): transpiration declines because plant stomates can open less to get the same amount of CO_2 (water use efficiency increases). The Bowen ratio does not increase in the Mediterranean, where transpiration is set by the amount of available water, and the increased water use efficiency boosts NPP while transpiration stays almost constant (Figure 9). In the Mediterranean, the latent heat flux does not change with time in either the fertilization and no-fertilization cases. In both cases, the warmer conditions are modeled to cause the soil to dry out more rapidly in the spring (at the end of the rainy season) by the end of this century (Figure 10).

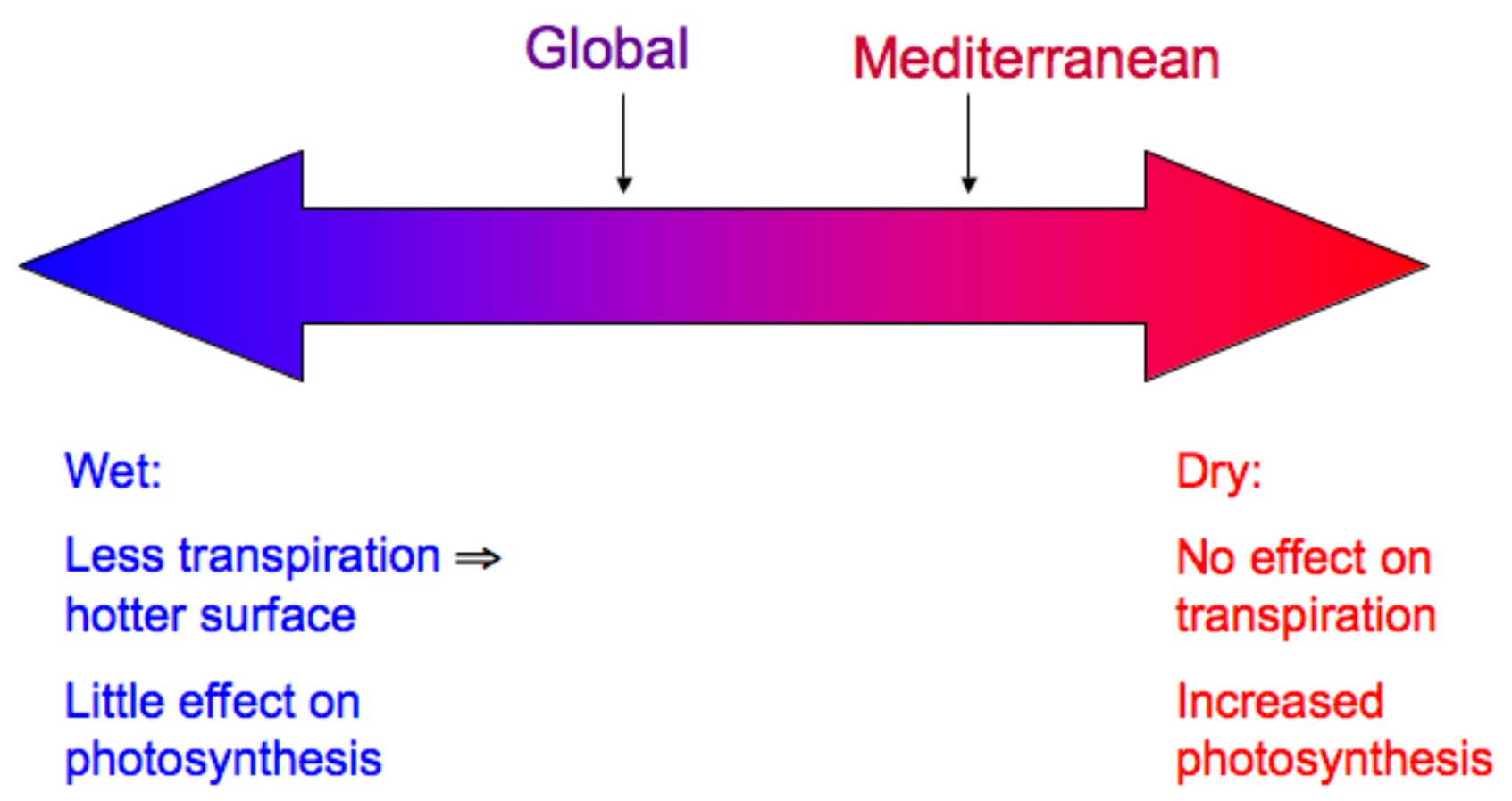

Figure 9. Conceptual model for regionally divergent responses of the air-land fluxes to CO_2 fertilization, which increases the water-use efficiency of photosynthesis. In dry regions where photosynthesis is limited by water, photosynthesis increases while transpiration stays roughly constant (set by the available moisture). In moist regions where photosynthesis is limited by other factors such as temperature, photosynthesis increases less sharply and transpiration declines.

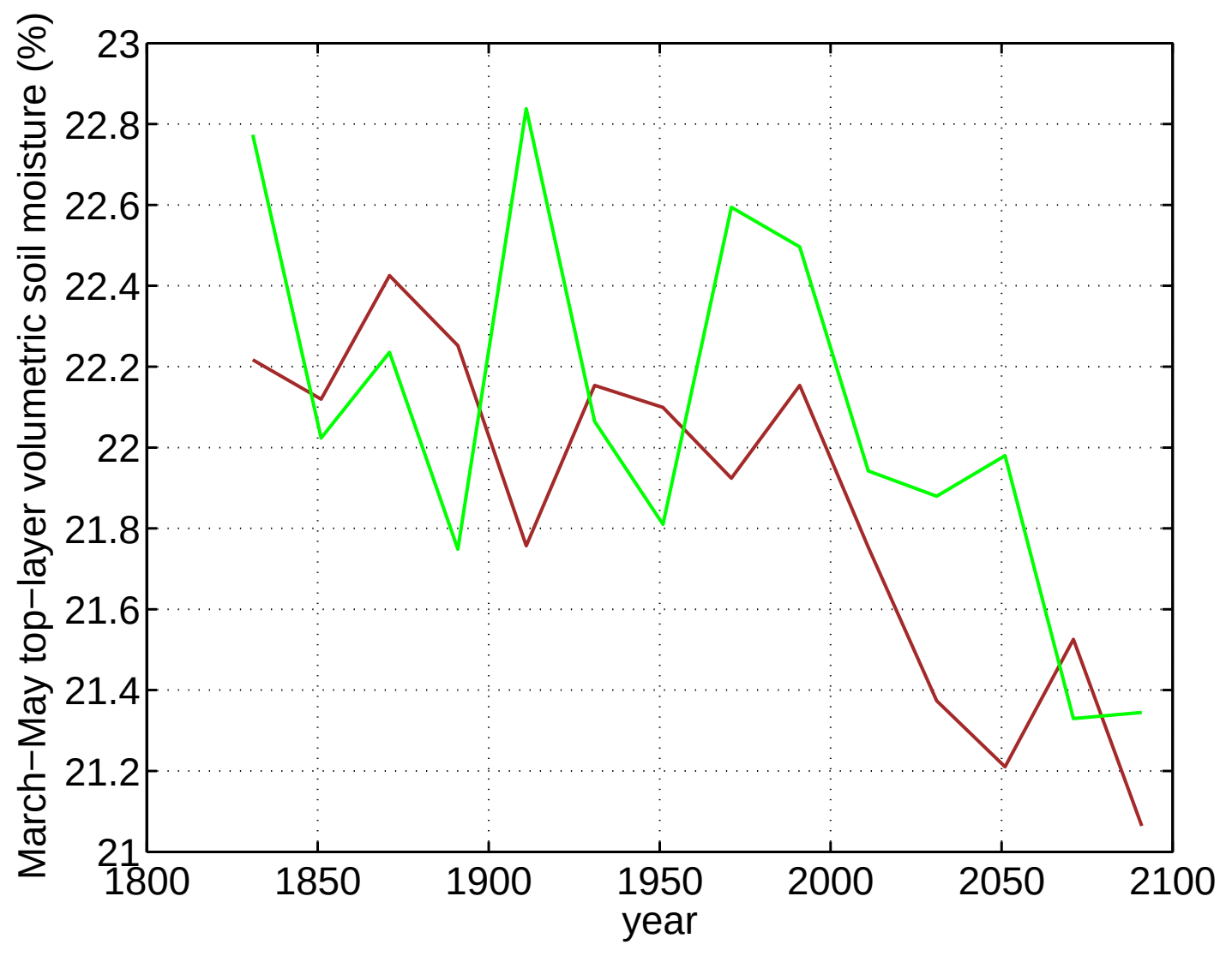

Figure 10. March-May mean top-layer soil moisture modeled for the Mediterranean region (green: with CO_2 fertilization, brown: without).

Discussion and conclusion

Previous modeling work has shown that over most land regions, plant physiological response to higher CO_2 levels enhances warming by suppressing transpiration and hence latent heat flux, which results in surface heating and increased sensible heat flux (Sellers et al. 1996). Our study illustrates that In water-limited regions like the Mediterranean, plants essentially transpire all available water even with CO_2 fertilization, so that this feedback need not occur – the increased water use efficiency afforded by CO_2 fertilization is manifested overwhelmingly as higher NPP rather than reduced transpiration (Figure 9). Some observational evidence suggests that CO_2 fertilization has already begun to increase plant growth in Mediterranean regions (Osborne and Woodward 2001). Free-air CO_2 enrichment experiments in Mediterranean ecosystems paint a more complex picture, with variable effects of CO_2 fertilization on productivity, soil moisture, and energy budgets depending on plant assemblage and sometimes differing between wet and dry years (Morgan et al. 2004).

Even without the physiological warming feedback, the projected impact of global warming will increase the stress on water supplies in the region. The longer dry season implied by accelerated spring soil moisture drawdown (Figure 8) would increase fire hazard (Fires are not included in the model.), potentially negating the carbon sink induced by CO_2 fertilization of plant growth.

The Keck Hydrowatch project (http://bie.berkeley.edu/keck) now underway aims to monitor soil moisture, surface fluxes, and vegetation health in California field sites, with the goal of testing and improving parameterizations of these processes in models of Mediterranean-climate lands and obtaining a baseline for assessing changes.

Acknowledgments

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