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LETTER

Potential impact of vegetation feedback on European heat waves in a 2 × CO_2 climate

Vegetation impact on European heat waves

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Abstract Inclusion of the effects of vegetation feedback in a global climate change simulation suggests that the vegetation–climate feedback works to alleviate partially the summer surface warming and the associated heat waves over Europe induced by the increase in atmospheric CO_2 concentrations. The projected warming of 4°C over most of Europe with static vegetation has been reduced by 1°C as the dynamic vegetation feedback effects are included. Examination of the simulated surface energy fluxes suggests that additional greening in the presence of vegetation feedback effects enhances evapotranspiration and precipitation, thereby limiting the warming, particularly in the daily maximum temperature. The greening also tends to reduce the frequency and duration of heat waves. Results in this study strongly suggest that the inclusion of vegetation feedback within climate models is a crucial factor for improving the projection of warm season temperatures and heat waves over Europe.

1 Introduction

Observational records show that Europe has been experiencing a drastic increase in summer (June-August) temperature over recent several decades (Schär et al. 2004; Della-Marta et al. 2007). The observed warming trend has been attributed to an increase in the concentration of anthropogenic atmospheric greenhouse gases

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(GHGs), specifically CO_2 (Solomon et al. 2007). As summers become warmer and drier, extreme climate events such as heat waves will become more frequent (Meehl and Tebaldi 2004) resulting in a substantial increase in natural disasters (Fischer et al. 2007). In Europe, the summer of 2003 is recognized as the hottest of the last 500 years with the mean temperature exceeding the late-20th century baseline by as much as 5 standard deviations (Schär et al. 2004). The extreme heat waves during the summer caused a large socio-economical impact in the region. Thus, a reliable projection of the impact of global warming on European heat waves is among the most important topics in the climate community.

Modeling studies in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) project that a continual increase in anthropogenic GHGs will raise summer temperature in Europe substantially and decrease precipitation (Christensen et al. 2007). These projections also show that heat waves over Europe will be severer, longer lasting, and more frequent due to intensified quasi-stationary anticyclone anomaly accompanied by future warming (Meehl and Tebaldi 2004; Della-Marta et al. 2007). Nevertheless, these projections are subject to large uncertainties because details of warming (and/or recurrent heat waves) depend on a variety of climate parameters—land surface conditions, radiative balance, and moisture availability among others (Fischer et al. 2007).

Vegetation-climate feedback—response of land vegetation to an altered climate condition and subsequent feedback—in shaping regional climate characteristics is among the important processes, but remains to be quantified. Previous studies reported that land–atmosphere interactions play an important role in determining the atmospheric circulation patterns associated with heat waves, particularly over the central and eastern Europe (e.g., Seneviratne et al. 2006; Fischer et al. 2007). In regions of sufficient soil moisture availability, enhanced greening due to warmer temperatures and higher CO_2 concentrations will increase evapotranspiration, and, in turn, moderate surface warming. The increased evapotranspiration can also increase rainfall further moderating warming (Fischer et al. 2007). Recently, observational and modeling studies by Jeong et al. (2009a, b) suggested that an increase in vegetation greenness has reduced warming over East Asia during spring via vegetation–climate feedback. These studies indicate that vegetation–climate feedback can affect the intensity, frequency, and duration of heat waves in Europe as well, which motivated the present study.

We investigate the impact of vegetation–climate feedback on the changes in temperature and the frequency and duration of heat waves in Europe under the condition of doubled atmospheric CO_2 concentration in a series of global climate model (GCM) experiments. The impact of vegetation–climate feedback in a double CO_2 climate is quantified by contrasting the results from two century-long GCM simulations with and without coupling dynamic global vegetation model (DGVM).

2 Model and experiments

2.1 Model

The GCM used in this study is the National Center for Atmospheric Research (NCAR) Community Atmosphere Model version 3 (CAM3) configured at a T42 horizontal resolution with 26 hybrid-sigma vertical layers. The details of CAM3 are referred to Collins et al. (2006). Land surface processes in CAM3 are calculated by the Community Land Model version 3 (CLM3) (Oleson et al. 2004). It includes DGVM, a modified version of the Lund–Potsdam–Jena scheme, for computing vegetation establishment (i.e., plant types) and phenology (i.e., leaf area index) for given climate variables (Levis et al. 2004). The leaf area index (LAI) and its climatic impacts simulated in the CAM3 with DGVM (hereafter CAM3–DGVM) agree well with observations (Levis and Bonan 2004; Jeong et al. 2009b).

2.2 Experimental design

A series of ensemble climate experiments has been performed using CAM3–DGVM to generate climate conditions under the present-day (e.g., $1 \times CO_2 = 355$ ppmv) and the doubled CO_2 (e.g., $2 \times CO_2 = 710$ ppmv) conditions. Prior to all simulations, CAM3–DGVM has been spun up for 500 years in order to obtain a potential vegetation under the present-day climate using the climatological mean sea surface temperatures (SSTs) and sea ice distributions (SICs) from the Hadley Centre for 1950–2000 and the climatological-mean GHG concentration (i.e., $1 \times CO_2$). A hypothetical vegetation state that would occur in the absence of such human influences as urbanization, deforestation, and changes in cultivated area is assumed in this study. Starting from bare ground, CAM3–DGVM vegetation was brought to an equilibrium state around model year 400 and established the present vegetation distribution. We have run the model for another 100 years (i.e., total 500 years) and finally adopted the mean potential vegetation distribution during the last 30 years. This is used as the initial vegetation distribution in the following experiments.

Using the potential present-day vegetation as the initial field, we have performed three 100-year-long global ensemble simulations in order to investigate the impact of vegetation feedback on climate changes induced by doubling the present-day CO_2concentrations: (1) VegOff_1× represents a climate under the present-day CO_2 concentration (e.g., $1 \times CO_2$) with the prescribed climatological vegetation fields calculated from the last 30 years of spin-up simulation, (2) VegOff_2× represents a climate under the $2 \times CO_2$ condition in the absence of dynamic vegetation feedback, namely, with the same vegetation fields used in VegOff_1×, and (3) VegOn_2× represents a climate under the $2 \times CO_2$ condition with fully coupled DGVM. The additional 100-year model run time should be enough to obtain stabilized results for an experiment, e.g., VegOn_2×. When we have carefully checked the last 30-year model results, all ensemble simulations reached equilibrium states; climatology during the last 30 years in each experiment is used for analysis in the present study. Each experiment consists of five ensemble members with slightly different atmospheric initial conditions randomly selected in the last 5 years of the 500-year spin-up simulation. To include the impact of the oceans, SSTs and SICs derived from the 1990 control run and the $2 \times CO_2$ Community Climate System Model version 3 (CCSM3) run (Collins et al. 2006) have been used for the present-day and the $2 \times CO_2$ simulations, respectively. The SSTs and the SICs datasets were obtained from the Earth System Grid (http://www.earthsystemgrid.org).

From these three ensembles, we computed the radiative effect of CO_2 increase and that of vegetation–climate feedback as follow: VegOff_2× minus VegOff_1× represents the radiative effect due to CO_2 increase; VegOn_2× minus VegOff_1×

denotes the effect of the increased CO_2 and vegetation feedback combined; VegOn_2× minus VegOff_2× denotes the effect of vegetation feedback only.

3 Results

3.1 Temperatures and LAI

Figure 1 shows the changes in the daily mean (T_{mean}), maximum (T_{max}), and minimum (T_{min}) surface air temperatures and LAI during summer over Europe in response to the doubled CO_2. The first column (Fig. 1a–c) represents the simulated changes by radiative effect due to CO_2 doubling. The middle column (Fig. 1d–g)

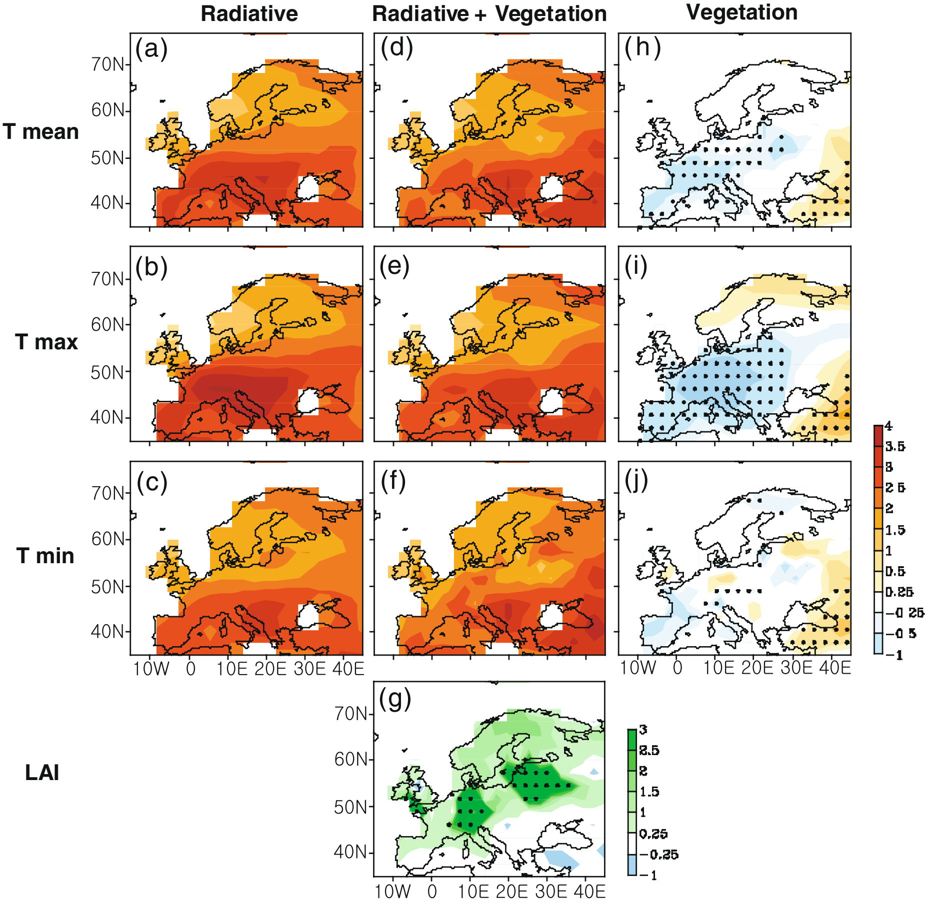

Fig. 1 Simulated changes in the daily mean (T_{mean}), daily maximum (T_{max}), daily minimum (T_{min}) surface air temperatures and leaf area index (*LAI*) during summer (June-August) in Europe under the doubled CO_2 condition. *Dotted areas* represent regions where temperature and LAI changes are statistically significant at the 95% confidence level

shows the results with radiative plus vegetation effects. The third column (Fig. 1h–j) isolates the effects of vegetation feedback. The radiative effect will increase summer temperature over Europe with the largest warming of over 3°C in the central Europe and the Mediterranean region with smaller warming over the Scandinavian region (Fig. 1a–c). The statistical significance of the warming signal exceeds the 95% confidence level in most regions. Overall, the warming projected with the radiative effect only is similar to the projection reported in the IPCC AR4 (IPCC 2007).

A comparison of the temperature changes obtained with radiative effect only (Fig. 1a–c) and with the radiative plus vegetation effects (Fig. 1d–f) reveals that vegetation feedback considerably modulates the radiatively-induced regional warming. In general, the vegetation feedback can be composed of the changes in physiological and structural components. The combined change of those is called vegetation greenness, a quantity determined by the amount of green leaves and the chlorophyll content that plays a major role in photosynthesis. The present DGVM parameterizes this vegetation greenness in terms of LAI, and related canopy density and ecosystem productivity (Levis et al. 2004). In this context, we consider LAI change as a main representative of vegetation greenness change in response to the doubled CO_2 climate.

In the simulations with the effects of radiative forcing and vegetation feedback, LAI increases in response to the CO_2-induced warming. The results show that CO_2 doubling has considerable influences on both the plant distribution and LAI. The grass fraction increases substantially in the regions that experience a decrease in tree species (figure not shown). An increase in LAI over Europe is mostly accompanied by increased grass fractions. With increasing CO_2, the climate generally becomes warmer and drier, especially in central and southern Europe. Increase in temperature and moisture depletion seems to yield a more favorable condition for grass growth while suppressing the growth of trees species. These results are consistent with the previous climate model simulations by Sitch et al. (2008). Thus, the inclusion of vegetation feedback generally results in enhanced vegetation greenness in Europe. As shown in Fig. 1g, the LAI increase in the central Europe is most noticeable with a statistical significance exceeding 95%. On the contrary, the LAI changes are relatively small in the southern Iberian Peninsula and the Balkans.

In the presence of vegetation feedback, changes in vegetation over Europe modulate the regional warming by CO_2 radiative effects particularly for the daily mean and maximum temperature (T_{mean} and T_{max}) with significant regional variations (Fig. 1h–j). The effect of vegetation feedback reduces the increase in T_{mean} and T_{max} by 1°C over Europe except for the Scandinavian region. This substantial cooling effect is robust at the 95% confidence level. Vegetation feedback on T_{min}, is much weaker and is statistically insignificant. While an increase in T_{max} is generally deterred due to vegetation feedback, it is interesting to note that T_{max} increases further with the vegetation effect in the northern Scandinavian region and to the east of the Black Sea (Fig. 1i); however a statistical significance of this additional warming is below 95%. Despite the regional variations in vegetation feedback, LAI increases over the entire domain except in the region to the south and east of the Black Sea.

The impact of vegetation change on the regional temperature change can be interpreted from net effect of the two possible LAI-mediated feedbacks; an increase in LAI reduces albedo thus leading to further warming (positive feedback) and, at the same time, enhances evapotranspiration thereby weakening the warming (negative feedback). In order to further examine the impact of vegetation feedback on the surface air temperatures, area-averaged surface energy fluxes, precipitation, and LAI were calculated over the central Europe (0°–20°E, 40°N–50°N), where vegetation feedback reduces warming associated with the increased anthropogenic GHGs (Table 1). In the absence of the vegetation effect ("radiative" column in Table 1), the largest change in the surface energy budget is the increase in shortwave (SW) radiation (+16.3 W m^{-2}). The net radiation, the sum of SW and longwave (LW) radiative fluxes at the surface, also increases (+8.5 W m^{-2}). The SW increase is mainly balanced by the increase in the sensible heat flux (SH) (15.3 W m^{-2}) and upward LW (−7.8 W m^{-2}). The latent heat flux (LH) decreases (−8.1 W m^{-2}). The increase in surface insolation and the decrease in LH may be related with the decrease in precipitation (−0.5 mm day^{-1}) in the double CO_2 climate via the decrease in cloudiness and soil moisture, respectively. The area-mean surface fluxes show that vegetation feedback in central Europe tends to alleviate warming due to the increased CO_2. Compared to the results in the simulations that do not include vegetation feedback, the runs with vegetation feedback ("radiative plus vegetation" column in Table 1) yield much smaller increase in the SW and net radiation and smaller decreases in LH and precipitation in conjunction with smaller warming. The enhanced local transpiration by vegetation greening provides more precipitation by 0.3 mm day^{-1}. This is qualitatively consistent with the previous studies which reported positive relationship between vegetation greenness and precipitation (Cowling et al. 2009). Thus, the increase in transpiration by vegetation feedback also increases (or less decrease in) cloudiness. Less decrease in cloudiness with vegetation feedback resulted in a smaller increase in the SW and net radiation. These results agree closely with the change of surface energy budget in association with the changes in LAI found by Levis and Bonan (2004) and Jeong et al. (2009b).

In general, LAI is related with the efficiency of canopy evaporation through the canopy conductance parameterization. Changes in LAI modulate the evaporation via regulating the role of roughness length, and stomatal conductance (Betts et al. 1997). For example, although an increase in the atmospheric CO_2 generally reduces the stomatal conductance, the corresponding increase in LAI can offset the effect of reduced stomatal conductance to increase evapotranspiration (Betts et al. 1997; Levis et al. 1999). Thus, an increase in vegetation greenness reduces the warming

Table 1 Differences in the selected surface energy fluxes, precipitation, and leaf area index (LAI) under the doubled CO_2 condition over central Europe (0°–20°E, 40°N–50°N) for the VegOff_2× and the VegOn_2× experiments

	Radiative	Radiative + vegetation	Vegetation
SW	16.3	9.8	−6.5
LW	−7.8	−4.3	3.5
SH	15.3	7.7	−7.6
LH	−8.1	−3.5	4.6
G	0.5	0.5	0.0
Precipitation	−0.5	−0.2	0.3
LAI	–	2.1	2.1

The last column shows the difference (vegetation effect only) between the two experiments. The acronyms stand for SW: net shortwave flux, LW: net longwave flux, LH: latent heat flux, SH: sensible heat flux, and G: ground heat flux with the unit of W m^{-2}. Positive (negative) flux indicates increase heating (cooling) at the surface. The unit of precipitation is mm day^{-1}, and that of LAI is m^2 m^{-2}

by increasing evapotranspiration. This is confirmed by the differences in latent heat fluxes between the runs with and without the effects of vegetation feedback.

While vegetation feedback weakens surface warming over central Europe, surface warming, particularly T_{max}, increases slightly in northern Europe. Examination of the surface fluxes shows that in the northern Scandinavian region, increased absorption of SW due to the decrease in surface albedo in response to the increased greenness dominated the increase in LH, resulting in the increase in T_{max}. The increase in T_{max} due to vegetation feedback in the region, however, is below the 95% statistical confidence level.

Besides the present target region, vegetation feedback also notably modulates temperature changes over the whole Northern Hemisphere. While not shown in the figure, the influence of vegetation greening on temperature changes is found to be different depending on latitudes; enhanced vegetation greenness in mid-latitudes reduces a warming via increased evapotranspiration and decreased solar radiation. Although vegetation greenness is also distinctively enhanced in high-latitudes, the greening works to reinforce a warming by increasing radiation via surface albedo feedback.

3.2 Heat waves

Given the warmer temperatures and less precipitation in the double CO_2 climate, it has been the general consensus that the frequent and duration of heat waves are likely to increase in Europe (Meehl and Tebaldi 2004; IPCC 2007). However, our results suggest that the vegetation feedback can modulate the temperature change considerably, particularly for T_{max}. On the basis of these findings, we have investigated the potential impact of vegetation feedback on the characteristics of heat waves including the frequency and duration.

The probability distribution function (PDF) of the summertime daily T_{max} anomalies averaged over the central Europe, where cooling effects of vegetation feedback are significant, is examined below (Fig. 2). Figure 2a shows the PDF of daily T_{max} anomaly for the VegOff_2× and the VegOff_1× experiments and the relative changes in the PDF of daily T_{max} anomalies associated with the radiative effect. The PDFs of the VegOff_2× is skewed more toward positive anomalies than that of the VegOff_1× (e.g., skewness is 0.6); this is clearer in the change in relative frequencies. This shift represents notable changes in extreme values particularly for high positive anomalies. For example, the frequency of 4.5–5.5°C temperature anomalies has increased by 200% with statistical significance well above the 95% confidence level. With vegetation feedback, the frequencies of extreme positive temperature anomalies are slightly lowered (Fig. 2a vs. b). The PDF for events with 4.5–5.5°C in the VegOn_2× experiment has decreased by 60% of the VegOff_2× experiment, which is statistically significant at the 90% confidence level. This implies that vegetation feedback may exert a considerable influence on the possibility of changes in the frequency and duration of heat waves. Change in the frequency of temperature anomalies plays an important role in the determining the features of extremes (Schär et al. 2004).

In this study, heat waves are defined based on two specific temperature thresholds (Meehl and Tebaldi 2004). The first threshold (T1) is defined as the 97.5th percentile of the distribution of T_{max} from the seasonal climatology at a given location, and the

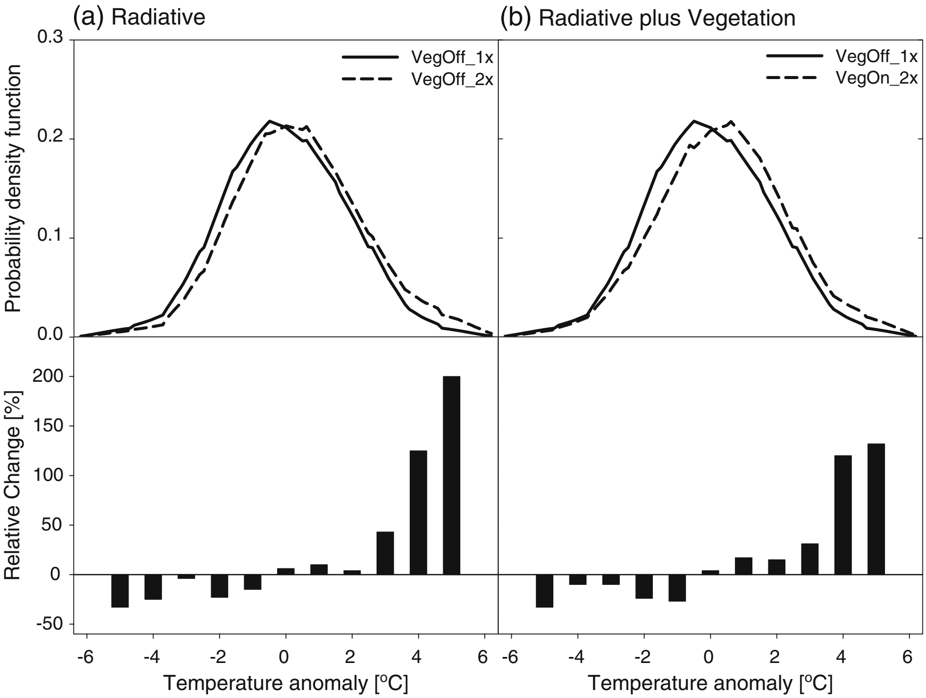

Fig. 2 Statistical distribution of the daily maximum temperature anomalies during summer (June–August) averaged over central Europe (0°–20°E, 40°N–50°N). **a** *Upper panel* shows the probability density function in the VegOff_2× and the VegOff_1×, and *lower panel* shows "relative" frequency change defined as the ratio of the two PDFs. (**b**) is the same as (**a**) but for the VegOn_2×. The *black bars* in the relative changes denote statistically significant regions at the 95% confidence level

second one (T2) is defined as the 81st percentile. A heat waves occurrence over a specific period is determined when the following three conditions were satisfied: (1) T_{max} were above T1 for at least 3 days, (2) the average T_{max} were above T1 for the entire period, and (3) T_{max} were above T2 for every day of the period of heat waves (Meehl and Tebaldi 2004).

Figure 3 shows the probability distribution of (a) the number of annual heat waves and (b) the duration of individual heat waves in the target region. The model performance is also compared with the National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Sciences (NCAR) reanalysis data (Kalnay et al. 1996). The probability distribution in the VegOff_1× experiment is in marginal agreements with that calculated from the NCEP/NCAR reanalysis. The annual-mean number of heat wave occurrence in the present-day simulation, VegOff_1×, is 1.3, which is very close to the value from the reanalysis. As the CO_2 concentration is doubled (i.e., VegOff_1× vs. VegOff_2×), the mean number increases from 1.3 to 1.7 and the most probable number of heat waves changes from one per year to two per year. The increase in the heat wave frequency for the double-CO_2 condition does not occur when vegetation feedback is included (i.e., VegOff_1× vs. VegOn_2×). In addition, the range of heat wave occurrences slightly shifts toward the reduction of heat waves although the most probable number of

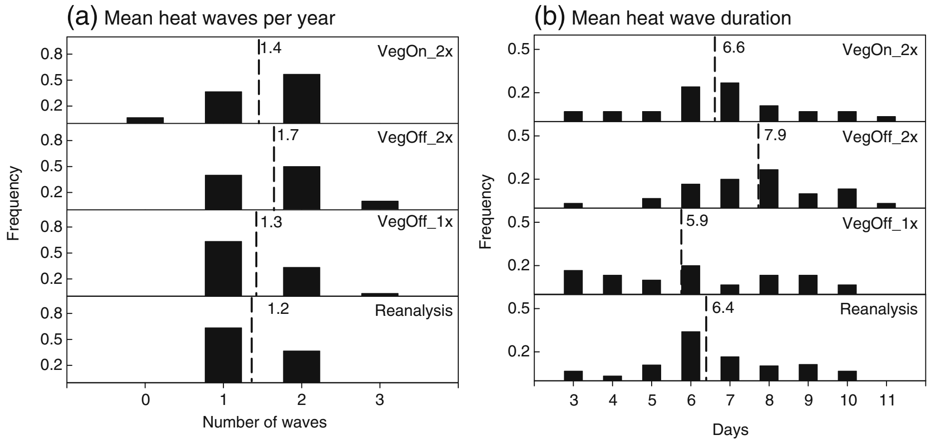

Fig. 3 **a** Probability distribution of the average numbers of heat waves per year over central and Europe (0°–20°E, 40°N–50°N), and **b** probability distribution for the average durations of heat waves. *Dashed vertical lines* represent the mean values

annual heat waves increases from one to two times a year. It is also noteworthy that the duration of heat waves is significantly modified by vegetation feedback. As CO_2 doubled, the average duration of heat waves has increased by about 2 days in the VegOff_2× experiment, which is approximately a 33% increase from the VegOff_1× experiment. In contrast, the average duration of heat waves has increased only by 0.7 days in the VegOn_2× experiment, which is approximately a 65% reduction from the VegOff_2× experiment. This reduction of the average duration of heat waves increases also shows statistically significant at the 90% confidence level. These results suggest that severity of more frequent and longer lasting heat waves as a result of CO_2 doubling will slightly diminish due to vegetation feedback.

4 Summary and discussion

We have examined the potential impact of vegetation feedback on the changes in the surface air temperatures and heat waves over the Europe under doubled CO_2 climate. CAM3–DGVM experiments suggest that CO_2 doubling induces significant increases in the mean temperature regardless of the presence of vegetation feedback, but the surface warming is weakened as enhanced greenness exerts a cooling effect by inducing more evaporation from surface and subsequent precipitation. Such cooling effect is conspicuous for the changes in daily maximum temperatures. Also, the frequency of occurrence and duration of heat waves slightly reduced due to the vegetation feedback effect. This result implies that vegetation feedback should be considered as one of the important factors for predicting future heat wave activity.

The IPCC AR4 models have traditionally focused on one aspect of changes in anthropogenic GHGs impact on climate. So, their results prospect the climate of Europe becoming more Mediterranean, with warmer summers, reduced rainfall and more frequent and severe heat wave by increase in GHGs and associated feedback in the atmosphere and ocean (Christensen et al. 2007). But, it missed many other important direct or feedback effects. Our model simulation results show that one such process, vegetation–evapotranspiration feedback may reduce the warming and related heat wave activity in Europe under warmer climate. Thus, we suggest the IPCC modeling groups to potential importance for dynamic vegetation coupling within climate models for simulating future climate projections.

Although this study identifies the impact of vegetation feedback under the 2 × CO_2 condition, there are some shortcomings. First, only one model has been used in the projection making it impossible to assess uncertainties in the projected impact of vegetation feedback. Similarities between the results in this study and previous studies of similar subjects (Levis et al. 1999; Sitch et al. 2008) support that the results obtained in our study is plausible, at least qualitatively. Second, the simulation was performed at a relatively coarse horizontal (T42) resolution. The horizontal distribution of temperatures and vegetation change is insufficient to capture the spatial details of the local climate characteristics. Third, the CAM3–DGVM system simulates only the 'potential' natural vegetation. Any anthropogenic land-use changes (e.g., cropland and urbanization) are not considered but it may have considerable influence on the regional climate over Europe. For example, these studies suggest that agricultural expansion by removing natural vegetation may have induced additional warming and moisture depletion in Europe (Zhao et al. 2001; Feddema et al. 2005; Betts et al. 2007). Further, this land-cover change may alter the frequency, intensity, and duration of heat wave. These concerns will be the subject of our follow up studies. For an accurate assessment of vegetation feedback, it is necessary to carry out complicated experiments on a fine resolution and investigate the difference between the potential natural vegetations (i.e., deciduous forest and evergreen forest) and the human-induced vegetation (i.e., crop and wheat) in terms of their impacts on climate.

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References

Betts RA, Cox PM, Lee SE, Woodward FI (1997) Contrasting physical and structural vegetation feedbacks in climate change simulations. Nature 387:796–799

Betts RA, Fallon PD, Goldewijk KK, Ramankutty N (2007) Biogeophysical effects of land use on climate: model simulations of radiative forcing and large-scale temperature change. Agric For Meteorol 142:216–233

Christensen JH et al (2007) Regional climate projections. In: Solomon S et al (eds) Climate change 2007: the physical science basis. Contribution of working group 1 to the fourth assessment of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, pp 847–940

Collins WD et al (2006) The community climate system model version 3 (CCSM3). J Climate 19:2122–2143

Cowling SA, Jones CD, Cox PM (2009) Greening the terrestrial biosphere: simulated feedbacks on atmosphere heat and energy circulation. Clim Dyn 32:287–299

Della-Marta PM, Luterbacher J, von Weissenfluh H, Xoplaki E, Brunet M, Wanner H (2007) Summer heat waves over western Europe 1880–2003, their relationship to large-scale forcings and predictability. Clim Dyn 29:251–275

Feddema JJ, Oleson KW, Bonan GB, Mearns LO, Buja LE, Meehl GA, Washington WM (2005) The importance of land-cover change in simulating future climates. Science 310:1674–1678

Fischer EM, Seneviratne SI, Lüthi D, Schär C (2007) Contribution of land–atmosphere coupling to recent European summer heat waves. Geophys Res Lett 34:L06707. doi:10.1029/2006GL02068

Intergovernmental Panel on Climate Change (2007) The physical science basis. In: Solomon S et al (eds) Contribution of working group 1 to the fourth assessment of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, pp 872–878

Jeong SJ, Ho CH, Jeong JH (2009a) Increase in vegetation greenness and decrease in spring time warming over East Asia. Geophys Res Lett 36:L0270. doi:10.1029/2008GL036583

Jeong SJ, Ho CH, Kim KY, Jeong JH (2009b) Reduction of spring warming over East Asia associated with vegetation feedback. Geophys Res Lett 36:L18705. doi:10.1029/2009GL039114

Kalnay E et al (1996) The NCEP/NCAR 40-year reanalysis project. Bull Am Meteorol Soc 77(3):437–471

Levis S, Bonan GB (2004) Simulating springtime temperature patterns in the community atmosphere model coupled to the community land model using prognostic leaf area. J Climate 17(23):4531–4540

Levis S, Foley JA, Pollard D (1999) Potential high-latitude vegetation feedbacks on CO_2-induced climate change. Geophys Res Lett 26:747–750

Levis S, Bonan GB, Vertenstein M, Oleson KW (2004) The community land model's dynamic global vegetation model (CLM-DGVM): technical description and user's guide. Technical Note NCAR/TN-459+IA, National Center for Atmospheric Research, Boulder, CO

Meehl GA, Tebaldi C (2004) More intense, more frequent, and longer lasting heat waves in the 21st century. Science 305:994–997

Oleson KW et al (2004) Technical description of the Community Land Model (CLM). Technical Note NCAR/TN-461+STR, 174 pp

Schär C, Vidale PL, Lüthi D, Frei C, Häberli C, Liniger MA, Appenzeller C (2004) The role of increasing temperature variability in European summer heat waves. Nature 427:332–336

Seneviratne SI, Lüthi D, Litschi M, Schär C (2006) Land–atmosphere coupling and climate change in Europe. Nature 443:205–209

Sitch S, Huntingford C, Gedney N, Levy PE, Lomass M, Piao SL, Betts R, Ciais P, Cox P, Friedlingstein P, Jones CD, Prentice IC, Woodwards FI (2008) Evaluation of terrestrial carbon cycle, future plant geography, and climate–carbon cycle feedback using five Dynamic Global Vegetation Models (DGVMs). Glob Chang Biol 14:2015–2039

Solomon S et al (2007) Technical summary. In: Solomon S et al (eds) Climate change 2007: the physical science basis. Contribution of working group 1 to the fourth assessment of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, pp 19–91

Zhao M, Pitman AJ, Chase T (2001) The impact of land cover change on the atmospheric circulation. Clim Dyn 17:467–477