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Assessing the benefits of crop albedo bio-geoengineering

Joy S Singarayer[1], **Andy Ridgwell and Peter Irvine**

Bristol Research Initiative for the Dynamic Global Environment (BRIDGE),
School of Geographical Sciences, University of Bristol, University Road, Bristol BS8 1SS, UK
and
Bristol Bio-geoengineering Initiative (BRISBI), University of Bristol, University Road,
Bristol BS8 1SS, UK

E-mail: joy.singarayer@bris.ac.uk

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Abstract

It has been proposed that growing crop varieties with higher canopy albedo would lower summer-time temperatures over North America and Eurasia and provide a partial mitigation of global warming ('bio-geoengineering') (Ridgwell *et al* 2009 *Curr. Biol.* **19** 1–5). Here, we use a coupled ocean–atmosphere–vegetation model (HadCM3) with prescribed agricultural regions, to investigate to what extent the regional effectiveness of crop albedo bio-geoengineering might be influenced by a progressively warming climate as well as assessing the impacts on regional hydrological cycling and primary productivity. Consistent with previous analysis, we find that the averted warming due to increasing crop canopy albedo by 0.04 is regionally and seasonally specific, with the largest cooling of $\sim$1 °C for Europe in summer whereas in the low latitude monsoonal SE Asian regions of high density cropland, the greatest cooling is experienced in winter. In this study we identify potentially important positive impacts of increasing crop canopy albedo on soil moisture and primary productivity in European cropland regions, due to seasonal increases in precipitation. We also find that the background climate state has an important influence on the predicted regional effectiveness of bio-geoengineering on societally-relevant timescales (ca 100 years). The degree of natural climate variability and its dependence on greenhouse forcing that are evident in our simulations highlights the difficulties faced in the detection and verification of climate mitigation in geoengineering schemes. However, despite the small global impact, regionally focused schemes such as crop albedo bio-geoengineering have detection advantages.

Keywords: climate change, geoengineering, crops, albedo

1. Introduction

On its own, a very substantial curtailing of carbon dioxide (CO_2) emissions in the future is unlikely to prevent thresholds of unmanageable or 'dangerous' climate change being crossed, with even stabilization at 10% of present-day emissions by 2050 eventually resulting in temperature increases crossing a 2 °C threshold (Weaver *et al* 2007). In addition to proposals for the capture of CO_2 from the air, a variety of geoengineering schemes have been devised to directly mitigate climate change (e.g., see reviews by Vaughan and Lenton (2009) and Irvine and Ridgwell (2009), and papers in this volume). Most schemes typically require the creation of vast new infrastructures and industries, may need costly maintenance, and, in the case of stratospheric sulfate aerosols and iron fertilization, continued re-application (Wigley 2006, Zeebe and Archer 2005). However, other schemes exist, which, while providing much less climate mitigation globally, may prove less risky and more practical in the near term.

[1] Author to whom any correspondence should be addressed.

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We recently devised a scheme with the potential to provide significant regional-scale mitigation of climate change–growing crop plants with increased leaf surface reflectivity (i.e., higher albedo)—'bio-geoengineering' (Ridgwell *et al* 2009). This bio-geoengineering approach to climate mitigation has its basis in the albedo differences that exist between plants. For instance, crop plants tend to have a higher albedo than natural vegetation when fully out in leaf, with barley at northern European latitudes having a higher albedo (0.23) than, for instance, does deciduous (0.18) or coniferous (0.16) woodland (Monteith and Unsworth 1990). Historical conversion of land for agriculture should thus have already led to more solar energy being reflected on average and hence reduced heating at the surface (Betts *et al* 2007, Costa *et al* 2007), with an (global annual mean) cooling estimated at 0.17 °C (Matthews *et al* 2003). Different crop plants also differ in their albedo. However, although the replacement of, for example, barley (albedo = 0.23 at 52 °N (Monteith and Unsworth 1990)) with sugar beet (0.26) would in theory provide a further local cooling of climate in addition to the impact of the historical clearance of natural vegetation cover, large-scale reorganization of which crops are grown would be unduly disruptive to farming and food processing industries.

One advantage of bio-geoengineering is that different varieties of the same crop also differ in their albedo. For individual leaves, differences of up to 0.05 (abaxial surface) and 0.16 have been reported between varieties of wheat (Uddin and Marshall 1988) and between various mutants of sorghum (Grant *et al* 2003), respectively. This variability appears to be mainly governed by differences in the thickness and characteristics of leaf waxes (Febrero *et al* 1998, Grant *et al* 2003, Holmes and Keiller 2002, Uddin and Marshall 1988). At the canopy level, albedo variations of up to 0.01 and 0.08 have been observed between several different commercial varieties of barley (Febrero *et al* 1998) and maize (Hatfield and Carlson 1979), respectively. In the case of maize, the morphology (arrangement) of the leaves in the canopy is thought to be the primary controlling factor of canopy albedo (Hatfield and Carlson 1979). The 'hairiness' of leaves is also known to play a further role in setting overall plant albedo, but tends to qualitatively differ from the effect of waxes by having greater reflectance at longer (towards IR) wavelengths compared to the UV (Holmes and Keiller 2002). In some plants this may be due to the strong UV absorption properties of leaf hairs (Karabourniotis *et al* 1992).

In theory, the implementation of bio-geoengineering thus only requires a change in the variety (not type) of crop grown, and hence would not create serious disruption to farming nor any loss in the area given over to food production. There also need not be deleterious implications for yield, as increasing the fraction of incoming photosynthetically active radiation (PAR) reflected back by the canopy does not necessarily imply a reduction in total photosynthesis (Rosati *et al* 2007) and by inference, productivity. Indeed, it has been observed that glaucous (waxy) lines of wheat exhibit higher grain yield (Merah *et al* 2000) while cotton yield is significantly increased when reflective kaolinite sprays are applied to the upper canopy leaves (Moreshet *et al* 1979). For dryland crops, the beneficial effect of increased leaf reflectivity is often attributed to greater water use efficiency and reduced leaf heating (Moreshet *et al* 1979, Ogbuehi *et al* 1980), although other studies caution that the relationship between glaucousness and transpiration efficiency is not simple (Merah *et al* 2000). Achieving a more even distribution of PAR absorption within the canopy can lead to unchanged or increased whole canopy photosynthesis even if total absorbed PAR is reduced (Rosati *et al* 2007), a consequence of the greater photosynthetic efficiency of inner, compared to outer, canopy leaves. This effect is supported by the occurrence of increasing plant productivity despite reduced total solar radiation in recent decades (solar dimming) (Mercado *et al* 2009), attributed to an increase in diffuse radiation that penetrates more effectively through to more light-limited leaves within the canopy. Thus, by improving the transfer of light into the canopy via increased reflectivity of individual leaves or altered canopy structure, crop varieties could in theory be optimized for higher overall albedo without reduced yield.

Although some assessment of the potential for bio-geoengineering has previously been made, it was of limited scope, focusing on global temperature patterns and analysis with respect to a single climate state (×2 modern; 700 ppm) (Ridgwell *et al* 2009). In this paper, we examine the climate impacts of increasing the crop canopy albedo in greater, regional detail, and assess the implications of bio-geoengineering for the hydrological cycle and plant productivity. We also investigate whether the efficacy of this approach depends on the climate state, by comparing the impact of increasing crop canopy albedo at modern, ×2 and ×4 CO_2 scenarios.

2. Modelling approach

In this study we employ the Hadley Centre coupled climate model (HadCM3) to assess the impact of crop albedo bio-geoengineering on regional climate and climate variability. HadCM3 comprises 3D dynamical ocean and atmosphere components, as well as a thermodynamic/free-drift sea-ice model (Gordon *et al* 2000), surface exchange scheme (MOSES2.1; Essery *et al* 2003), and an interactive, dynamic vegetation model (TRIFFID; Cox 2001). The resolution of the atmospheric component is 3.75° × 2.5° with 19 vertical levels, and the ocean resolution is 1.25° × 1.25° with 20 vertical levels. In the TRIFFID model, nine surface types are specified: 5 plant functional types (broadleaf trees, needleleaf trees, C3 grasses, C4 grasses, and shrubs) and 4 non-vegetation types (bare soil, inland water, urban and ice). Using a tiled grid cell scheme, the fractional area of each grid cell covered by each surface type is calculated based on the local climate. As there is no explicit agricultural crop model, the global crop area is instead designated by a cropland mask (figure 1), derived from Betts *et al* (2007), which can only be occupied by agricultural-type vegetation (i.e. C3 and C4 grasses) or bare soil. Hence, the actual cropland is equivalent to the mask area, less inland water, urban and ice tiles, and less the area covered by nongrassland vegetation or bare soil.

Table 1. Global and European SAT impacts of both increasing equilibrium CO_2, and increasing cropland canopy albedo. The European continental region was averaged over 5–20° long, 45–55° lat. The figures in brackets are the standard deviations over 100 years. Simulation key: MOD = modern control (350 ppmv); 2 × CO_2 = doubled CO_2 control (700 ppmv); 4 × CO_2 = quadrupled CO_2 control (1400 ppmv); MODa = modern CO_2 simulation with crop albedo increased by +0.04, and similar for 2 × CO_2a and 4 × CO_2a.

	MOD	2 × CO_2–MOD	4 × CO_2–MOD	MODa–MOD	2 × CO_2a–2 × CO_2	4 × CO_2a–4 × CO_2
Global annual SAT	14.25 (0.10)	+3.53 (0.16)	+6.80 (0.20)	−0.07 (0.14)	−0.17 (0.15)	−0.05 (0.21)
Europe Annual SAT	8.46 (0.58)	+4.84 (0.75)	+9.37 (0.79)	−0.31 (0.75)	−0.63 (0.74)	−0.18 (0.80)
Europe crop area-weighted JJA SAT	20.43 (1.22)	+8.03 (1.84)	+14.55 (1.47)	−0.59 (1.70)	−1.44 (1.98)	−0.66 (1.65)

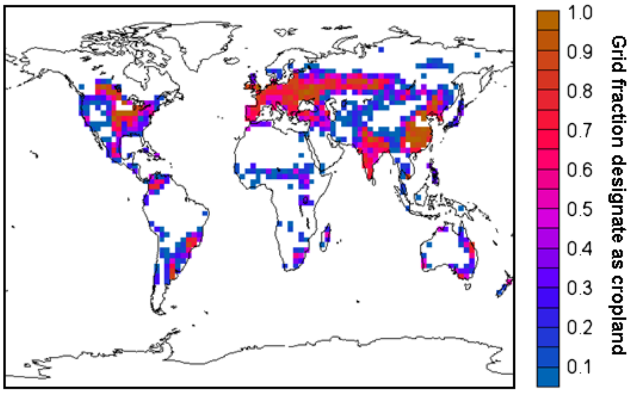

Figure 1. Global distribution of croplands, as prescribed in HadCM3 (and based on Betts *et al* (2007)). The cropland area can only be occupied by C3 and C4 grass PFTs to represent the major crop species. Wheat and rice are examples of C3 grasses, and sugarcane and maize are examples of C4 grasses.

The maximum snow-free canopy albedo of C3/C4 grasses in MOSES/TRIFFID is set by default to a value 0.2. This constant is used to calculate albedo as a function of modelled leaf area index (albedo declining towards that of bare soil as the leaf area index decreases). In order to simulate the effect of higher crop albedo we uniformly increase the maximum snow-free albedo of C3/C4 grasses scaling with the fractional crop mask to a maximum of +0.04. This represents a potential 20% increase in canopy albedo, which is within the range of intra-species variation of crop albedo reported in the literature (see: Ridgwell *et al* 2009). In implicitly adjusting the canopy albedo across all crop species identically, we are necessarily extrapolating from the limited number of crop characterization studies currently available. However, it is seems likely that significant variations in leaf waxiness and/or canopy morphology (and hence albedo) will exist between the varieties of all major food crops.

In this study we considered three different atmospheric CO_2 concentrations (350 ppmv, 700 ppmv and 1400 ppmv) and hence baseline climate states against which the effectiveness of crop albedo bio-geoengineering is evaluated (see table 1). The choice of a 'present-day' CO_2 value of 350 ppm was taken to produce a climate roughly consistent with the timeframe for the prescribed cropland area (Betts *et al* 2007). For each of the three different CO_2 values, a control simulation was run together with one where C3/C4 crop canopy albedo was increased by +0.04, a total of 6 simulations. The simulations were run for 200 years and initialized from prior control simulations that have been run at those CO_2 values. The climatologies discussed in the results sections are based on averages of the final 100 years of each simulation. The trends in global mean temperature during this period were between 0.001 °C/decade and 0.02 °C/decade in all simulations; sufficiently small to be approaching equilibrium. Due to the relative magnitude of the bio-geoengineering climate impacts compared to the size of inter-annual variability observed both globally and regionally, such a long integration time was necessary for a statistically significant analysis.

3. Impacts on surface air temperature

Analysis of global average surface air temperature (SAT) anomalies (table 1) confirms a relatively small impact of crop bio-geoengineering on the global scale, as previously reported (Ridgwell *et al* 2009). Whilst doubling CO_2 leads to an increase of roughly 3.0 °C (based on either 2 × CO_2–MOD or 4 × CO_2–2 × CO_2), the mitigation achieved by increasing crop albedo is only ~0.1 °C. However, despite the small global annual average effect, crop albedo bio-geoengineering produces a rather larger regional and seasonal impact. For instance, during northern hemisphere summer (June July, August average; JJA) in the 2 × CO_2 and 4 × CO_2 control simulations, the greatest warming due to increased CO_2 occurs over northern mid-latitude continental regions (figure 2(c) and (e)). For all three CO_2 scenarios, the introduction of increased crop canopy albedo reduced local temperatures in these regions by 0.5 to 2 °C (figure 2(b), (d) and (f)) with Europe, in particular, showing the largest and most consistent summer-time cooling in the three experiments.

Focusing on the regional and seasonal impacts of bio-geoengineering: we find the maximum mitigation of climate change occurs in Western Europe in the summer time (figures 2(a) and (c)), with a cooling effect that amounts to ~20% of the SAT increase due to equilibrium doubling of CO_2 from modern. The impacts of increasing crop albedo are minimal in winter after the harvest season. Crop cycling is not included in our model, but we find that in any case there is little impact of increasing crop albedo during the winter season, due to low insolation levels and reduced canopy cover (figures 3(a) and (c)). The exception to this is the 2 × CO_2 experiment, which has a significant cooling of >1 °C in places, which is accompanied by a cooling over the Atlantic storm

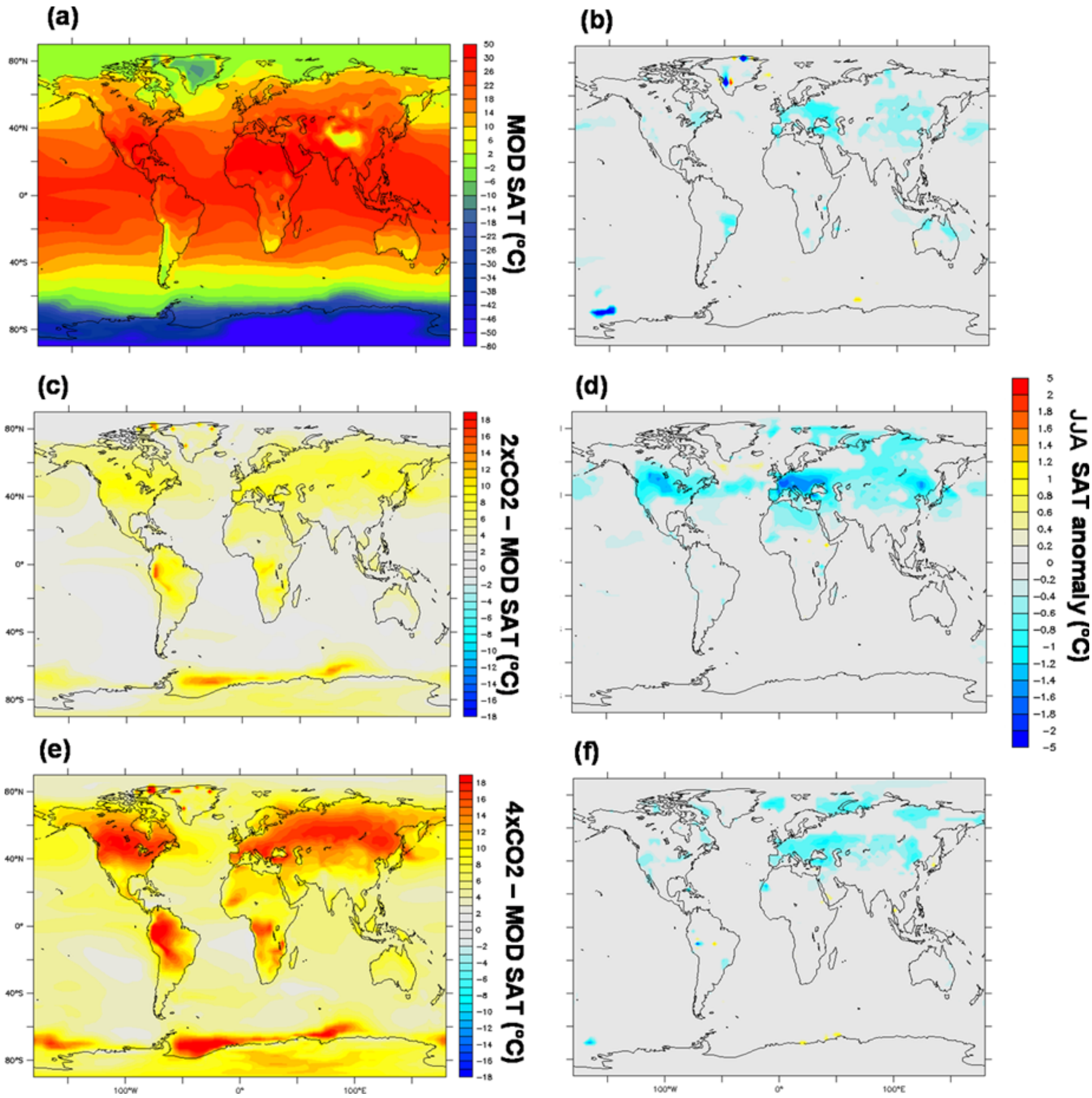

Figure 2. Surface air temperatures and anomalies during northern hemisphere summer (JJA). (a) SATs for the modern control simulation (MOD), (c) SAT anomalies for $2 \times CO_2$ minus MOD (e) anomalies for $4 \times CO_2$ minus MOD, and the right-hand sub-plots are anomalies from each of the control simulations due to increasing crop albedo by +0.04 (b) MODa-MOD (d) $2 \times CO_2$ a–$2 \times CO_2$ (f) $4 \times CO_2$a–$4 \times CO_2$. Only differences which are statistically significant at a 99% confidence level, as given by a Student T test, are plotted.

track, and even larger Arctic Ocean cooling. Further analysis reveals that the North Atlantic region in particular is subject to multi-decadal variability, which can (and indeed does, under a $2 \times CO_2$ climate) induce winter temperature anomalies unrelated to crop canopy albedo changes. This results in the larger global temperature anomaly with increased crop canopy albedo at $2 \times CO_2$ than either MOD or $4 \times CO_2$ experiments.

We find that considerable increases in winter temperatures, due to increased atmospheric CO_2 concentrations, occur in tropical continental regions, including S Asia (figure 3(b)), which is another region of intense agriculture (figure 1). Notably, the magnitude of SAT decrease due to increasing crop canopy albedo in the S Asian region is larger in winter than summer (figure 3(d)). This results from a sequence of events starting early in the year and relating to monsoonal circulation. In spring, the increase in cropland albedo decreases surface temperatures by up to 1 °C. As a result, the land–sea temperature contrast decreases in the crucial lead into the summer monsoon season. A decrease in cloud cover over land in summer is then a consequence of reduced monsoonal winds, and counteracts any decrease in temperature due to crop albedo increases (figures 3(b) and (d)). In winter, unlike Europe, there is still high insolation and little seasonal change in canopy cover in the model over India. As a result the impact of crop albedo on winter SATs is large.

4. Hydrological changes and plant productivity

As demonstrated in the previous section, Europe is one of the regions that have a large and robust temperature signal

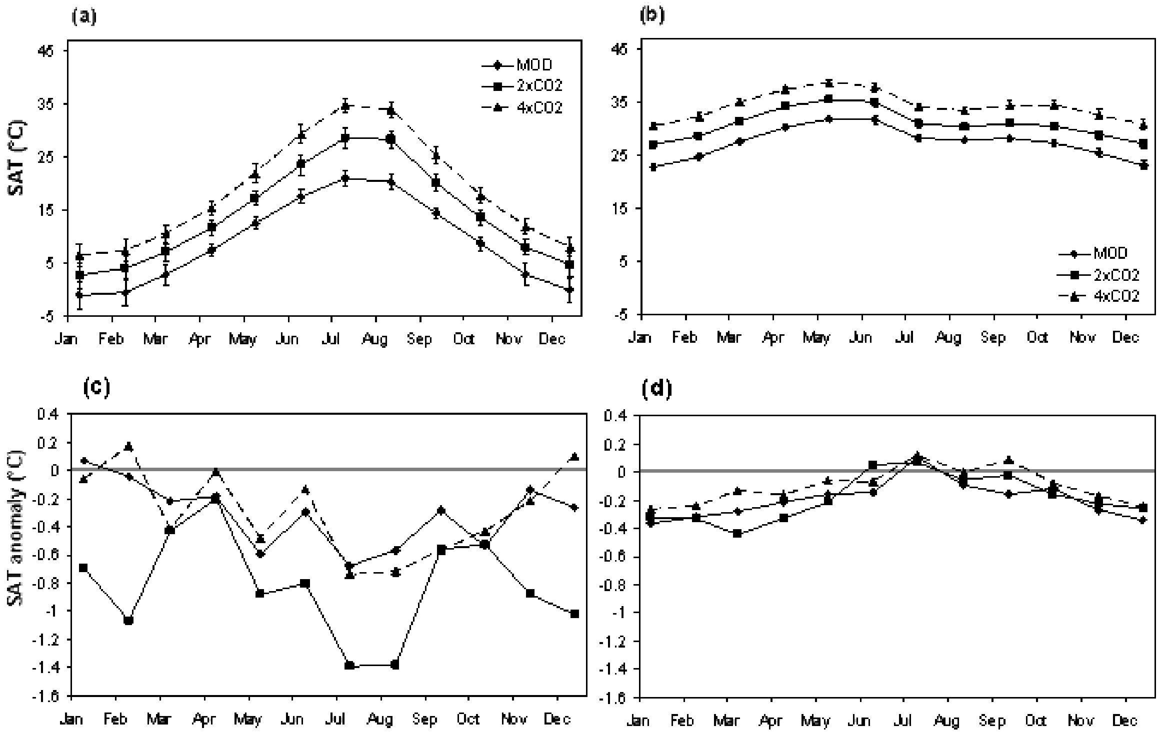

Figure 3. Seasonal cycle of SAT over Europe (a) and India (b) for each equilibrium CO_2 control simulation. In the lower plots the anomalies due to raising crop canopy albedo are shown for Europe (c) and India (d). The average for the European region was taken over 5–20°E and 45–55°N. The Indian region is 70–90°E and 10–25°N.

in the northern hemisphere summer, induced through crop bio-geoengineering. A concurrent impact occurs in the hydrological cycle in the same season. The response of the European region to increasing CO_2 levels in the atmosphere is increasingly dry summers (figure 4(a)). The crop albedo increase counteracts a significant portion of this drying in all three CO_2 scenarios, partly due to the effect on humidity of the regional cooling (figure 4(a)). During the northern hemisphere winter (DJF) there are no equivalent anomalies in precipitation, except for the $2 \times CO_2$ experiment, which shows anomalously drier conditions (not shown) as a result of the natural multi-decadal variability observed.

The increase in summer precipitation experienced over Europe due to increased crop albedo also results in higher evaporation rates, although the overall surface water balance anomaly (precipitation minus evaporation) is positive. The soil moisture over much of Europe also increases, with a more uniform pattern than the precipitation minus evaporation balance. We find that these impacts are similar across all of the different CO_2 scenarios.

Similar trends in the hydrological cycle were found for North America, whilst Australia and parts of sub-Saharan Africa display the opposite sensitivities. In these regions, annual average soil moisture in particular decreases as a result of increasing crop albedo. Neither of these is a locality with a high fraction of the land surface used for agriculture in the model, but is instead a result of remote forcing of a monsoonal region. The sign of the anomalies is robust in all three CO_2 scenarios.

One major aspect for consideration is the effect of climate change on the productivity of cropland areas. The model simulations include primary productivity and vegetation carbon as prognostic variables. Net primary productivity (NPP) depends on several factors including water stress, temperature and CO_2. Total NPP in Europe decreases as CO_2 and global warming increases, as does NPP for C3 grasses (figure 4(b)), although NPP of C4 grasses increases slightly as they favourably compete against other plant functional types in warmer, drier regions. The introduction of increased crop albedos leads to an increase in NPP of C3 grasses (and to a lesser extent C4 also). This is illustrated in figure 4(b), in which we have concentrated on summer months, being most vital for the majority of European cropping cycles. The increase in NPP results from reduced water stress (due to the increase in precipitation-minus-evaporation) and lower temperatures, and demonstrates potential benefits to crop canopy manipulation in addition to the impact on temperatures.

5. Discussion

Croplands cover over 10% of the total global land surface, with dense agricultural regions in Europe, South Asia and the Eastern United States (figure 1). In comparing figures 1 and 2, the continental regions with the greatest warming due to increasing CO_2 (Europe, South and East Asia and the Eastern United States) are also generally the regions where the cropland concentration is greatest. This correspondence between the magnitude of climate impacts and density of agriculture has potentially serious implications for future food production (Lobell and Field 2007), making summer-time climatic conditions across major cropland regions of

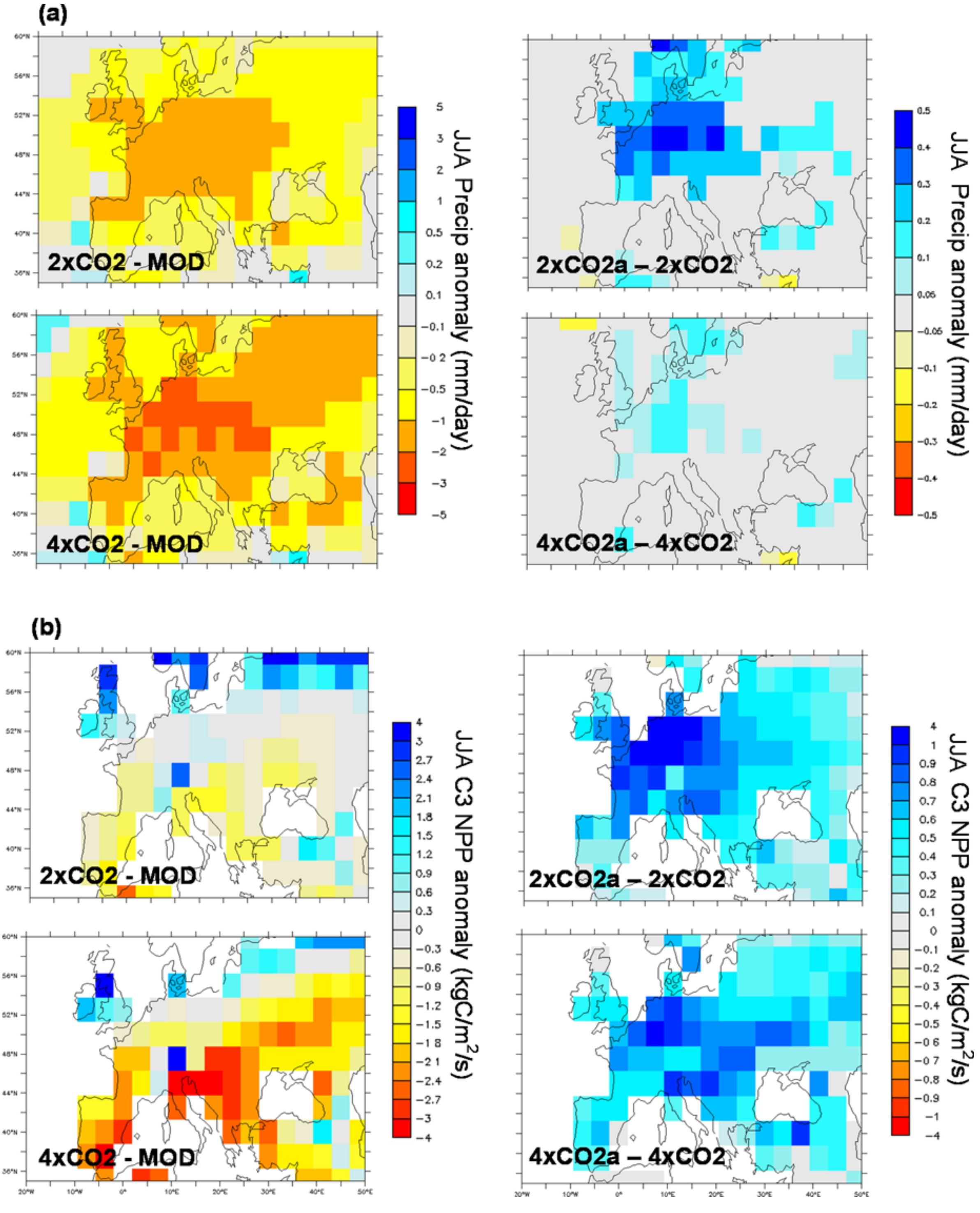

Figure 4. Summer-time (JJA) anomalies in (a) precipitation and (b) NPP of C3 grasses. Left-hand side plots show anomalies of $2 \times CO_2$ and $4 \times CO_4$ from modern, and right-hand plots show anomalies due to the introduction of increased crop albedo. Differences which are statistically significant at a 99% confidence level, as given by a Student T test, are plotted.

particular importance. Because bio-geoengineering provides its greatest cooling benefits during summer in many regions closely associated with arable regions, it provides a focused mitigation benefit disproportionate to the modest global average temperature reduction. The major cropland areas also, unsurprisingly, tend to be closely associated with the greatest population densities. Bio-geoengineering may thus also provide similarly spatially and seasonally focused benefits with respect to the incidence of heat waves and associated mortality (Meehl and Tebaldi 2004), as well as surface hydrology and crop productivity. However, whether the same regional benefits (e.g., to Europe) would be accrued if cropland changes were made only in one region (e.g., Europe) or whether bio-geoengineering needs to be applied on a global scale remains

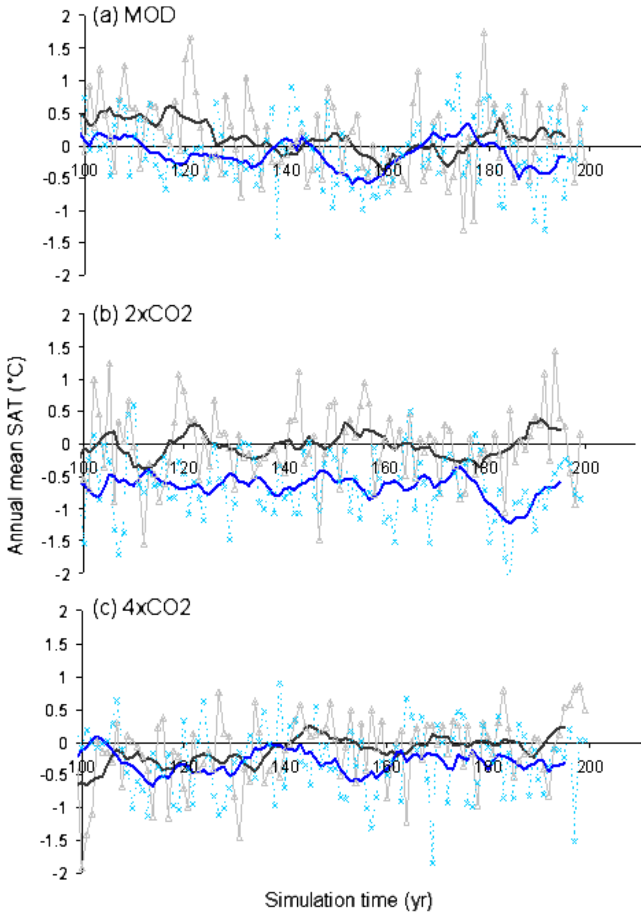

Figure 5. Time series of European annual average SATs, relative to the long term average of the control. (a) Modern simulations, (b) $2 \times CO_2$ simulations (c) $4 \times CO_2$ simulations. In each sub-plot the grey triangles are the annual mean of the control, the thick black line is the 10-year running mean of the control, the blue crosses are the annual mean of the increased crop albedo simulation, and the thick blue line is the 10-year running mean.

to be determined in models. That background CO_2 and hence greenhouse warming imparts an influence on our predicted mitigation benefits suggests that climate teleconnections are important to the details of the benefit gained.

Quantifying the exact mitigation benefit provided is not straightforward because the standard deviation (a measure of year to year variability) of European summer temperatures is as large as or larger than the impact of introducing high albedo crops (table 1). Examination of the longitudinal variation in annual mean SATs for Europe under modern CO_2 reveals that there is a significant multi-decadal variability as well as inter-annual variability (figure 5). One example of multi-decadal variability previously found in HadCM3 that may be important for Europe involves the North Atlantic overturning circulation (AMOC), with a periodicity of ~25 years (Dong and Sutton 2005).

It is interesting that the temperature decrease resulting from the introduction of crop canopy albedo increase is apparently larger at $2 \times CO_2$ than either modern or $4 \times CO_2$ scenarios. Whilst a component of this larger difference at $2 \times CO_2$ is related to multi-decadal variability, there is also a more persistent difference at this level of CO_2 (seen in the global annual SAT time series, figure 5). Larger SAT anomalies when increasing crop albedo at $2\times CO_2$ than modern or $4\times CO_2$ are evident over the North Atlantic region and storm track regions from North America to Europe, including large winter temperature anomalies due to Arctic sea-ice cover changes. It will be necessary to continue the simulations to validate the long term persistence beyond multi-decadal variability of the larger anomalies at $2 \times CO_2$ when bio-geoengineering is introduced. The implication, if this is the case, is that the sensitivity of the climate system to geoengineering solutions is different at different CO_2 levels. For example, the extent of Arctic sea-ice cover at $1\times$, $2\times$ and $4 \times CO_2$ is very different, and sea-ice/ocean feedbacks may be more sensitive to small changes in climate in one scenario than another (and not necessarily linearly increase with CO_2).

Detection and verification of the effectiveness of bio-geoengineering, if implemented, must therefore take into account decadal-scale regional climate variability, and how it evolves as atmospheric CO_2 increases further. Since observational intervals counted in many decades to centuries would not be practical, climate models, and increasingly, large ensembles of climate models, will have to be relied upon to quantify the mitigation benefits of bio-geoengineering. However, in the case of bio-geoengineering, the regional nature of the surface radiation budget modification may provide spatial patterns that enable the natural variability and climate mitigation signals to be separated. It is also possible that evaluation of geoengineering could be done using measures that in effect integrate different climate impacts and provide superior signal-to-noise.

6. Conclusions

In this study we have assessed the climate impacts of crop albedo bio-geoengineering and its effectiveness in mitigating global warming across a range of modern and future atmospheric CO_2 concentrations. The results demonstrate a relatively robust ca 1 °C regional summer-time cooling over Europe and winter-time cooling over SE Asia. The introduction of higher crop canopy albedos over Europe induces increased precipitation and ultimately increased net primary productivity of C3/C4 plant functional types, as well as other vegetation. As this occurs in the Boreal summer season this will provide maximum benefit when considering crop yield.

The relatively subtle regional and seasonal nature of bio-geoengineering and the magnitude of variability here may cause potential issues in terms of evaluating this approach over several years (unlike the 100-year average presented in this study). Large initial-condition climate model ensembles under transiently increasing CO_2 scenarios will most likely be a necessary component in the assessment of bio-geoengineering.

There are a number of advantages of this approach to global warming mitigation. Bio-geoengineering is relatively low cost, in development and implementation, with the global infrastructure required to create and propagate specific physiological leaf traits through to large-scale cultivation already existing. In addition to the existence of varieties of crops with different leaf and canopy albedos, and in the same way that traits such as herbicide resistance are introduced into crops, it may eventually be possible to introduce traits such as higher albedo via genetic modification. Thus, some degree of bio-geoengineering could in theory take place almost immediately, although realistically it is likely to be of the order of a decade of more for 'climate-friendly' varieties to become commercially available for most major food crops.

There are fewer potential issues concerning irreversibility than other proposed schemes. As crops are replanted on a yearly basis, 'maintenance' is less of a problem, although to maintain the mitigation benefit, the crops grown could not be replaced with lower albedo varieties or species. Furthermore, the climate impacts are inherently focused in the regions most important to food production and to population centres, giving it the advantage of providing more 'targeted' (concentrated) benefits even if applied globally in practice. Thus, despite likely challenges in detection and verification, the clear mitigation benefits accrued, particularly in summertime cooling and increased plant productivity in Europe, lead us to recommend that extensive spectral characterization of existing species and varieties should be carried out and the development of 'climate-friendly' varieties of major crops initiated. Indeed, crop bio-geoengineering could represent one method within a multi-facetted approach to mitigating climate change. However, these potential technologies for manipulating incoming solar radiation are unquestionably no alternative to reducing CO_2 emissions to mitigate global warming.

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