

1 **The Biogeophysical Climatic Impacts of Anthropogenic**
2 **Land Use Change during the Holocene**

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14

15 **Abstract**

16 The first agricultural societies were established around 10kaBP and had spread across much
17 of Europe and southern Asia by 5.5kaBP with resultant anthropogenic deforestation for crop
18 and pasture land. Various studies (e.g. Joos et al., 2004, Kaplan et al., 2011, Mitchell et al.,
19 2013) have attempted to assess the biogeochemical implications for Holocene climate in
20 terms of increased carbon dioxide and methane emissions. However, less work has been done
21 to examine the biogeophysical impacts of this early land use change. In this study, global
22 climate model simulations with HadCM3 were used to examine the biogeophysical effects of
23 Holocene land cover change on climate, both globally and regionally, from the early
24 Holocene (8 kaBP) to the early industrial era (1850 CE).

25 Two experiments were performed with alternative descriptions of past vegetation: (i) potential
26 natural vegetation simulated by TRIFFID but no land-use changes, and (ii) where the
27 anthropogenic land use model, KK10 (Kaplan et al., 2009, 2011) has been used to set the
28 HadCM3 crop regions. Snapshot simulations have been run at 1000 year intervals to examine

1 when the first signature of anthropogenic climate change can be detected both regionally, in
2 the areas of land use change, and globally. Results from our model simulations indicate that in
3 regions of early land disturbance such as Europe and ~~S-E~~South-east Asia detectable
4 temperature changes, outside the normal range of variability, are encountered in the model as
5 early as 7kaBP in the June/July/August (JJA) season and throughout the entire annual cycle
6 by 2-3kaBP. Areas outside the regions of land disturbance are also affected, with virtually the
7 whole globe experiencing significant temperature changes (predominantly cooling) by the
8 early industrial period. The global annual mean temperature anomalies ~~were found to be in our~~
9 single model simulations were ~~—~~ -0.22°C at 1850 CE, -0.11°C at 2kaBP and -0.03°C at
10 7kaBP. Regionally, the largest temperature changes were in Europe with anomalies of -
11 0.83°C at 1850 CE, -0.58°C at 2kaBP and -0.24°C at 7kaBP. Large-scale precipitation
12 features such as the Indian monsoon, the intertropical convergence zone (ITCZ), and the
13 North Atlantic storm track are also impacted by local land use and remote teleconnections.
14 We investigated how advection by surface winds, mean sea level pressure (MSLP) anomalies,
15 and tropospheric stationary wave train disturbances in the mid- to high-latitudes led to remote
16 teleconnections.

17

18 **1 Introduction**

19 The first agricultural societies were established in the Near East around 10kaBP and had
20 spread across most of Europe by 5.7kaBP (Zohary et al., 2012) and to India by 9kaBP
21 (Tauger, 2013). In China domestication of millet and rice began about 8.5 kaBP initially
22 spreading more slowly than in Europe but reaching S.E. Asia by 5.5kaBP (Roberts, 2013;
23 Tauger, 2013). Agriculture was also independently developed in Mesoamerica with maize
24 possibly being cultivated as far back as 9kaBP (Piperno et al., 2009) but, as in China, it spread
25 slowly to other areas.

26 The most important anthropogenic alteration of the natural environment was the clearing of
27 forests to establish cropland and pasture, and the exploitation of forests for fuel and
28 construction materials (Darby, 1956). This long history of anthropogenic land cover change
29 (ALCC) has implications for regional hydrology and climate, and possibly for global climate.
30 Deforestation results in both biogeochemical and biogeophysical changes. The
31 biogeochemical changes tend to increase temperature by the emission of greenhouse gases
32 such as CO₂ and CH₄ (CH₄ emissions are influenced not just directly by deforestation but by

1 irrigation in rice agriculture and by emissions from livestock and humans). The impacts of
2 biogeophysical changes are many and varied, being dependent on the local climate, soil, and
3 the natural vegetation that is being replaced, e.g. if natural savannah or grassland is replaced
4 by crops the impact will not be as great as if woodland is replaced.

5 There are several mechanisms by which biogeophysical changes due to deforestation can
6 affect regional climate. A combination of reduction in aerodynamic roughness, in the root
7 extraction of moisture and in the capture of precipitation on the canopy leads to reduced
8 evaporation and thus decreases the fluxes of moisture and latent heat from the surface to the
9 atmosphere. These changes work to increase the local surface temperature (Lean and
10 Rowntree, 1993). Conversely, the increase in surface albedo due to deforestation acts to
11 decrease surface temperature by increasing the reflection of shortwave radiation. This is
12 particularly true at high latitudes where lying snow is a factor for some of the year and the
13 snow covered ground is no longer masked by the canopy of the forest. Generally, in mid to
14 high latitudes the albedo increase is considered to be the dominant effect; leading to a net
15 cooling of the regional surface temperature, whereas in the moist tropics the evaporation is
16 more important and, therefore, a localised overall warming may result (Betts et al., 2006).

17 During the Holocene the climate has been influenced by natural forcings. Orbital variations
18 have caused a decline in summer solar insolation in the Northern Hemisphere over the last
19 6000 years. During the same period concentrations of greenhouse gases such as CO₂ and CH₄
20 have been increasing. On decadal to centennial timescales fluctuations in solar and volcanic
21 activity have also had a climatic impact. (Wanner et al., 2008; Schmidt et al., 2011) The
22 impact of ALCC is superimposed on these natural forcings. The extent and timing of these
23 early anthropogenic land surface changes is the subject of much debate, as is their role in
24 changing Holocene climate. Ruddiman (2003) proposed the idea that anthropogenic impacts
25 on greenhouse gases, and consequently climate change, began thousands of years ago as a
26 consequence of early agriculture and have been increasing in amplitude ever since, which he
27 termed 'the early anthropogenic hypothesis'. The idea has been hotly debated in the literature
28 (e.g. Broecker and Stocker, 2006; Joos et al., 2004; Singarayer et al., 2011; Mitchell et al.,
29 2013; Kaplan et al., 2011). Whilst the early anthropogenic hypothesis may likely not account
30 entirely for the pre-industrial rises in CO₂ and CH₄ there is no doubt that land use changes do
31 have climatic impact on both regional and global scales. The real debate is the scale of these
32 effects of early agriculture.

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1 Whilst paleoecological and archaeological evidence of anthropogenic land use changes exists,
2 there are not enough sites to comprehensively determine continental scale impacts of
3 deforestation (Kaplan, 2009). Therefore, in order to better estimate impacts of anthropogenic
4 land use, several databases of land use change have been developed. Examples of these
5 include the HYDE 3.1 (History Database of the Global Environment, Goldewijk et al., 2011),
6 KK10 (Kaplan et al., 2009 and 2011) and Pongratz et al. (2008) models. Although the
7 methodologies differ in the details, the basic premise of these models is that from an
8 estimated database of historical population trends, anthropogenic deforestation is calculated
9 based on population density and the suitability of land for crops or pasture.

10 To quantify the impact of ALCC on climate, datasets of past ALCC can be used in
11 conjunction with climate models. Several studies have estimated the influence of pre-
12 industrial ALCC on global climate (He et al., 2014; Kutzbach, 2011; Pongratz et al., 2010).
13 Globally, the biogeophysical effects of anthropogenic land use change have been estimated to
14 cause a slight cooling that is offset by the biogeochemical warming, giving a net global
15 warming (He et al., 2014; Pongratz et al., 2010). At the local to regional scale, in the most
16 intensively altered landscapes of Europe, Asia, and North America, the biogeophysical effects
17 can be comparable with the biogeochemical (He et al., 2014; Pongratz et al., 2010). In
18 addition, Strandberg et al. (2014) used a regional climate model to evaluate the climatic effect
19 of anthropogenic deforestation in Europe at 6kaBP and 0.2kaBP with both the HYDE 3.1 and
20 KK10 ALCC scenarios. For the KK10 scenario at 6kaBP small but significant temperature
21 differences were found in summer and, at 0.2kaBP, changes up to ± 1 °C were found over
22 widespread areas in both summer and winter. Other authors (e.g. Oglesby et al., 2010; Cook
23 et al., 2012) have modelled a decrease in precipitation in response to deforestation in
24 Mesoamerica.

25 These existing studies are, however, limited in either temporal or spatial extent and do not
26 address the question of when anthropogenically induced climate change first occurs. In this
27 study global climate model simulations are used to provide a comprehensive evaluation of the
28 influence that the biogeophysical effects of regional human-induced land cover change have
29 had on the climate both globally and regionally throughout much of the Holocene. As
30 described in detail in Sect. 2, the period under consideration is from 8kaBP to pre-industrial
31 (1850) and snapshot simulations with HadCM3 were run at 1000-year intervals. The results
32 are highlighted in Sect. 3. For evaluation purposes palaeoclimate reconstructions from

1 Bartlein et al .(2011) and Marcott et al .(2013) have been compared with the results from the
2 model runs (Sect. 4). The implications are discussed in Sect. 5.

3

4 **2 Methodology**

5 **2.1 Model Description**

6 The climate simulations in this study were performed with the UK Hadley Centre coupled
7 global climate model, HadCM3 (Gordon et al., 2000; Pope et al., 2000) with the Met Office
8 Surface Exchange Scheme (MOSES2.1) (Essery, 2003) and TRIFFID (Top-down
9 Representation of Interactive Foliage and Flora Including Dynamics) (Cox, 2001) dynamic
10 vegetation. The experimental set-up is summarised in Table 1.

11 HadCM3, is a coupled atmospheric, ocean and sea ice model. The atmospheric component
12 has a horizontal resolution of 2.5° latitude and 3.75° longitude with 19 unequally spaced
13 levels in the vertical and a 30 minute time step. It has an Eulerian advection scheme and
14 includes effects of CO₂, N₂O, CH₄, CFC11 and CFC12. The spatial resolution over the ocean
15 is 1.25° by 1.25° with 20 unequally spaced layers extending to a depth of 5,200m. It also
16 includes a 1.25° by 1.25° resolution model for the formation of sea-ice with simple dynamics
17 whereby the sea-ice drifts on the ocean currents (Cattle and Crossley 1995).

18 TRIFFID is coupled to the GCM (General Circulation Model) via MOSES every 10 days of
19 the model run. Within TRIFFID nine surface types are specified: 5 plant functional types
20 (PFTs) and 4 non-vegetation types.

21 HadCM3 was widely used in both the third and fourth assessment reports of the
22 Intergovernmental Panel on Climate Change (IPCC, 2001, 2007) and still performs well in a
23 number of tests relative to other global GCMs (Covey et al., 2003; IPCC, 2007). For the fifth
24 IPCC assessment it has been superseded by HadGEM2 (Collins et al., 2011), but being
25 relatively computationally efficient HadCM3 can be the better choice for some palaeoclimate
26 modelling applications as it allows more and/or longer runs to be conducted than would be
27 possible with a higher-resolution model.

28

1 **2.2 Project-Specific Model Configuration**

2 The version of HadCM3 used does not include interactive ice, carbon cycle, or methane and
3 thus must be forced with prescribed changes in orbit, greenhouse gases and ice-sheet
4 evolution. Orbital parameters are taken from Berger and Loutre (1991), atmospheric
5 concentrations of gases are determined from ice cores (CO₂ from Vostok (Petit et al., 1999;
6 Loulergue et al., 2008) and CH₄, and N₂O from EPICA (Spahni et al., 2005)) and the ice-
7 sheet evolution is estimated using the ICE5G model of Peltier (2004). For further details of
8 these natural forcings of the climate model readers are referred to Singarayer et al. (2011).

9 To prescribe Holocene ALCC the KK10 dataset of Kaplan et al. (2009 and 2011) was used.
10 The original dataset is on a 5' spatial resolution and has modelled crop and pasture land use
11 for every year from 8 kaBP to present. For this study the data at 1000-year intervals were
12 taken (8kaBP, 7kaBP, etc.) for both crop and pasture combined and upscaled to the spatial
13 resolution of HadCM3 to formulate a time series of cropland masks (Fig. 1). Within TRIFFID
14 the global crop area is designated by a cropland mask, which can only be occupied by
15 agricultural-type vegetation (i.e. C₃ and C₄ grasses) or bare soil (Betts et al., 2007). Hence, the
16 actual cropland is equivalent to the mask area, less inland water, urban and ice tiles, and less
17 the area covered by non-grassland vegetation or bare soil. The crop mask area is not
18 dynamically updated by climate data. The cropland area incorporates the natural C₃/C₄ grass
19 fractional areas before converting tree fractions.

20 For each simulation, the boundary condition forcings (orbit, greenhouse gases and ice sheets)
21 were specified, and in all simulations the initial conditions were the same, based on a spun-up
22 early industrial simulation. Simulations were run for 1000 years. By the final 500 years of the
23 simulation the climate system has adjusted to a new surface equilibrium and thus these final
24 500 years were averaged to result in the mean altered climatic conditions. The relatively long
25 averaging period increases the signal-to-noise ratio between the modified and control
26 climates, and thus distinguishes differences that are statistically significant, but which can be
27 hidden by decadal/multidecadal variability in shorter averaging periods. This is especially
28 important for assessing the impact of agriculture in the earlier time slices of the Holocene
29 when the land use change is small and localised.

30

1 **3 Results**

2 **3.1 Surface Air Temperature**

3 **3.1.1 Local Impacts of Land Use**

4 In the regions where ALCC was significant, surface air temperature changes can be seen in all
5 the time slice simulations (Figs. 2, 3 and 4) and for all time slices except 8kaBP (not shown)
6 the temperature anomalies in most regions are outside the normal range of variability, which
7 is considered to be within 2 standard deviations of the mean. The anomalies are more
8 pronounced in the JJA season (Fig. 2) than DJF (Fig. 3). This is due to a combination of the
9 land imbalance between the northern and southern hemispheres, the lack of land surface
10 changes in the extra tropical southern hemisphere and the enhanced effect of land surface
11 changes during the season of greatest solar insolation and plant growth (which is JJA in the
12 northern hemisphere).

13 The direct temperature response to ALCC varies with the degree of latitude but the
14 relationship is not straightforward as it depends on local climate, soil, and the natural
15 vegetation. In the extratropics, where the albedo effect is generally dominant, there is a trend
16 towards increasing (negative) anomalies with an increase in disturbance fraction (Fig. 5a for
17 P.I.). At 7kaBP the range of extra tropical temperature anomalies within the areas of land
18 disturbance is $+0.1/-1.2^{\circ}\text{C}$ (JJA) and $+0.6/-0.5^{\circ}\text{C}$ (DJF), by 4kaBP it has increased to $+0.4/-$
19 2°C (JJA) and $+0.9/-1^{\circ}\text{C}$ (DJF) and by the pre-industrial period (PI; 1850) it had reached
20 $+0.7/-4^{\circ}\text{C}$ (JJA) and $+0.3/-2^{\circ}\text{C}$ (DJF). Although there are some positive temperature
21 anomalies, the vast majority of grid points show a negative temperature trend. Regions with
22 the highest ALCC intensity show the largest negative temperature anomalies, in particular
23 Europe and E. Asia/China, where the agricultural land use occurs earliest and has the highest
24 concentration of land conversion (Figs. 2, 3, 4 and 5a).

25 The tropical response shows less of a trend because the impact of reduced evaporation is more
26 significant and thus there are conflicting signals between the cooling effect of increased
27 albedo and the warming effect of reduced evaporation. In some tropical areas ALCC leads to
28 net cooling while in other areas net warming is simulated (Figs. 2, 3, 4 and 5a), partly
29 dependent on the availability of moisture at the surface and partly on cloud cover changes
30 (not shown). The main areas that show a warm anomaly response are Southern Africa and
31 India in JJA from 5kaBP and in DJF the area bordering the Bay of Bengal where E. India is

1 warmer from 6kaBP extending to the east coast of the Bay of Bengal by 2kaBP. The Indian
2 JJA warming is enhanced by cloud feedbacks; a decrease in monsoon circulation leads to
3 decreased cloudiness, thus increasing the shortwave radiation reaching the surface and
4 warming the lower atmosphere. In contrast, tropical South America generally shows a net
5 cooling in response to ALCC. Around the mid to late Holocene the tropical temperature
6 anomaly range within the areas of land disturbance is $\pm 0.5^{\circ}\text{C}$ and by the early industrial era
7 (1850CE) it had reached $\pm 1^{\circ}\text{C}$ (Fig. 5a).

8 Analysis of the standard deviation of both the KK10 and Control simulations indicated no
9 significant changes in the amplitude of interannual variability of surface temperature or
10 precipitation (using the F-test statistic).

11 **3.1.2 Remote Impacts of Land Use**

12 In addition to the local temperature changes described above, cooling can also be observed in
13 regions remote from the areas of major ALCC, particularly in the Northern Hemisphere. The
14 most intense cooling is always in the regions of ALCC but even as early as 7kaBP in the JJA
15 season our model simulations show a band of cooling that stretches across much of the extra-
16 tropical Northern Hemisphere and the North Atlantic (Fig. 2). This cooling starts influencing
17 the northern Pacific regions by 5kaBP and by the early industrial era the surface air
18 temperature over most of the world's land masses and much of the ocean is cooler due to the
19 effects of ALCC in remote areas.

20 In the DJF season in the Northern Hemisphere ALCC leads to cooling both locally and
21 regionally starting at 7kaBP (Fig. 3). The model simulations also show cooling in the Arctic
22 and warming in Siberia. Cooling remote from the areas of major ALCC becomes more
23 extensive by 3kaBP and most landmasses of the Northern Hemisphere are cooler than the
24 control simulation by 2kaBP. The Siberian warm anomaly has ceased by 3kaBP but it remains
25 less affected by the cooling than other regions. In the Southern Hemisphere, cooling remains
26 more localised until 2kaBP by which time the majority of the land surface is cooler than the
27 control.

28 There is an increased temperature anomaly response for the same level of disturbance fraction
29 in the later timeslices (Fig. 5b) implying that the responses to the land use changes are not just
30 due to the local effects. Some possible mechanisms for these remote impacts are large-scale
31 circulation changes (such as stationary waves in the upper troposphere at mid-high latitudes

1 and monsoonal circulation changes), near-surface advection, and the amplifying factors of
2 snow cover. These mechanisms will be discussed in more detail in Sect. 3.2 for atmospheric
3 dynamics and Sect. 3.3.2 for snow cover changes. Changes to the natural vegetation cover
4 (outside the regions of land use) due to the climatic impacts of land use were also investigated
5 as a potential mechanism of further feedbacks but were not found to be significant.

6 **3.2 Atmospheric Dynamics**

7 **3.2.1 Upper Tropospheric Dynamics**

8 There are several factors that can impact the dynamics of the upper troposphere in response to
9 ALCC. Cooler surface air temperature means that the density of the air is greater and,
10 therefore, the geopotential height in cooler regions will be lower (See Fig. 7c and d). [The](#)
11 [changes to Mean Sea Level Pressure \(MSLP\) described in Sect. 3.2.2 can change the areas of](#)
12 [convergence and divergence leading to changes in regions of vertical motions. The unequal](#)
13 [latitudinal distribution of the temperature anomalies, with the regions of greatest cooling in](#)
14 [the mid-latitudes of the Northern Hemisphere, affects the meridional temperature gradient](#)
15 [leading to a change in baroclinicity, which has been shown to impact storm tracks \(Yin,](#)
16 [2005\).](#)

17 In the JJA season from 7kaBP there is a reduction of the 500hPa geopotential height over the
18 extra-tropical Northern Hemisphere in a pattern similar to the temperature pattern but more
19 extensive, completely encircling the globe. From 3kaBP onwards the height reduction
20 expands southwards so the geopotential height is lowered almost everywhere by pre-industrial
21 times. The most intense reduction is always in a zonal belt across Europe and E. Asia. The
22 Southern Hemisphere response from 5kaBP appears to show a standing wave pattern affecting
23 the subtropical highs.

24 In the DJF season a stationary wave in the anomaly field in both the Northern and Southern
25 Hemispheres is apparent at all timeslices but most pronounced at 4kaBP (Fig. 7d). This is a
26 recognised response to surface temperature anomalies as described in Hoskins and Karoly
27 (1981) although, in this case, there are multiple thermal anomalies caused by ALCC. By
28 2kaBP there is a reduction in 500hPa geopotential height over most of the globe. Note that
29 there are several areas that are not statistically significant in Fig. 7c and d implying a large
30 amount of variability. These geopotential height changes contribute to the simulated remote
31 temperature changes by altering the regions of vorticity, which in turn influence the regions of

1 ascent and descent and thus the MSLP and surface climatic conditions. The geopotential
2 height anomalies can also alter the pattern of the upper level winds thus influencing surface
3 storm tracks.

4 In particular, the positioning of the geopotential height anomalies in the earlier timeslices (up
5 to 4kaBP, Fig.7d) indicate an increased tendency towards a positive Tropical/ Northern
6 Hemisphere (TNH) pattern (Barnston et al., 1991) with above average heights over the
7 Bering Strait/ Gulf of Alaska and northeastward of the Gulf of Mexico and below average
8 heights over eastern Canada. This would be expected to cause cooler temperatures over the
9 continental United States by increasing the transport of cold polar air into the United States.
10 In several time slices it can be seen that DJF temperature anomalies over Bering Strait/Alaska
11 (e.g. Fig. 3) show a warming pattern where there are positive geopotential height anomalies in
12 Fig. 7c and d. The DJF temperature anomalies (warming) over Siberia up to 4ka (Fig. 3) also
13 relate to the stationary wave pattern. The decreased heights over the polar regions in most of
14 the time slices are indicative of a positive Arctic Oscillation (AO) (Fig. 7b) which has been
15 shown to be correlated with milder winters in Siberia (Tubi and Dayan, 2012).

16 ~~The unequal latitudinal distribution of the temperature anomalies, with the regions of greatest~~
17 ~~cooling in the mid latitudes of the Northern Hemisphere, affects the meridional temperature~~
18 ~~gradient leading to a change in baroclinicity, which has been shown to impact storm tracks~~
19 ~~(Yin, 2005).~~

21 3.2.2 Mean Sea Level Pressure

22 Changes to ~~Mean Sea Level Pressure~~MSLP (MSLP) can also have an effect on the climate
23 system. The colder surface air temperature in the region of disturbance means reduced ascent
24 in those regions and thus higher MSLP, ~~and as discussed in Sect. 3.2.2 the changes in the~~
25 ~~upper troposphere can influence the surface conditions.~~ ~~This~~The MSLP changes can be seen
26 quite clearly in China from 6ka and in Europe by 4kaBP (Fig. 6 for PI JJA), although the DJF
27 situation in Europe is less coherent probably due to more remote influences such as the North
28 Atlantic storm track. These MSLP changes could play a part in steering weather systems and
29 thus influencing the climate in remote regions. For example, the JJA MSLP anomaly pattern
30 (Fig. 7a and b) over the North and Central Atlantic is indicative of a negative phase of the
31 North Atlantic Oscillation (NAO) with above-normal pressure over the North Atlantic and

1 below-normal pressure over the central Atlantic. This pattern is apparent from 5kaBP. The
2 NAO alters the intensity and location of the North Atlantic jet stream and storm track and thus
3 the patterns of heat and moisture transport (Hurrell, 1995). A negative NAO would contribute
4 to a tendency to wetter summers in all but the southernmost regions of Europe (Folland et al.,
5 2009) and this was seen in the results described in Sect. 3.3.1. The DJF NAO shows a trend
6 towards a positive NAO which could result in drier winters over the Mediterranean region
7 (Hurrell et al., 2003) although it is difficult to ascertain whether this is the case as the pattern
8 is not as consistent as JJA.

9 **3.2.3 Surface Advection**

10 Some of the cooling in regions adjacent to the areas of land disturbance is due to advection by
11 low-level winds. In regions with a prevailing wind direction an advection pattern can be
12 clearly seen. Fig. 6 shows advection of cold air from the areas of land use change in East Asia
13 to the east across the West Pacific and from the region of land disturbance in Mexico to the
14 west across the East Pacific, this also affects the sea surface temperatures (SSTs) in these
15 regions of the Pacific (not shown). In other areas where the surface wind direction is more
16 variable the effect is more difficult to detect but probably does contribute to the spread of the
17 cold anomaly outward from the region of land disturbance.

18 **3.3 Hydroclimate**

19 Our model simulations show precipitation changes in response to ALCC but it should be
20 noted that there are larger uncertainties in climate model simulated precipitation and other
21 variables related to model dynamics than for temperature, which is primarily controlled by
22 thermodynamics (Shepherd, 2014). Different climate models show a wide range of responses
23 in their dynamics to palaeo and future climate change scenarios and we acknowledge that
24 aspects of the precipitation anomaly patterns in this study may be less robust than that for
25 other climate variables.

26 The pPprecipitation responses to ALCC (Fig. 8 for JJA and Fig. 9 for DJF) tend to be caused
27 by a response to large-scale circulation changes rather than being directly attributable to local
28 land use. The European precipitation response in the DJF season is not entirely consistent
29 throughout the time slices but the general response is a slight decrease in precipitation around
30 the western and Mediterranean coasts with this dryness extending further into the continent by
31 1 kaBP. The simulations show that Europe in the JJA season has an increase in precipitation

1 compared to the control from 7kaBP onwards, which gradually increases in extent, possibly
2 influenced by the increased tendency to a negative North Atlantic Oscillation (NAO). Positive
3 anomalies begin in the warm pool of the Gulf of Mexico and extend across the North Atlantic
4 following the track of positive anomalies to the 850hPa wind field (Fig. 10). In addition, as
5 the cooler temperature anomalies extend quite high in the troposphere over Europe this
6 increases relative humidity throughout the low to mid troposphere (not shown) and thus the
7 likelihood of large-scale precipitation.

8 In India there is a decrease in monsoon precipitation from 5kaBP, which then gradually
9 increases in intensity. This is partly driven by the slightly cooler Indian sub-continent
10 temperatures (Fig. 11) in the critical months for monsoon development and also by cooler
11 temperatures in Europe and East Asia and increased snow cover on the Tibetan plateau. This
12 leads to decreased monsoonal circulation and decreased cloudiness. There are also changes to
13 the East Asian monsoon with wetter conditions to the north and south of the region and drier
14 conditions in the centre. This pattern is seen reasonably consistently from 4kaBP onwards.

15 ~~It should be noted that there are larger uncertainties in climate model simulated precipitation~~
16 ~~and other variables related to model dynamics than for temperature, which is primarily~~
17 ~~controlled by thermodynamics (Shepherd, 2014). Different climate models show a wide range~~
18 ~~of responses in their dynamics to palaeo and future climate change scenarios and we~~
19 ~~acknowledge that aspects of the precipitation anomaly patterns in this study may be less~~
20 ~~robust than that for other climate variables.~~

21 **3.3.1 Inter Tropical Convergence Zone (ITCZ)**

22 Analysis of the precipitation fields (Figs. 9 and 10) shows an overall southward migration of
23 the ITCZ. These changes are most obvious in the Atlantic and Pacific Oceans and over the
24 continent of Africa. In the DJF season there are changes to the ITCZ in the Western Pacific
25 but a consistent pattern is not seen until 3ka when there is southward shift in the ITCZ over
26 the Atlantic and Atlantic coasts leading by 2kaBP to a decrease in precipitation in the interior
27 of southern Africa and wetter conditions on the coasts. There is generally increased
28 precipitation over the Indian Ocean and the Amazonian region of South America and a
29 reduction over the Bay of Bengal but this pattern is not entirely consistent throughout the
30 timeslices. Similarly, in the JJA season there are changes to the ITCZ throughout all the
31 timeslices but these do not all show a consistent pattern. The most persistent changes are

1 increased precipitation over the Pacific from 5kaBP, over Central America from 7kaBP and a
2 southward shift from 2kaBP. This southward shift in the ITCZ in the JJA season impacts the
3 West African monsoon with lower precipitation in a belt across the monsoon region by 2kaBP
4 although the west coast of North Africa is wetter.

5 The generally cooler temperatures in the Northern Hemisphere may influence the latitudinal
6 position of the Hadley cell and thus the location of the ITCZ via the influence on the inter-
7 hemispheric temperature gradient resulting in the strengthening of the northward cross-
8 equatorial energy transport (e.g. Kang et al., 2008). This shift south of the ITCZ to transport
9 heat to the cooler northern hemisphere is seen in both the DJF and JJA seasons.

10 **3.3.2 Snow Cover**

11 Lower surface air temperatures in the ALCC scenario relative to the control lead to an
12 increase in winter snow accumulation (Fig. 12). This increase is seen by 5kaBP mostly in
13 northern and mountainous regions. The areas affected gradually increase so that by 3kaBP
14 more temperate and lower lying areas see increases in snow depth. The effects are most
15 pronounced in North America and Europe. In regions outside the areas of permanent snow
16 cover increases in snow depth will delay the melting of the snow pack and thus result in a
17 longer period of snow cover. The increased snow cover due to the cold temperature anomalies
18 will cause additional cooling due to the increased albedo. This will be greatest in regions of
19 deforestation where the snow-covered ground is no longer masked by the canopy of the
20 forest. This increased snow cover would also lead to decreases in precipitation due to lower
21 rates of moisture recycling over land. It should be noted that the modelling of snow fall is
22 subject to the same uncertainties as described in Sect. 3.3.

23

24 **4 Temporal Evolution of Holocene Climate**

25 In the control experiment the changes in orbital configuration, greenhouse gases(GHG), and
26 icesheets/sea level lead to monotonically increasing global temperatures through the Holocene
27 (Fig. 13a). Analysis of previous experiments to assess the sensitivity to different natural
28 forcings (data from Singarayer and Valdes, 2010; Singarayer et al., 2011) suggest that while
29 the changes to orbital configuration effect a cooling in global temperature over the Holocene,
30 this is outweighed by increases in greenhouse gases (~17ppm CO₂ from 8kaBP to late pre-
31 industrial time), which result in overall warming. Cooling through the Holocene occurs in

1 northern hemisphere summer, when forced with orbit and GHG variations, but is not as
2 pronounced as when only forced by orbital variations. In winter, when HadCM3 is forced
3 with orbit-only variation there is little change in temperature, but when GHG increases are
4 included this becomes a warming over the Holocene, which then outweighs the reduced
5 summer cooling. Whilst this contrasts with recent data compilations that suggest a general
6 decline in global temperatures since the mid-Holocene (Marcott et al., 2013) it is within the
7 range of other climate model responses when compared with the Paleoclimate Model
8 Intercomparison Project 3 (PMIP3) Mid-Holocene (MH) minus late Pre-Industrial (PI)
9 temperature anomalies. Although palaeodata syntheses may suggest a cooling of northern
10 hemisphere temperatures, there are regional and seasonal variations in the data such as that
11 from the Bartlein et al.(2013) (Fig. 14c) and Mauri et al (2015) data compilations. In both
12 these compilations and the combined proxy reconstructions of Wanner et al. (2008) the
13 cooling is most evident over the higher latitude northern hemisphere.

14 For our specific configuration of HadCM3 tThe inclusion of land use changes through the
15 Holocene has a significant impact on the progression of modelled global average
16 temperatures, such as to alter the direction of the multi-millennial trend described above thus
17 reducing the mismatch between the model simulations and the proxy reconstructions most of
18 which show an extra-tropical cooling trend throughout the Holocene. The increasing
19 magnitude and spread of ALCC through the Holocene reconstructed in KK10 counteracts the
20 influence of increasing greenhouse gases, so that temperatures are effectively steady from
21 3kaBP in HadCM3 (Fig. 14a).

22 These global trends are composed of considerable heterogeneity at the regional scale. When
23 broken down into zonal regions it can be clearly seen that the difference in trends
24 with/without land use is greatest in the Northern extratropics (Fig. 13b), where the Holocene
25 trend is modified from increasing temperatures to decreasing temperatures in the late
26 Holocene by the addition of ALCC. There are impacts on mean temperatures in the tropics
27 (Fig. 13c) and southern extratropics (Fig. 13d) but not sufficient to influence the direction of
28 the Holocene trend.

29 MH minus PI anomalies of annual mean surface air temperature (Fig. 14a) show near global
30 distribution of cooling, except over high latitude sea-ice regions, which are particularly
31 influenced by changes in obliquity (higher in the MH than PI). The PMIP3 suite of models
32 show a similar pattern of surface air temperature anomalies. The cooling is most dramatic

1 over the tropics and monsoonal regions, where changes in the seasonality of insolation (due to
2 orbital precession variation) intensify monsoon circulation in the early and mid-Holocene and
3 the resulting additional cloud cover reduces incoming shortwave radiation as well as
4 increased surface water altering the balance of sensible to latent heat fluxes. The inclusion of
5 land use change in the KK10 experiment reduces the magnitude of MH cooling, especially in
6 the mid-latitudes. Over Europe and eastern North America the anomaly is reversed to a
7 warming (i.e. over these regions the cooling from deforestation shown in Fig. 2, increases and
8 outstrips the warming from greenhouse gases). These are also regions where there is the
9 highest concentration of pollen reconstructions (Fig. 14c; Bartlein et al., 2011; Mauri et al.,
10 2014). The influence of land use change improves the data-model comparison with the
11 reconstruction by Bartlein et al. (2011) over these key areas (Fig. 14a-c). Likewise, when
12 simulated top-level ocean temperatures are compared with SST data used within the Marcott
13 et al. (2013) compilation, the inclusion of land use improves the data-model comparison (Fig.
14 14d and e). However, the largest MH warming in the model is in the summer months,
15 whereas, recent seasonal temperature reconstructions (also using pollen; Mauri et al., 2014)
16 suggest the largest and most widespread MH warming may have occurred in winter in the
17 MH.

18 In contrast, using the KK10 ALCC scenario as a boundary condition to the climate model
19 does not improve the agreement in annual mean MH - PI precipitation anomalies when
20 compared to the palaeoclimate reconstruction of Bartlein et al. (2011) (Fig. 15). Model and
21 data are in reasonable agreement in most regions except for Europe and the temperate regions
22 of Asia where the data implies a wetter MH than PI, which is not seen in the model runs. The
23 difference over Europe is exacerbated by the inclusion of land use, which results in a drier
24 MH.

25

26 **5 Discussion**

27 Anthropogenic land cover change leads to climate change well beyond the core regions of
28 land use early in the Holocene. These results suggest that regional ALCC has an effect on the
29 atmospheric circulation, e.g. the ITCZ shift is a remote response on global scale. The
30 implications of this finding are that regional models or atmospheric-only models would not
31 simulate these atmospheric circulation changes as well as a global coupled model. In this
32 study we observed multiple thermal anomalies (from intense regions of cooling directly over

1 anthropogenic land use change), but the standing wave response of the geopotential height
2 field would likely also be seen even for a single thermal source from just one region (Hoskins
3 and Karoly, 1981). Regional models have the advantages of higher spatial resolution and
4 more detailed orography but they may not include these potential remote atmospheric changes
5 possibly resulting in different impacts from the same land cover forcing in regional and global
6 model simulations. The positioning of the major temperature anomalies in the mid-latitudes
7 and at similar latitudes may be particularly significant in producing the stationary wave
8 pattern.

9 Whilst these are the results from only one model there are many similarities in the distribution
10 of the temperature anomalies with those found by He et al. (2014) for 1850 CE and Pongratz
11 et al. (2010) for the 20th century although the temperature changes found in this study were
12 greater e.g. a pre-industrial global annual mean temperature anomaly of -0.23°C as opposed to
13 the -0.17°C estimated by He et al. (2014). Running similar simulations with a greater number
14 of models would improve the robustness of the results particularly with respect to
15 hydroclimate due to the high uncertainties involved. The variability in the results from
16 different models can be greater than the variability of the property that is being assessed
17 (Pitman et al., 2009; de Noblet-Ducoudre et al., 2012; Brovkin et al., 2013). These
18 inconsistencies have been attributed to disagreements in how land use change is implemented,
19 the parameterisation of albedo, the representation of crop phenology and evapotranspiration
20 and the partitioning of available energy between latent and sensible heat fluxes (Pitman et al.,
21 2009; de Noblet-Ducoudre et al., 2012; Boisier et al., 2012). The albedo and turbulent heat
22 fluxes from our model simulations for the North America/Eurasia region (Fig. 16) are
23 within the range of other climate model responses when compared with those from the Land-
24 Use and Climate, IDentification of robust impacts (LUCID) set of experiments (Boisier,
25 2012). The negative turbulent and latent heat fluxes would offset some of the cooling due to
26 the increased albedo. Although the largest albedo changes are in the DJF season the impact of
27 this will be lessened due to the lower levels of incoming solar radiation in this season.
28 Results could be further improved by the running of transient simulations that could capture
29 events such as the Maunder minimum. A transient simulation response could result in
30 different biogeophysical impacts to the ones achieved when using a long equilibrium
31 simulation where the ocean-land-atmosphere system can reach more of a steady state and the
32 climate sensitivity is different.

1 From late preindustrial era simulations, one using observed atmospheric greenhouse gas
2 concentrations and the other using greenhouse gas concentrations in a world with no
3 anthropogenic emissions (based on linear projection from earlier Holocene trends from
4 Kutzbach et al., 2011), He et al. (2014) estimated a net global warming of 0.9°C due to the
5 biogeochemical effects of ALCC, with between 0.5 and 1.5°C warming in the areas of most
6 intense land use changes. Incorporating this degree of warming into our early industrial era
7 (1850 CE) simulations there would still be a net cooling in Europe, E. Asia and N.E. America
8 with, e.g., a net cooling of up to 2°C in parts of Europe. To put this in perspective the IPCC
9 (IPCC WG II, 2014a) consider a temperature rise of more than 2°C to be undesirable and that
10 changes of 1°C could have an impact on vulnerable ecosystems. However, the temperature
11 changes in this study took place over a much longer period than the timeframe considered in
12 the IPCC and ecosystems and human societies would have had more time to adapt. The
13 consequences of these changes for agricultural societies would vary depending on the pre-
14 existing conditions. For example, in drier regions, where crops are more likely to be water
15 limited, cooler, wetter summer conditions may have been beneficial to the agricultural output
16 although the risk of erosion would be increased. The generally lower temperatures might also
17 make societies more vulnerable to further transient cooling effects such as volcanic activity.

18 There are discrepancies between simulations of the mid-Holocene climate and the
19 independent data-based reconstructions. Both the simulations from this study and virtually all
20 the PMIP3 (Palaeoclimate Model Intercomparison 3; <https://pmip3.lsce.ipsl.fr>) models show a
21 temperature increase from the mid-Holocene to the PI whereas the Marcott et al. (2013) (and
22 Mann et al. (2008) on a shorter timescale) reconstructions show a decrease. It is interesting to
23 note that ALCC reduces this mismatch for HadCM3, especially in key areas such as Europe.
24 Other factors that could lead to this discrepancy are uncertainties in the proxy reconstructions
25 and deficiencies in climate models (e.g. [Lohmann et al., 2013](#)). These climate model
26 deficiencies include low resolution and sensitivity and, importantly, their dependence on soil
27 moisture whereby energy is utilised for evaporation rather than for temperature increase.

28 This study shows a significant increase in precipitation over Europe with increasing land use
29 which means that the PI becomes wetter than the mid-Holocene, which leads to increases in
30 soil moisture and changes in the sensible to latent heat flux balance and, in combination with
31 increased albedo caused by deforestation, this results in cooler temperatures for PI than MH.

1 If the land-atmosphere coupling strength was different and soil moisture was strongly reduced
2 with deforestation it is likely that the cooling effect would be smaller (cf. Strandberg, 2014).

3 Further uncertainties arise from the robustness of the land use reconstructions, which is
4 difficult to evaluate due to the lack of global-scale evidence for human impact on the Earth's
5 land surface. Much of the uncertainty comes from the lack of knowledge about the magnitude
6 and distribution of the global human population and the rate of technological evolution and
7 intensification through time. As part of our initial investigations simulations were also run
8 using an alternative land use scenario (the HYDE 3.1 dataset; Goldewijk et al., 2011). The
9 HYDE 3.1 reconstruction has substantially lower levels of land use early in the Holocene (as
10 compared with KK10), which resulted in a later development of consistent temperature
11 anomalies at 4kaBP (not shown) in comparison with the KK10 land use scenario. The
12 decision was taken to proceed with the KK10 data due to its assumptions of a larger per capita
13 land use earlier in the Holocene when agricultural methods were less efficient. Several
14 ongoing international initiatives that aim to synthesise palaeoecological and archaeological
15 data promise to lead to more robust reconstructions of Holocene ALCC in the future (e.g.
16 PAGES LandCover6k project; <http://www.pages-igbp.org/workinggroups/landcover6k/intro>).

17 By the early industrial period simulated biogeophysical temperature changes in the regions of
18 land disturbance are of the same order of magnitude (e.g. 0.83°C annual anomaly in the main
19 agricultural areas of Europe) as the changes seen due to CO₂ increases during the industrial
20 period (0.85°C, IPCC synthesis report, 2014b). Part of Ruddiman's original hypothesis
21 (Ruddiman, 2003) is that pre-industrial global warming caused by anthropogenic CO₂/CH₄
22 emissions should have been ~2 °C at higher latitudes, but there was no evidence for this
23 warming. Ruddiman (2003) attributed this to a natural cooling trend caused by decreasing
24 summer insolation. This study suggests that biogeophysical effects of the land use changes
25 may also have played a part in counteracting the warming due to anthropogenic greenhouse
26 gas emissions as acknowledged in Ruddiman (2013). The precipitation changes might also
27 have an impact on the availability of water for rice irrigation and on natural wetlands thus
28 affecting the production of methane.

29

30 **6 Conclusions**

31 In our global model simulations that use a Holocene ALCC scenario as a boundary condition,
32 a surface temperature response to the biogeophysical effects of ALCC is seen in regions of

1 early land use such as Europe and S.E. Asia as early as 7kaBP in the JJA season and
2 throughout the entire annual cycle by 2-3kaBP. Areas outside the major regions of ALCC are
3 also affected, with virtually the whole globe experiencing significant temperature changes
4 with a net global cooling of 0.22°C by the pre-industrial period. Although the temperature
5 changes are predominantly cooling some regions such as India, Southern Africa and Siberia
6 show warming as a response to ALCC. The greatest changes are generally seen in the JJA
7 season with a mean regional cooling of 1.4°C experienced in Europe and 1°C in E. Asia in the
8 early industrial period (1850 CE). Much of the precipitation response to the land use tends to
9 be due to large-scale circulation changes such as a decrease in the intensity of the Indian
10 monsoon, the southward movement of the ITCZ and changes to the North Atlantic storm
11 track. In Europe there is a slight decrease in precipitation in the DJF season and a more
12 substantial increase in the JJA season. Some causal factors for the teleconnections are
13 advection by surface winds, MSLP anomalies, and tropospheric stationary wave train
14 disturbances in the mid- to high-latitudes.

15 The potential for an early global impact of ALCC on climate strongly implied by this study
16 suggests that due consideration of this should be taken in simulations covering the Holocene.
17 The inclusion of ALCC in the model improves the model comparison for surface air
18 temperature with the data-driven palaeoclimate reconstructions especially in key areas such as
19 Europe. The remote teleconnections seen in this study have implications for the regional
20 modelling of land use change due to circulation changes that occur outside the domain of the
21 regional model.

22 Overall, our model simulations indicate an increase in global surface air temperatures through
23 the Holocene. Globally, the inclusion of ALCC data reduces the magnitude of this warming
24 especially in the late Holocene when the temperatures remain relatively constant. Regionally,
25 in the Northern extratropics, this warming is reversed in the late Holocene. It should be noted
26 that in this study it is not possible to distinguish the anthropogenic component of the
27 biogeochemical changes as the same atmospheric CO₂ and CH₄ concentrations (from ice core
28 measurements) are prescribed for both the KK10 and control simulations. However, the level
29 of early industrial warming due to the biogeochemical impacts of ALCC predicted by He et
30 al. (2014) would negate the early industrial biogeophysical cooling seen in this study in all
31 regions except for the most intensively altered landscapes of Europe, E. Asia and N.E.
32 America.

1 Other caveats are the large uncertainties in the land use data and, therefore, in our
2 understanding of the Holocene evolution of land surface-climate interactions as well as our
3 ability to evaluate climate models. To reduce these uncertainties there is an urgent need to
4 extend land cover reconstructions and prehistory of land use globally (cf. LandCover6k
5 PAGES initiative). It must also be stressed that these are the results from only one model and
6 the use of equilibrium simulations may produce different results from a transient simulation.
7 However, these uncertainties are more likely to impact the timing, intensity and regional
8 details of the changes rather than the overall trends and patterns.

9

10 **Data Availability**

11 Data is available from the Bristol Research Initiative for the Dynamic Global Environment
12 website: <http://www.bridge.bris.ac.uk/resources/simulations>

13

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19

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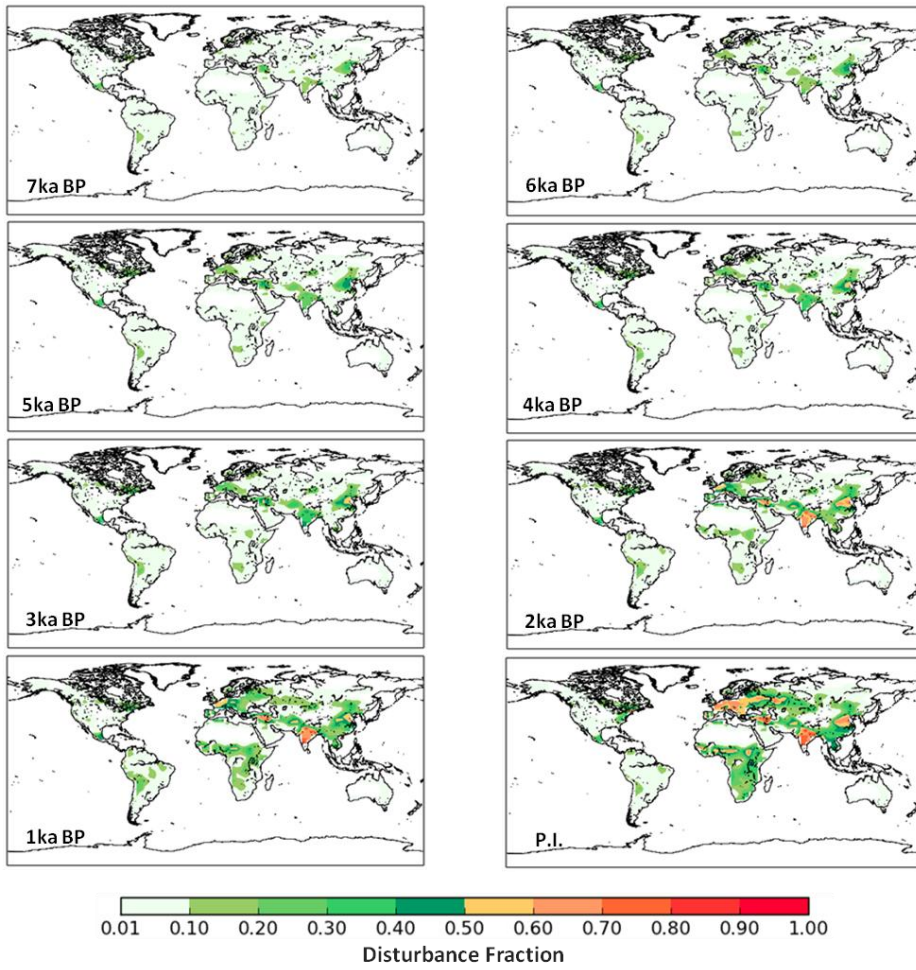
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Component	Model Name	Details		
GCM	HadCM3	Description	Coupled atmospheric, ocean and sea ice model	
		Atmosphere	Horizontal Resolution	2.5° latitude and 3.75° longitude.
			Vertical	19 unequally spaced layers
			Time Step	30 minutes
		Advection Scheme	Eulerian	
		Chemistry	CO ₂ , N ₂ O, CH ₄ , CFC11 and CFC12	
		Ocean	Horizontal Resolution	1.25° by 1.25°
			Vertical	20 unequally spaced layers extending to depth of 5200m
Ice	Horizontal Resolution	1.25° by 1.25°		
Land Surface Scheme	MOSES 2	Coupled to GCM every 10 days of model run.		
Dynamic Vegetation	TRIFFID	Nine surface types including 5 plant functional types		
Boundary conditions		Orbit (Berger and Loutre, 1991), greenhouse gases (from ice cores) and ice sheets (Peltier, 2004)		
Initial Conditions		Based on a spun-up early industrial simulation.		
Simulations	KK10	Dynamic vegetation from TRIFFID with crop mask based on KK10 land use data set (Kaplan et al., 2009 and 2011)		
	Control	Natural dynamic vegetation from TRIFFID		
Simulation dates		8 kaBP, 7 kaBP, 6 kaBP, 5 kaBP, 4kaBP, 3kaBP, 2kaBP, 1kaBP, 1850CE		
Length of simulation		1000 years		

Averaging Period		500 years
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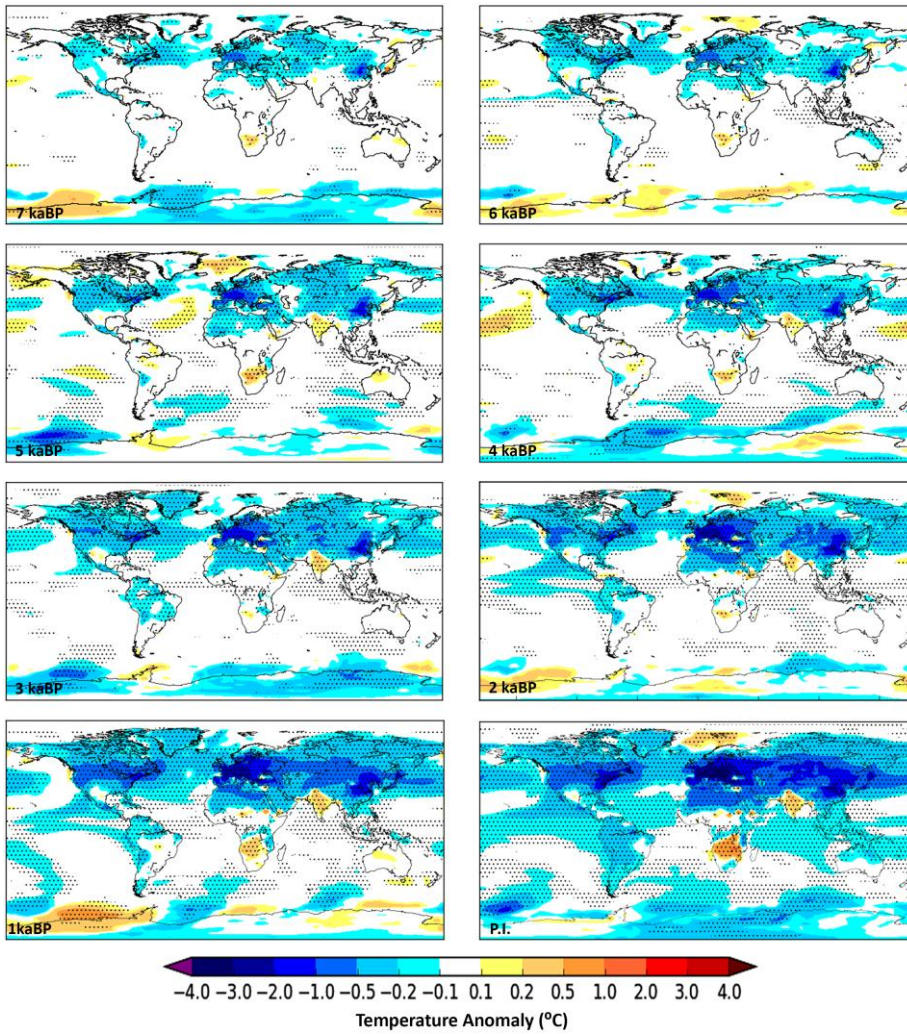
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2 **Table 1.** Summary of the experimental set-up.

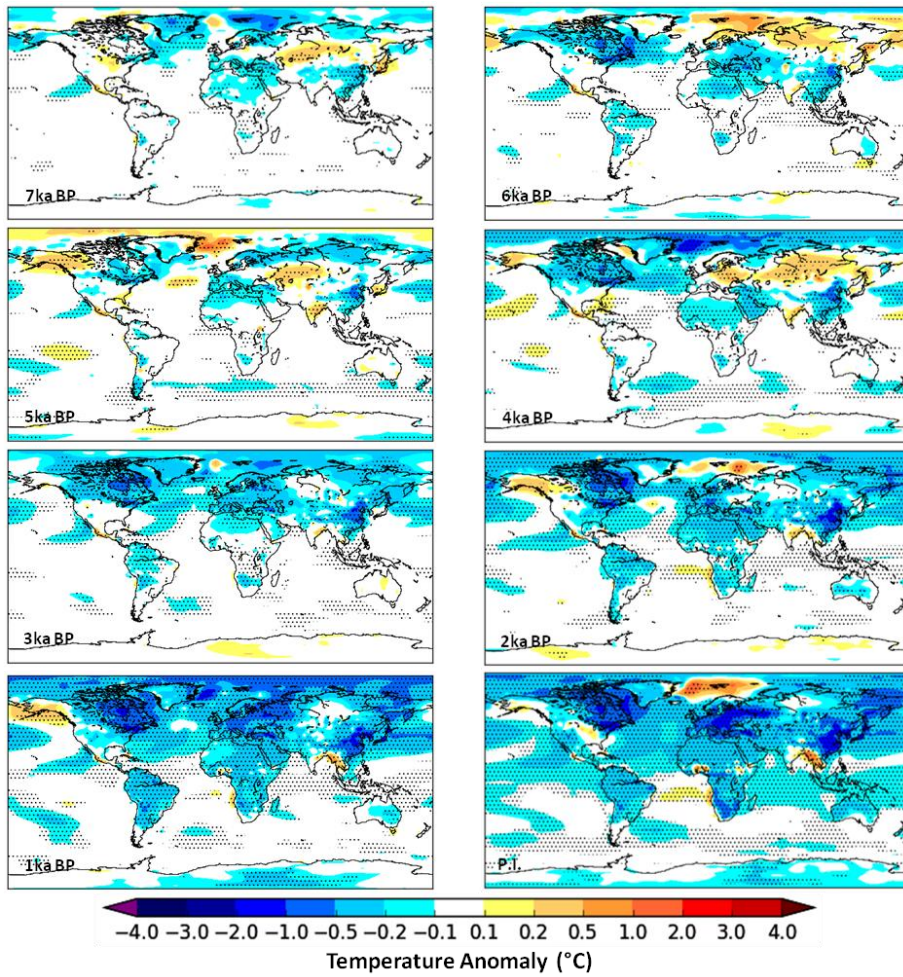


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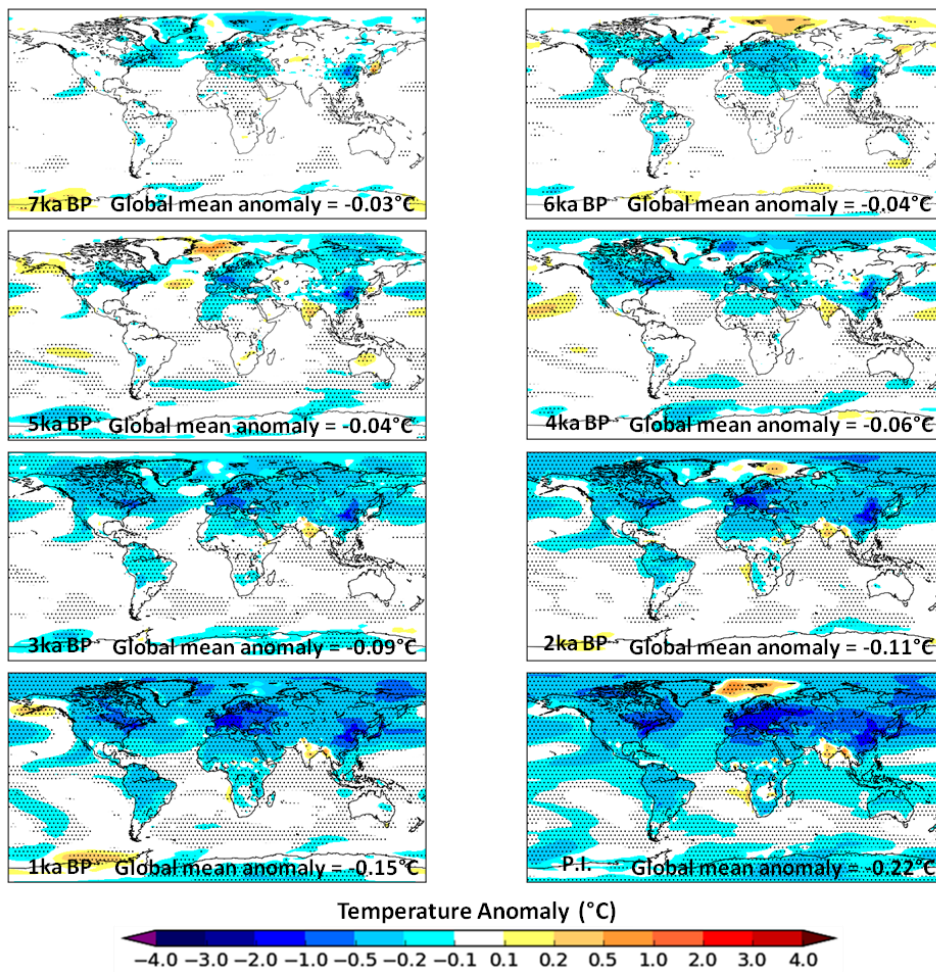
Figure 1. Fraction of anthropogenically disturbed land at 1000 year intervals from the late pre-industrial (1850 CE) period to 7kaBP. The land disturbance data is based on the anthropogenic land-use scenario KK10 (Kaplan et al., 2009, 2011).



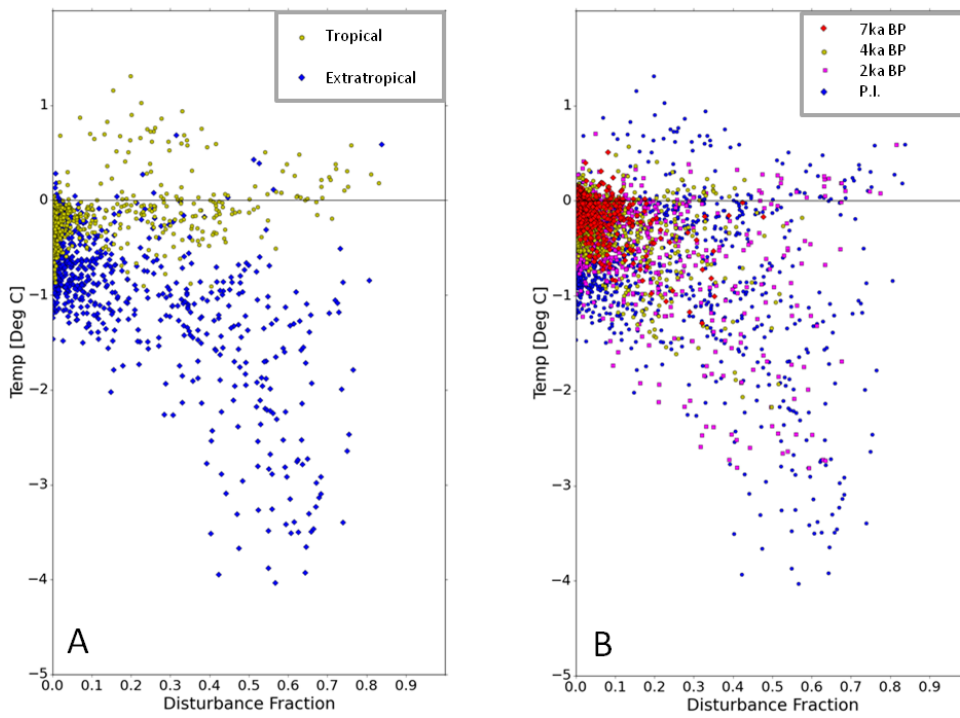
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 3 **Figure 2.** JJA Temperature Anomalies (°C) for KK10 minus Control at timeslices from the
 4 late pre-industrial period (1850 CE) to 7kaBP. The stippling indicates grid boxes where the
 5 anomalies are significant at the 95% level using Wilcoxon ranksum statistical analysis.



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 3 **Figure 3.** DJF Temperature Anomalies (°C) for KK10 minus Control at timeslices from the
 4 late pre-industrial period (1850 CE) to 7kaBP. The stippling indicates grid boxes where the
 5 anomalies are significant at the 95% level using Wilcoxon ranksum statistical analysis.
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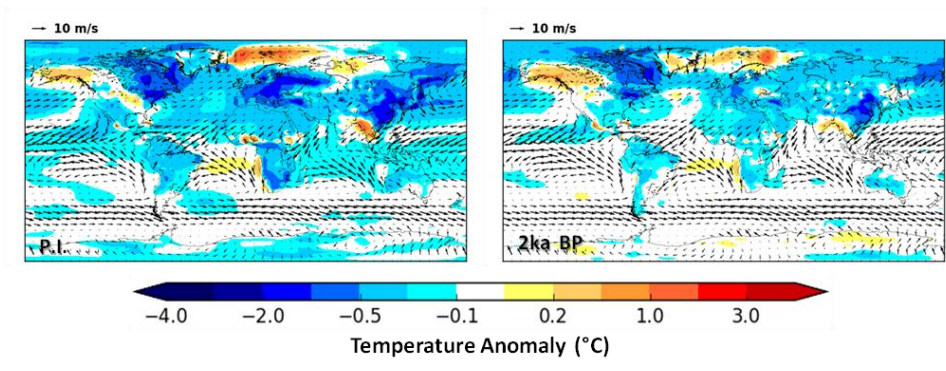


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3 **Figure 4.** Annual Temperature Anomalies (°C) for KK10 minus Control at timeslices from
4 the late pre-industrial period (1850 CE) to 7kaBP. The stippling indicates grid boxes where
5 the anomalies are significant at the 95% level using Wilcoxon ranksum statistical analysis.
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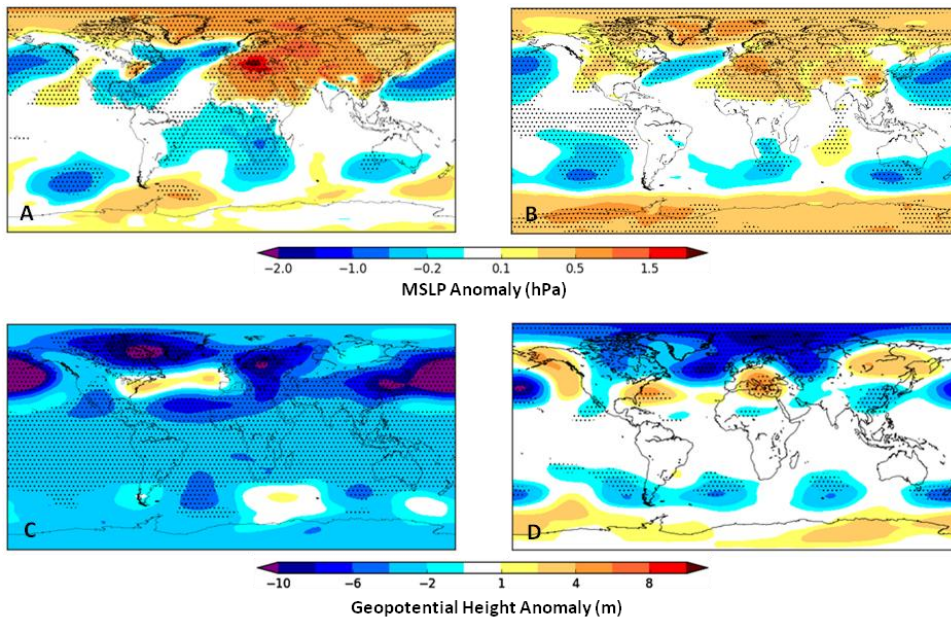
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Figure 5. Relationship between the fraction of anthropogenically disturbed land (from KK10) and the resultant JJA temperature anomaly ($^{\circ}\text{C}$). **(a)** For the late pre-industrial (1850 CE) period for extratropical and tropical grid cells. **(b)** For 7kaBP, 4kaBP, 2kaBP and late pre-industrial (1850 CE) timeslices.



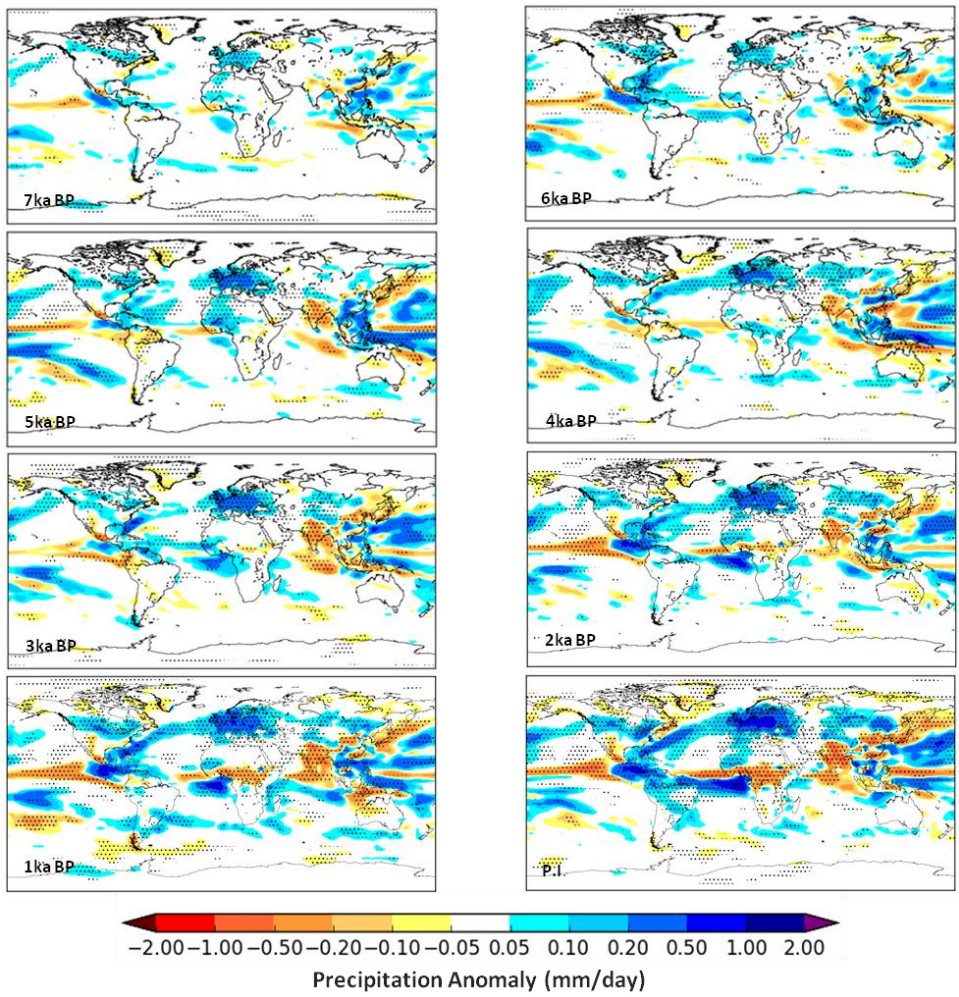
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Figure 6. DJF surface temperature anomalies for KK10 - Control and KK10 surface winds for the late pre-industrial (1850 CE) and 2kaBP.

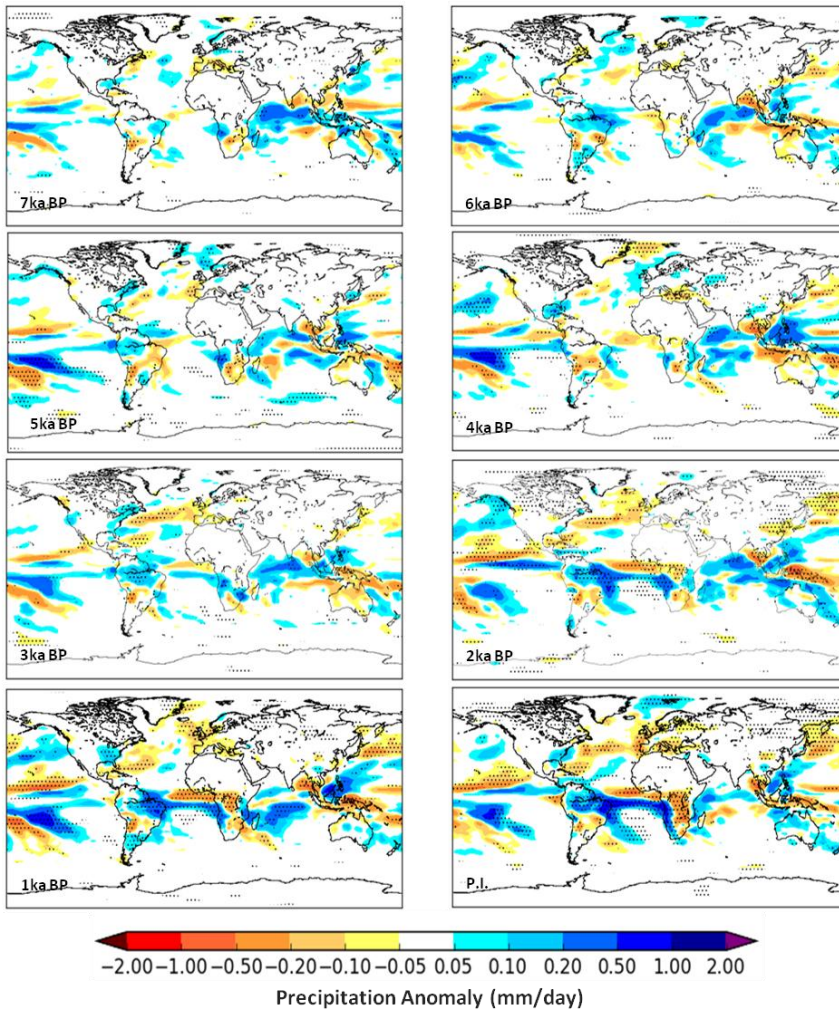


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Figure 7. Modifiers of climate in regions outside the areas of anthropogenic land use change. All anomalies are for KK10 - Control: **(a)** JJA MSLP changes at 1850 CE, the stippling indicates grid boxes where the anomalies are significant at the 95% level using Wilcoxon ranksum statistical analysis; **(b)** as **(a)** but for 4kaBP; **(c)** DJF 500Pa geopotential height anomalies at 1850 CE demonstrating stationary wave pattern. The stippling indicates grid boxes where the anomalies are significant at the 95% level using Wilcoxon ranksum statistical analysis. **(d)** as **(c)** but for 4kaBP.

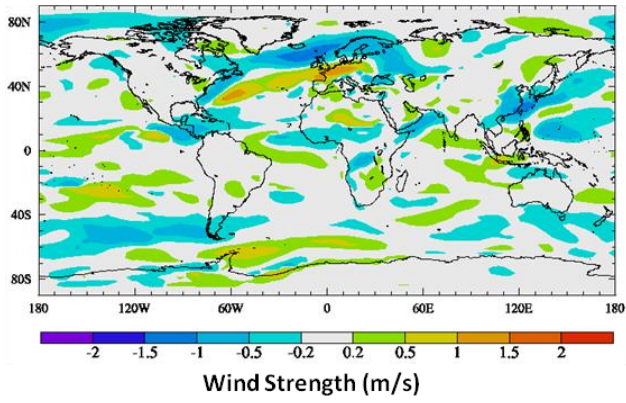


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 3 **Figure 8.** JJA Precipitation Anomalies (mm day^{-1}) for KK10 minus Control at timeslices from
 4 the late pre-industrial period (1850 CE) to 7kaBP. The stippling indicates grid boxes where
 5 the anomalies are significant at the 95% level using Wilcoxon ranksum statistical analysis.



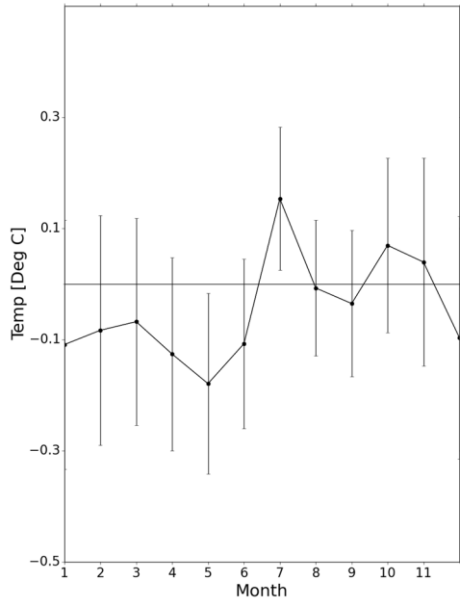
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Figure 9. DJF Precipitation Anomalies (mm day^{-1}) for KK10 minus Control at timeslices from the late pre-industrial period (1850 CE) to 7kaBP. The stippling indicates grid boxes where the anomalies are significant at the 95% level using Wilcoxon ranksum statistical analysis.



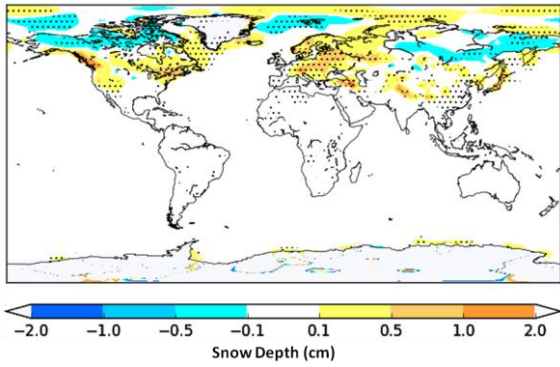
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Figure 10. JJA 850hPa Wind Strength Anomalies (ms^{-1}) for KK10 minus Control for the late pre-industrial period (1850).



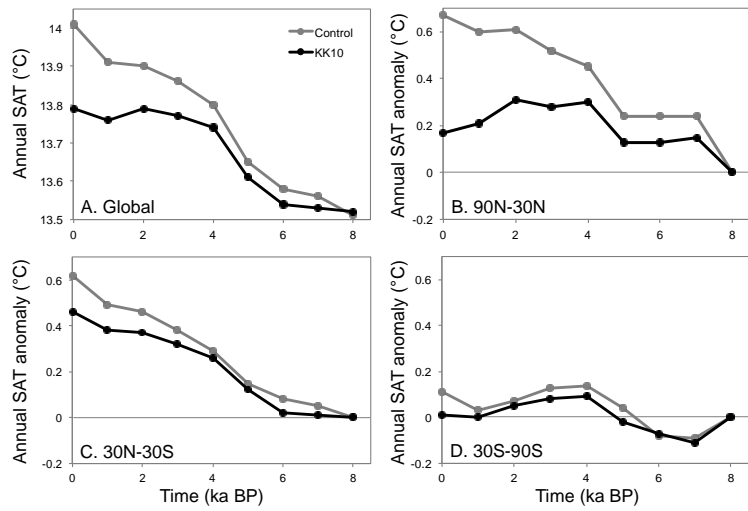
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Figure 11. Indian temperature seasonality; KK10 - Control surface temperature anomalies for the late pre-industrial (1850CE) simulation; the vertical bars indicate the normal range of variability which is considered to be within 2 standard deviations of the mean.



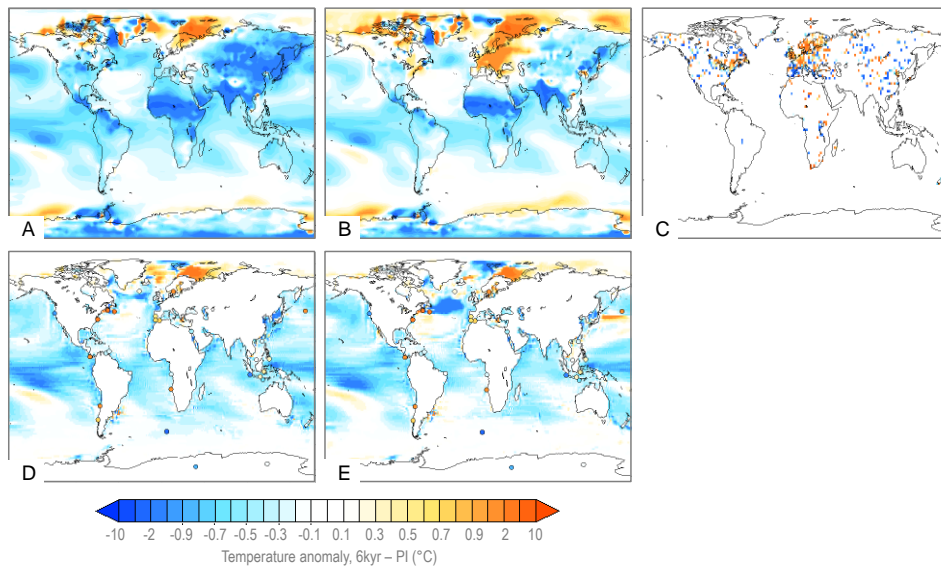
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3 **Figure 12.** DJF Snowdepth Anomalies (cm) for KK10 minus Control for the late pre-
4 industrial period (1850 CE). The stippling indicates grid boxes where the anomalies are
5 significant at the 95% level using Wilcoxon ranksum statistical analysis.



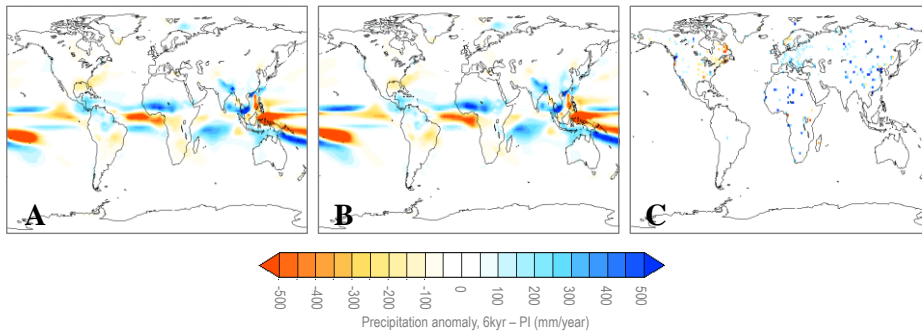
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2 **Figure 13.** Time series plots for the Holocene simulations from HadCM3. **(a)** annual mean
3 global Surface Air Temperature (SAT) for the Control simulation in grey, and KK10
4 simulation in black; **(b)** anomaly in northern extratropical (30-90N) annual mean temperature
5 from the equivalent simulation at 8kaBP; **(c)** same as **(b)** but for the tropics (30N-30S); **(d)**
6 same as **(b)** but for the southern extratropics (30-90S).

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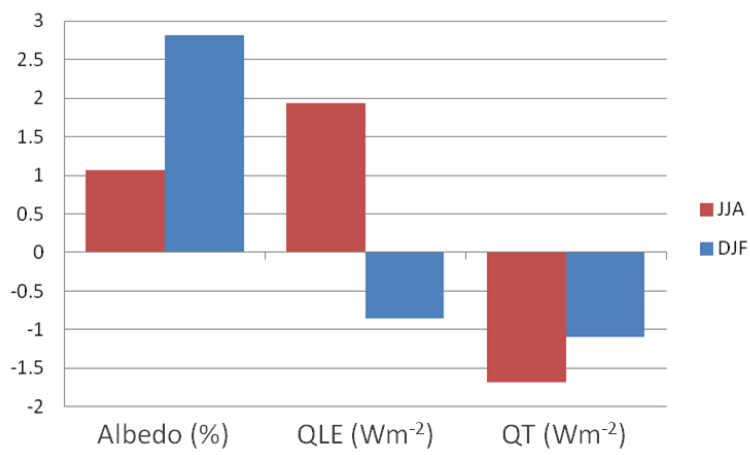
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 2 **Figure 14.** Mid-Holocene minus Pre-Industrial temperature anomalies. **(a)** annual mean
 3 surface air temperature anomalies from the control experiment; **(b)** annual mean surface air
 4 temperature anomalies from the KK10 experiment; **(c)** Bartlein et al. (2011) pollen-based
 5 reconstructions of the mean annual air temperature anomaly; **(d)** ocean annual mean
 6 temperature for the top two layers (25m) from the control experiment with palaeo-proxy
 7 reconstructions (Marcott et al., 2013) overlain in coloured circles ; **(e)** as in **(d)** but for the
 8 KK10 experiment.

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 2 **Figure 15.** Mid-Holocene minus Pre-Industrial precipitation anomalies. **(a)** annual mean
 3 precipitation anomalies from the control experiment; **(b)** annual precipitation anomalies from
 4 the KK10 experiment; **(c)** Bartlein et al. (2011) pollen-based reconstructions of the mean
 5 annual precipitation anomaly.

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Figure 16. JJA and DJF albedo, latent heat flux (QLE) and turbulent heat flux (QT) anomalies for KK10 minus Control for the late pre-industrial period (1850 CE) for the North America/Eurasia land surface.

1 **Authors' response**

2

3 Many thanks for taking the time to review the manuscript again and for helping us to
4 improve it.

5

6 **Comment:**

7 Still one concern in my opinion relates to the robustness of the conclusions and statements related
8 to the global importance of land use changes during the (early) Holocene given uncertainties related
9 to the i) idealized character of the experiments (time slices) ii) the reconstruction of land use itself
10 and iii) the fact that only one model is used – I addressed a suggestion to put those very strong
11 arguments into perspective.

12 **Response:**

13 We have added more to the abstract and the conclusions to stress the uncertainties.

14 **Comment:**

15 Abstract: try avoid abbreviations (i.e. South-east Asia)

16 **Response:**

17 The abbreviation has been expanded

18 **Comment:**

19 line 18/19: use a subscript for CO₂ and CH₄

20 **Response:**

21 This has been corrected

22 **Comment:**

23 p. 10 ll 58ff: this sentence is very loosely added – please try to integrate it better in the context of the
24 arguments stated above.

25 p. 10 Mean sea level pressure – maybe try to link the chapters of upper tropospheric dynamics and
26 MSLP because they are also both physically related. One or two sentences at the beginning of the
27 chapter would help the reader to find a connection.

28 **Response:**

29 A paragraph integrating the above has been added to the beginning of Sect. 3.2.1

30 **Comment:**

31 p13. l. 18ff. Please move this paragraph at the beginning of the chapter that the reader is already
32 aware from the beginning that precipitation from GCM is afflicted with large uncertainties – a hint on
33 uncertainties on realistically simulating snow cover with GCMs is also important.

34 **Response:**

35 The paragraph has been moved to the beginning of Sect. 3.3 and an additional note about snow
36 cover uncertainties has been added to Sect 3.3.2.

37 **Comment:**

1 p.15 l.19: I find this argument is too strong and it should be put into perspective – please explicitly
2 state that you find this in i) your model ii) under specific model configurations and iii) that most
3 proxy data indicate a cooling trend throughout the Holocene over the extratropical hemisphere (see
4 also the data-model comparison of SST sensitive proxies of Lohmann et al. 2013)

5
6 **Response:**

7 We have made the requested statement in Sect. 4. and referenced Lohmann in Sect.5.

8
9 **Comment:**

10 Figures: In my copy of the pdf the graphs and figures were reproduced with a very low quality. The
11 authors should take care that the figures and graphs are reproduced with a considerably higher
12 resolution so that at least in the pdf version all details in the graphs can be seen.

13
14 **Response:**

15 I am experimenting with the best combination of resolution and file size and the final submitted
16 figures will be higher resolution (Figure 2 has been improved for this version).

17
18
19 **List of major changes**

Page	Line Numbers	Change
2	8-9	Added reinforcement that results were from just one model
9	8-16	Added paragraph integrating factors in the atmospheric response to ALCC
10	16-19	Moved sentence to above paragraph
11	19-25	Moved paragraph from P.12, lines 15-20
13	21-22	Added note about snow cover uncertainties
14	14-18	Added clarification as requested
17	25	Added Lohmann reference
19	5-8	Emphasised the uncertainties more in the conclusion
24	17-19	Added Lohmann to references
31		Added a higher resolution Figure 2. (Although when saved as a PDF some resolution is lost again).

20

21

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23