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Late Pliocene lakes and soils: a data – model comparison for the analysis of climate feedbacks in a warmer world

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Abstract

Based on a synthesis of geological data we have reconstructed the global distribution of Late Pliocene soils and lakes which are then used as boundary conditions in a series of model experiments using the Hadley Centre General Circulation Model (HadCM3) and the BIOME4 mechanistic vegetation model. By combining our novel soil and lake reconstructions with a fully coupled climate model we are able to explore the feedbacks of soils and lakes on the climate of the Late Pliocene. Our experiments reveal regionally confined changes of local climate and vegetation in response to the new boundary conditions. The addition of Late Pliocene soils has the largest influence on surface air temperatures, with notable increases in Australia, southern North Africa and Asia. The inclusion of Late Pliocene lakes generates a significant increase in precipitation in central Africa, as well as seasonal increases in the Northern Hemisphere. When combined, the feedbacks on climate from Late Pliocene lakes and soils improve the data to model fit in western North America and southern North Africa.

1 Introduction

1.1 Background

The Late Pliocene (Piacenzian: 3.6–2.6 Ma) is the most recent geological time period of considerable global warmth, before the onset of the glacial-interglacial cycles of the Pleistocene (Dowsett et al., 1992, 1994; Haywood et al., 2011b; Salzmann et al., 2011). As it is, geologically speaking, relatively recent, it represents a recognisable world (in terms of its geography, orography and bathymetry) in which aspects of the Earth's climate can be explored through proxies and modelling studies to better understand the feedbacks, processes and impacts of sustained global warmth (Dowsett et al., 1996, 2012; Salzmann et al., 2009; Lunt et al., 2010, 2012). The focus on the Late Pliocene palaeoclimates has been driven by the PRISM (Pliocene Research Interpretations and

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Synoptic Mapping) project of the US Geological Survey. PRISM3D (the third iteration of the PRISM project, which includes a three-dimensional ocean reconstruction) provides palaeoenvironmental reconstructions of the Pliocene world, from geological data, in a form suitable for use in climate modelling studies (Dowsett et al., 2010). With the availability of boundary conditions (aspects of the world required to initialise climate modelling experiments) from PRISM, it has been possible to undertake meaningful climate modelling studies to explore Pliocene climates (e.g. Chandler et al., 1994; Sloan et al., 1996; Haywood et al., 2009; Lunt et al., 2012). Building on single model studies of the Pliocene, PlioMIP (Pliocene Model Intercomparison Project) has brought together ten different climate modelling groups to simulate identical experiments and investigate, not only the climate of the Pliocene, but inter-model variability and uncertainty (Haywood et al., 2010, 2011a; Dowsett et al., 2012, 2013; Salzmann et al., 2013). PlioMIP uses the palaeoenvironmental reconstructions from PRISM3D, which includes palaeogeography, orography, bathymetry, vegetation, ice sheet configuration and oceanic temperatures. However, there is currently no information on Late Pliocene global soils or lakes. In PlioMIP experiments 1 and 2, global soils were specified in a manner consistent with the vegetation, or they were kept as modern (Haywood et al., 2010; Contoux et al., 2012). Lakes were specified as absent and not included in any of the PlioMIP experiments. In this paper we present global datasets and palaeoenvironmental reconstructions of global Late Pliocene soils and lakes. These are intended to be incorporated into the PRISM4 Pliocene global reconstruction and future PlioMIP experimental design.

1.2 The importance of soils and lakes in palaeoclimate studies

Albedo-related soil and vegetation feedbacks are key uncertainties in the Earth System and climate models differ considerably in estimating their strength (e.g. Knorr and Schnitzler, 2006; Haywood and Valdes, 2006). For the terrestrial realm, large inland water bodies and wetlands have also been shown to significantly affect surface temperatures and energy balance in past and present climate systems (e.g. Delire et al., 2002; Sloan, 1994; Sepulchre et al., 2008; Burrough et al., 2009; Krinner et al., 2012). Studies of the African Humid Period in the Holocene have found that lakes and wetlands contribute to the "greening of the Sahara" by increasing regional precipitation (Krinner et al., 2012). A similar increase in regional precipitation was found for the Late Pleistocene Lake Makgadikgadi in the middle Kalahari (Burrough et al., 2009). In deeper time palaeoclimate studies, Sloan (1994) found that when simulating the Early Eocene of North America, the addition of a lake had as much impact on the climate of the continental interior as the 1680 ppmv CO_2 in the models atmosphere. The addition of a modest lake deflected the winter freezing line north and improved data – model winter temperature comparisons (Sloan, 1994).

Soil albedo has also been shown to have a large impact on regional precipitation (Knorr and Schnitzler, 2006). A series of climate model experiments on the mid to late Holocene showed that soil albedo in the Sahara had a larger effect on regional precipitation than orbital forcing and sea surface temperatures (Knorr and Schnitzler, 2006). Other experiments have shown that wetter and darker soils in the mid Holocene Sahara would have facilitated the northward movement of the African monsoon, creating a positive feedback (Levis et al., 2004).

Current palaeoclimate modelling studies of the Late Pliocene often struggle to generate sufficient precipitation, particularly in the semi-arid and arid tropical and subtropical regions, to match proxy data (Haywood et al., 2009; Pope et al., 2011; Salzmann et al., 2013). As lakes and soils have had significant regional impacts on mid Holocene precipitation (e.g. Krinner et al., 2012), it stands to reason that similar affects could be seen in the Late Pliocene. However, Holocene palaeoclimate studies benefit from comprehensive published data sets of soils and lakes (e.g. Hoelzmann et al., 1998) and presently no such data has been available for Late Pliocene climate model studies (Haywood et al., 2010). In this paper we present the first global datasets of Late Pliocene soil and lake distributions and these datasets have been transformed into climate model boundary conditions suitable for exploring the feedbacks of soils and

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lakes in a warmer world. Finally, we present the initial results of the first Late Pliocene palaeoclimate model studies using the new realistic soil and lake boundary conditions.

2 Methods

2.1 Construction of the lakes and soils database

Late Pliocene lakes and soils data have been collected and synthesised into an internally consistent format using a Microsoft Access – ArcGIS database that is based on the vegetation database TEVIS (Salzmann et al., 2008). The soils and lake data have been compiled from published literature: soil data (Fig. 1; Supplement, Table 1) is based upon paleosol occurrences (e.g. Mack et al., 2006), whereas evidence for lakes (Fig. 1; Supplement, Table 2) comes from sedimentology (e.g. Müller et al., 2001), DEM and topographic studies (e.g. Drake et al., 2008), fauna (e.g. Otero et al., 2009) or a combination of these (e.g. Adam et al., 1990). Both the soils and lake data are recorded with a latitude–longitude (for lakes this represents the centre), a maximum and minimum age in millions of years (Ma) and the method used to date the deposit. The documented soils data also include a soil type, which is based upon the orders of the USDA soil taxonomy scheme (Soil Survey Staff, 1999). The lakes data also records an estimated surface area extent, the shape of the lake and for lakes with a surface area greater than 1500 km^2 the latitude–longitude of its northern, eastern, southern and western most points. In addition to this, any reported information on water chemistry, details of inflows and outflows or whether the lake was ephemeral have also been recorded.

2.2 Preparing the data for inclusion in a climate model

From the geological data recorded in the Late Pliocene lakes and soil database we have produced three maps to allow the inclusion of lakes and soils in palaeoclimate modelling experiments. The three maps are: a global soils map, which is accompanied by a table providing preferred soil characteristics (Fig. 2a; Table 1); a dry-lakes scenario (Fig. 2b) and a wet-lakes scenario (Fig. 2c). All maps use a grid cell size of 2.5° latitude × 3.75° longitude, this equates to a spatial resolution of 278 km × 417 km at the equator.

To develop a global Late Pliocene soils map (Fig. 2a) from the 54 palaeosol occurrences recorded in the database (Supplement, Table 1), we combined the soil data with the Piacenzian biome reconstruction presented in Salzmann et al. (2008). This allowed a soil type to be assigned to each model grid cell even if Late Pliocene palaeosol data had not been reported from that region. This technique of combining a realistic biome reconstruction with palaeosol data uses the knowledge that at a global scale the distribution of each soil order mirrors certain vegetation biomes (Soil Survey Staff, 1999). When the palaeosol data were combined with the vegetation reconstruction there were no mismatches between a palaeosol occurrence and a biome that we did not expect to be associated with that soil order.

Both the Late Pliocene dry-lake scenario and wet-lake scenario are based upon the estimated surface area of the palaeolakes, translated into a percentage of a model grid cell (Fig. 2b, c). A wet and a dry scenario have been generated due to compensate for the uncertainty in the dating of many of these features, which often cover several orbital cycles. By producing a dry and a wet scenario map it is possible for climate modelling experiments to explore the impacts of Late Pliocene lakes in a warm-wet climate period or a cold-dry climate, this follows the vegetation work of Salzmann et al. (2013). Late Pliocene lake surface areas have been either taken from the published literature or calculated from published estimates of lake extent. These were then translated into percentages of grid cells by calculating how much of a grid cell would be occupied by each lake. Where mega-lakes occupied more than one grid cell, the geographic distribution of the lake was based upon the published shape and the distal most latitude–longitude points of the reconstructed lake.

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2.3 Uncertainties in reconstructing soils and lakes from geological data

This study is the first to present realistic Late Pliocene soil and lake maps derived from the synthesis of geological data (Fig. 2). Despite these maps being the current state-of-the-art it is important to discuss the uncertainty involved in them. For the global soils reconstruction the greatest uncertainty comes from the limited geographic distribution of data (Fig. 1) and the reliance on the global biome reconstruction (Salzmann et al., 2008) to fill in the gaps. However, there were no soil data points coinciding with a vegetation type they would not normally be associated with, so we can have confidence in our methodology to generate a global map. One discrepancy between the Late Pliocene reconstruction and the modern global soil orders map is that the Late Pliocene does not have any regions of inceptisols or entisols (Fig. 2a). Today these two soil orders make up about 30 % of the land surface and represent undeveloped or moderate pedogenic development (Soil Survey Staff, 1999). Producing a global soil order map for the Late Pliocene requires the incorporation of many distinct palaeosol occurrences and most of these are preserved as a pedogenically developed soil order, rather than preserved as an undeveloped or moderately developed soil (e.g. Gürel and Kadir, 2006). Where inceptisol palaeosols are preserved they are commonly associated with a fully developed soil order (e.g. Mack et al., 2006). Further to their limited geological preservation, inceptisols and entisols are not commonly associated with particular vegetation types, being a product of limited soil development rather than ambient climate and biome (Soil Survey Staff, 1999). This made them near impossible to plot on a Late Pliocene soils map with the available data and methodology. Inceptisols and entisols were therefore omitted from the reconstruction, but it should be noted that they were not absent during the Pliocene (Sangode and Bloemendal, 2004; Mack et al., 2006).

The reconstructed Late Pliocene lakes represent a synthesis of the published geological data. What is most obvious are the vast areas with no percentage of the grid cell covered by surface water (Fig. 2). This is not meant to mean that these regions were without any surface water, but that there are no published records of lake sediments with the lake extent estimated. With continued research into Late Pliocene lake faunas, floras and sediments these regions will contain more surface water. Of the lakes presented in the reconstructions of this study the one with the greatest uncertainty is the substantial mega-lake Zaire (Fig. 2). This mega-lake has long been speculated due to all the major tributaries of the Congo River being orientated to the centre of the basin (Summerfield, 1991; Goudie, 2005) and the presence of a submarine canyon rather than a delta (Cahen, 1954; Peters and O'Brien, 2001; Goudie, 2005). However, it has not been ground-truthed with recent geological data and this should be an imperative (Peters and O'Brien, 2001).

2.4 Modelling

The potential effects of the new lakes and soils databases on the Pliocene climate were tested using modelling simulations with the UK Met. Office General Circulation Model (GCM), HadCM3. This is a coupled atmosphere-ocean GCM described by Gordon et al. (2000) and Pope et al. (2000), with horizontal resolution of $3.75^{\circ} \times 2.5^{\circ}$ in the atmosphere and $1.25^{\circ} \times 1.25^{\circ}$ in the ocean. The atmospheric component has 19 levels in the vertical and 30 min timesteps while the oceanic component has 20 levels in the vertical and 1 h timesteps.

To investigate the impacts of realistic soil and lake distributions on the Late Pliocene climate we analyse the results of 4 simulations: a control simulation of 850 yr (PRISM3 control), a simulation with Late Pliocene lake levels from the wet-lakes scenario (PRISM3 + wet-lakes scenario) (Fig. 2c), a simulation with Late Pliocene soils (PRISM3 + soils) and a simulation with soils and the wet lakes scenario (PRISM3 + soils + wet-lakes scenario). The PRISM3 + wet-lakes scenario, PRISM3 + soils, and PRISM3 + soils + wet-lakes scenario simulations were all started 500 yr into the PRISM3 control simulation and were run for a further 350 yr. This is sufficient to spin up all atmosphere and vegetation parameters of interest (Hughes et al., 2006). The control experiment comprises boundary conditions (including orography

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and ice sheets) from PRISM3D (see Dowsett et al., 2010; Haywood et al., 2010, 2011), it has a modern orbit and CO_2 levels of 405 ppmv. Although the preferred boundary conditions for PRISM3D are to remove the west Antarctic ice sheet, here we utilise the alternative PRISM3D boundary conditions, which remove all ice from the west Antarctic ice sheet and reduce the topography to sea level. The initial vegetation patterns for the control run were prescribed from PRISM3D, however the version of HadCM3 used here comprises the MOSES2.1 land surface scheme and the TRIFFID dynamic vegetation model (Cox et al., 1999, 2001) such that vegetation dynamically changes with the climate; and the relative proportions of different vegetation types adjust throughout a long simulation. For the control simulation, soil parameters were set to be the same as modern and there were assumed to be no lakes.

The PRISM3 + wet-lakes scenario simulation was identical to the control except that the high level lakes were included in a very simple way. In the MOSES2.1/TRIFFID version of HadCM3, each grid box is assigned a fractional coverage of 9 different surface types (Broadleaf Trees, Needleleaf Trees, Shrubs, C_4 grasses, C_3 grasses, ice, urban, bare soil or water); lakes are included in a grid box by increasing the water surface type while the fractions of all other surface types are reduced as appropriate. It is noted that, although trees, grasses and shrubs can dynamically change throughout the model simulation, the lake fraction of the grid box will remain constant and will be neither increased by precipitation nor decreased by evaporation (Essery et al., 2001). This means that the lakes in the simulation are static and do not depend on precipitation/evaporation/runoff patterns.

The PRISM3 + soils simulation required changes to several HadCM3 boundary conditions. The simplest of these is soil albedo, which was determined from the colour of the soil type shown in Table 1. Following Jones (2008) light soils were prescribed an albedo of 0.35, medium soils an albedo of 0.17 and dark soils an albedo of 0.11. These albedo values are based on the assumption that medium and dark soils have average wetness, while light soils are dry. It is noteworthy that, although there are differences in soil types between the Late Pliocene and the modern, the simple way that these

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soil types are incorporated into HadCM3 means that their potential for changing the climate is limited. Table 1 shows that, of the 9 soil types to be included in the PRISM4 database, five are intermediate colour, three are dark and one is light. This means that even though a soil type may change between the Pliocene and the modern, it is only if the soil type changes to one of a different colour that the climate can be altered via albedo feedbacks. Other soil parameters used in HadCM3 (Clapp–Hornberger exponent, saturated hydraulic conductivity, saturated soil water suction, volumetric soil moisture concentrations at critical, saturation and wilting points, dry soil volumetric heat capacity and dry soil thermal conductivity) are assumed to depend on soil texture and are prescribed values from Cox et al. (1999). Again, it is noteworthy that even though a soil type may have changed between the modern and the Late Pliocene, it is where a soil changes to one of a different texture that will have the potential to impact the climate.

Although HadCM3 dynamically predicts vegetation patterns, this is limited to only 5 types of vegetation and these are difficult to compare with datasets of Late Pliocene vegetation such as PRISM3D (Salzmann et al., 2008). To facilitate a better comparison with palaeobotanical proxy data the climate output from HadCM3 was used to drive the offline vegetation model BIOME4. The BIOME4 model (Kaplan, 2001) is a mechanistic global vegetation model, which predicts the distribution of 28 global biomes based on the monthly means of temperature, precipitation, cloudiness and absolute minimum temperature. The model includes 12 plant functional types (PFTs) from cushion forb to tropical evergreen tree (Prentice et al., 1992). It is the bioclimatic tolerances of these that determine which is dominant in a grid cell and from this, which biome is predicted. The BIOME4 model was driven from the average annual climate data obtained from the last 30 yr of each HadCM3 experiment, to assess which PFTs were feasible in each grid box and to allocate an appropriate biome at each location.

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3 Results

In this section we will first describe the geographic distribution of Late Pliocene soils and lakes that have been reconstructed from geological data. and then the results of including these reconstructions in a series of GCM simulations using the PRISM3 boundary conditions.

3.1 Late Pliocene soils

During the Late Pliocene there were significant differences in the global distribution of soils (Fig. 2a). Overall, the distribution of soils reflects the warmer and wetter world seen in the vegetation reconstruction. Gelisols, associated with tundra type vegetation are restricted to very high latitude areas of North America, Greenland and Eurasia, as well as coastal regions of Antarctica (Fig. 2a). The more northern distribution of boreal and temperate forests is accompanied by extensive high latitude Spodosols and Alfisols at higher than modern latitudes (Fig. 2a). There is evidence supporting Alfisols at 54° N from around Lake Baikal, where grey forest soils are preserved (Mats et al., 2004). The extensive grassland and savannas in the continental interiors of North America and Eurasia are translated into extensive Mollisols (Fig. 2a). South of the Alfisol, in North America, there were Ultisols along the west coast and in the southeast of the continent (Fig. 2a). The centre of North America contains a large region of Aridisols, and a mixture of Alfisols (Abbott, 1981) and Vertisols (Mack et al., 2006) along the southern margin. In Europe there is evidence for Alfisols (Icole, 1970; Günster and Skowronek, 2001), Histosols (Basilici, 2001; Bechtel et al., 2003) and extensive Ultisols (Gerasimenko, 1993). At the eastern end of the Mediterranean there was a region of mixed Alfisols (Quade et al., 1994), Oxisols (Kelepertsis, 2002), Ultisols (Paepe et al., 2004) and Vertisols (Graef et al., 1997) (Fig. 2a). The Indian subcontinent contained a mixture of Ultisols and Vertisols during the Late Pliocene (Fig. 2a). There is also evidence for Alfisols close to the Himalayas (Sangode and Bloemendal, 2004). In

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Southeast Asia the biome reconstruction translates into extensive Ultisols across this region (Fig. 2a).

In South America there is a large region of Oxisols as evidenced from palaeosols (Mabesoone and Lobo, 1980) and the biome reconstruction. In southern South America Ultisols, molisols and Alfisols dominated during the Piacenzian (Fig. 2a). The soils reconstruction for Africa relies heavily on the biome reconstruction, except for direct evidence of Vertisols in east Africa (Wynn, 2000; Campisano and Feibel, 2008), Oxisols in South Africa (Helgren and Butzer, 1977) and Histosols in Madagascar (Lenoble, 1949). Combining these palaeosol occurrences with the biome reconstruction, the distribution of soils in Africa is shown to be dominated by Aridisols in northern Africa and Oxisols in central and southern Africa (Fig. 2a). Palaeosol evidence in Australia shows the presence of Aridisols in the middle of the continent (Hou et al., 2008) and Oxisols in the southeast (Firman, 1994; Hughes et al., 1999). The biome reconstruction of Salzmann et al. (2008) suggests the presence of Alfisols in the southwest and north of the continent, Vertisols in the east and Aridisols in the west and south (Fig. 2a).

3.2 Late Pliocene lakes

The global distribution of Late Pliocene lakes is dominated by mega-lakes in Africa and Australia (Fig. 2b, c). In Africa the largest mega-lake, in both the wet and dry scenario, is Lake Zaire (Beadle, 1974; Peters and O'Brien, 2001; Goudie, 2005). This large water body is reconstructed in the wet-scenario as occupying the majority of the modern river drainage basin (Fig. 2c), whereas it is reconstructed smaller in the dry-scenario (Fig. 2b). To the east of Lake Zaire was Lake Sudd, which was large during wet phases of the Pliocene (Fig. 2c). However, it is reported to have been a very shallow lake (Salama, 1987) and is therefore considerably reduced in the dry-scenario (Fig. 2b). In southern Africa there is evidence for surface water in the region of the modern Okavango Delta and the Makgadikgadi Pan (Ringrose et al., 2002, 2005), both of which have a reduced surface area in the dry-scenario (Fig. 2b, c). In east Africa there is evidence for Lake Malawi (Dixey, 1927) and Lake Tanganyika (Cohen et al.,

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1997), both of these occupy multiple grid cells of the reconstruction (Fig. 2b, c). There were also smaller (sub-grid-cell) lakes associated with parts of the Rift Valley (Deino et al., 2006). Northern Africa was dominated by Lake Chad, which was considerably bigger than modern during the Late Pliocene (Schuster et al., 2009; Otero et al., 2010). The sedimentology of the Chad Basin shows that there was considerable shifts from lake to sub-aerial environments during the late Neogene (Schuster et al., 2009) and we have represented this by using the reported sediment sections to define a wet-scenario (Fig. 2c) and dry-scenario (Fig. 2b) Late Pliocene mega-lake Chad. Further north there was Lake Fazzan and several smaller lakes in Libya, which were associated with an extensive river system (Drake et al., 2008). The lakes formed in topographic lows as volcanic eruptions restricted and blocked the flow of the river system (Drake et al., 2008).

In Australia there was a series of large lakes in the centre of the continent (Fig. 2b, c). The largest of these was mega-lake Eyre (Simon-Coinçon et al., 1996; Alley, 1998; Martin, 2006). To the east of Lake Eyre was Lake Tarkarooloo another large water body (Callen, 1977). Whilst to the northwest was Lake Amadeus, which may have fed mega-lake Eyre (Chen et al., 1993).

There is limited evidence for Late Pliocene lakes in South America and those reported are modest in size and associated with the Andes Mountains (Fig. 1; Supplement, Table 2). The Quillagua-Llamara Basin, Chile records an ephemeral Late Pliocene lake with evaporates present (Sáez et al., 1999). In Argentina a small saline, though permanent, lagoon is preserved at Llancanelo (Violante et al., 2010) and a small lake is reported from Bogota in Colombia (Wijninga and Kuhry, 1993).

In North America there is a swarm of small to modest sized lakes associated with the valleys of the Rocky Mountains (Fig. 2b, c). The largest of these was Glenn's Ferry in Idaho, which has been reconstructed from sediments and the distribution of fossil fishes (Smith, 1981; Thompson, 1992). There are many small lakes across Eurasia, but only Lake Baikal and Lake Suerkuli covered multiple grid cells (Fig. 2b, c). Lake Baikal is reconstructed as having a similar size to the modern lake, however there was

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a change in sedimentation related to tectonic activity at 3.15 Ma (Müller et al., 2001). Lake Suerkuli, located on the northern Tibetan Plateau had an estimated surface area of 4800 km^2, but was destroyed by activity of the middle Altyn Fault (Chang et al., 2012).

3.3 Impact of soils and lakes on simulating Late Pliocene climate and vegetation

Using the boundary conditions described in the previous section a series of modelling experiments was undertaken. The GCM simulations were designed to explore the impacts on Late Pliocene climate and vegetation that using realistic soil and lake boundary conditions can have. In this section we will present the differences in temperature and precipitation of the three experiments: PRISM3 + soils, PRISM3 + wet-lakes and PRISM3 + soils + wet-lakes, from the standard PRISM3 control. All results presented use average values from the final 30 yr of each simulation and are significant at the 0.1 % confidence level. We also show how the inclusion of soils and lakes could affect BIOME distributions in Pliocene simulations.

3.3.1 PRISM3 + soils

The mean annual Surface Air Temperature (SAT), in the PRISM3 + soils experiment shows a small degree of cooling across northern Africa and southwest North America and warming in northern South America, southern North Africa and South Africa, East Asia and central Australia (Fig. 3). During December-January-February (DJF) the differences with the PRISM3 control run are the same as in the annual, but with the addition of a strong warming in north-eastern Eurasia (Fig. 3). During June-July-August (JJA) the pattern of temperature difference with the PRISM3 control run are the same as the annual average (Fig. 3). In this experiment with Late Pliocene soils there is a small increase in Mean Annual Precipitation (MAP) in southern North Africa and eastern Africa and a reduction in the (MAP) across the Amazon region (Fig. 4). This reduction in MAP across South America is difficult to interpret as there are no changes in the soil boundary conditions over South America that are expected to alter precipitation. It is noted that the Amazon region has high precipitation with substantial internal model variability, and is a particularly sensitive region in HadCM3 (Good et al., 2013), however the changes seen here are substantial and the possibility of the changes occurring due to the influence of changes to soil parameters at remote locations cannot be discounted. It will be interesting to see if the results over South America are replicated with other GCM's that make use of the new soils database. Seasonal changes of precipitation attributable to soils shown in Fig. 4 include a modest increase in rainfall over central Africa during DJF and an increase in rainfall in a narrow band in the southern region of the Sahara and India during JJA (Fig. 4). These annual and seasonal climatological changes translate into very modest biome changes (Fig. 5). The main differences in this experiment from the PRISM3 control run is an increase of xerophytic shrubland in North Africa and South Africa (Fig. 5). In North Africa this replaces desert and relates to the increased JJA rainfall (Fig. 4). In South Africa xerophytic shrubland replaces warm-temperate forest and temperate sclerophyll woodland (Fig. 5). These changes are probably the result of increase winter temperatures and no change in MAP, leading to higher evaporation and limiting the development of lusher biome types. BIOME4 also predicts an expansion of desert in coastal Brazil and Australia, based upon the climate simulated by HadCM3 (Fig. 5).

3.3.2 PRISM3 + wet-lakes scenario

In the experiment using the Late Pliocene wet-lakes scenario boundary condition the most apparent change in mean annual SAT occurs in the northern North Atlantic (Fig. 3), however this cannot be attributed to the addition of lakes since model variability is large in this region – even at century scale timescales – and patterns such as this can also be seen by comparing the averages of two 30 yr periods in the control run. Temperature changes that can be clearly attributed to lakes are small and are localised to the immediate vicinity of the lakes. The decreases in SAT around the large lakes in North Africa are most pronounced in DJF (Fig. 3). There are also regional decreases

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in SAT associated with lakes in the mid-latitudes of the Northern Hemisphere during JJA. There are increases in precipitation associated with the mega-lakes in Africa and some of the smaller lakes in the Northern Hemisphere (Fig. 4).

The biome predictions indicate an expansion of temperate conifer forest and open conifer woodland in western North America, this replaces temperate xerophytic shrubland (Fig. 5). Cool mixed forest is replaced with temperate deciduous forest in the region of Europe-Russia. In North Africa, xerophytic shrubland has expanded along the Mediterranean coast, but with an additional grid cell of desert along the southern margin of the Sahara. However, there is also a two grid cell increase in savannah at the expense of tropical xerophytic shrubland, along the southern Sahara margin (Fig. 5). The xerophytic shrubland located in Southeast Asia, predicted by the PRISM3 control run, is replaced by savannah and tropical deciduous woodland (Fig. 5). Finally, the lakes in Australia have created a small reduction of desert in this region (Fig. 5).

3.3.3 PRISM3 + soils + wet-lakes scenario

In the experiment that contained both the Late Pliocene soils reconstruction and wet-lakes scenario boundary condition there are regions of slight cooling in mean annual SAT and areas of warming (Fig. 3). In southwestern North America, in the area containing multiple small lakes, there is a small decrease in mean annual SAT (Fig. 3). In North Africa the area with Aridisols shows a small decrease in mean annual SAT, but south of this where Alfisols and Oxisols underlie the vegetation there is a small increase in mean annual SAT (Fig. 3). An increase in mean annual SAT is associated with the Vertisols in Australia (Fig. 3). The patterns of temperature change in the mean annual are also seen in the seasonal plots (Fig. 3). The only pronounced change in rainfall is an increase in central Africa and a decrease in northern South America (Fig. 4).

As expected the biome reconstruction from this experiment shows a combination of the biome plots of PRISM3 + soils and PRISM3 + wet-lakes scenario experiments (Fig. 5). There is an increase in temperate conifer forest and woodland in western North America, which is associated with the lakes. Coastal Brazil has a significant increase of tropical xerophytic shrubland, seen in the PRISM3 + soils experiment and the slight increase in desert seen in both experiments (Fig. 5). The Sahara desert is slightly reduced and this has changed into xerophytic shrubland (Fig. 5). An expansion of xerophytic shrubland in southern Africa is at the expense of other biome types, except desert (Fig. 5). The xerophytic shrubland in Southeast Asia is replaced by savanna and the Australian desert has a small reduction, which was also seen in the PRISM3 + wet-lakes scenario (Fig. 5).

4 Discussion

The global distribution of soils and lakes is significantly different from present day (Fig. 2). Whereas soils reflect the global distribution of Late Pliocene biomes (Salzmann et al., 2008), the distribution and size of Late Pliocene lakes contribute to a land-surface covering dramatically different from the present day (Fig. 2). The increase in number and size of lakes is a response to the generally wetter global climate of the Late Pliocene (e.g. Salzmann, 2008). However, application of these boundary conditions into HadCM3, alongside the other PRISM3 boundary conditions, produced subtle results (Figs. 3, 4, 5). The changes in climate and vegetation attributable to Pliocene soils and lakes seen in this study are generally less than seen in similar studies of the mid-Holocene. Palaeoclimate studies on the mid Holocene have shown that it is possible to double regional precipitation with large lakes (Krinner et al., 2012) and move the African monsoon northwards by modifying soil albedo in the Sahara (Levis et al., 2004). Although the results of our study are not as obvious as those from the Holocene they do offer a glimpse that some of the processes, previously identified in the Holocene, may operate in the Pliocene. Although the addition of Late Pliocene lakes did not double regional precipitation, as was simulated for the Holocene (Krinner et al., 2012), our experiments do show a 50 % increase around Lake Chad and notable summer increases in western North America. This would suggest that similar forcings are operating in the Pliocene and the Holocene, with regard to large lakes.

The parameterisation of Alfisol along the southern margin of the Late Pliocene Sahara led to a summer increase in precipitation (Figs. 2a, 4), which led to a change from the desert biome type to a tropical xerophytic shrubland (Fig. 5). The Alfisol is a darker soil type than the Aridisol (Table 1) and this result is comparable, although more subtle, to those presented by Levis et al. (2004). However, when the soils and wet-lakes boundary conditions were combined this precipitation signal was lost, but some of the vegetation change remained (Figs. 4, 5). A northwards shift of the Sahel-Sahara boundary is consistent with the few vegetation data available for this region (Leroy and Dupont, 1994; Salzmann et al., 2008).

Despite the climatological changes being very small in western North America (Figs. 3, 4), the change from drier open biomes to a region dominated by temperate conifer forest and conifer parkland is consistent with reconstructions from palaeobotanical data (Thompson, 1991; Fleming, 1994; Salzmann et al., 2008). The main driving force for these vegetation changes appears to be the lakes, but in the soils and lakes experiment there is a further increase in wetter biome types (Fig. 5). This would suggest that although very little difference between the control experiment and the PRISM3 + soils experiment occurred, the combination of realistic Late Pliocene soils and lakes has positive feedbacks that facilitate the expansion of wetter vegetation types. Despite the limited improvements in the modelled climates and biome distribution of the Late Pliocene, there are positive changes between the experiments containing the soils and lake data and the control run. We therefore encourage the use of the Late Pliocene soils and lake boundary conditions in future climate modelling studies, including the future PlioMIP experiments (Haywood et al., 2010, 2011a).

5 Conclusions

Through a synthesis of geological data we have reconstructed the global distribution of Late Pliocene soils and lakes. From these reconstructions we have conducted a suite of climate modelling experiments to test the impacts of realistic soils and lakes on the

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climate of the Late Pliocene. The inclusion of soils and lakes does not significantly modify global climate, but does have important regional impacts. These regions have previously been simulated as too dry, when compared to palaeobotanical data. We see improvements in the seasonal amounts of precipitation in southern North Africa and western North America, which results in the model predicted biomes comparing more favourably with vegetation proxy data. We strongly encourage the use of these newly developed boundary conditions in future Late Pliocene climate research. These new boundary conditions improve regional data-model comparisons and their feedbacks in a warmer world should be explored further in future palaeoclimate modelling studies.

Supplementary material related to this article is available online at: http://www.clim-past-discuss.net/9/3175/2013/cpd-9-3175-2013-supplement.zip.

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Table 1. The colour (for albedo) and texture translations for the soil orders used in the modelling of Late Pliocene soils.

Soil	Colour	Texture
Gelisol	Intermediate	Medium
Histosol	Dark	Fine
Spodosol	Intermediate	Medium/Coarse
Oxisol	Intermediate	Fine/Medium
Vertisol	Dark	Fine
Aridisol	Light	Coarse
Ultisol	Intermediate	Fine/Medium
Mollisol	Dark	Medium
Alfisol	Intermediate	Medium

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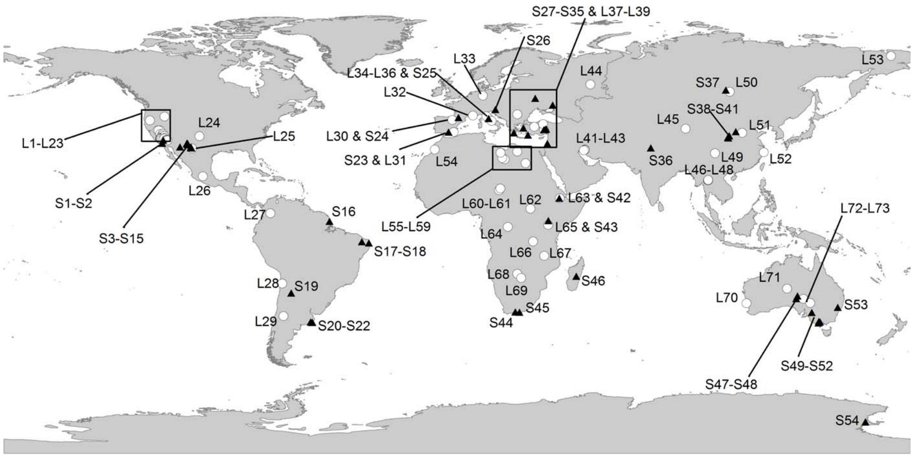

Fig. 1. The location of the soils and lake data used in this study to reconstruct global Late Pliocene land surface features. Soils data has the prefix S (Supplement, Table 1), whilst lakes data has the prefix L (Supplement, Table 2).

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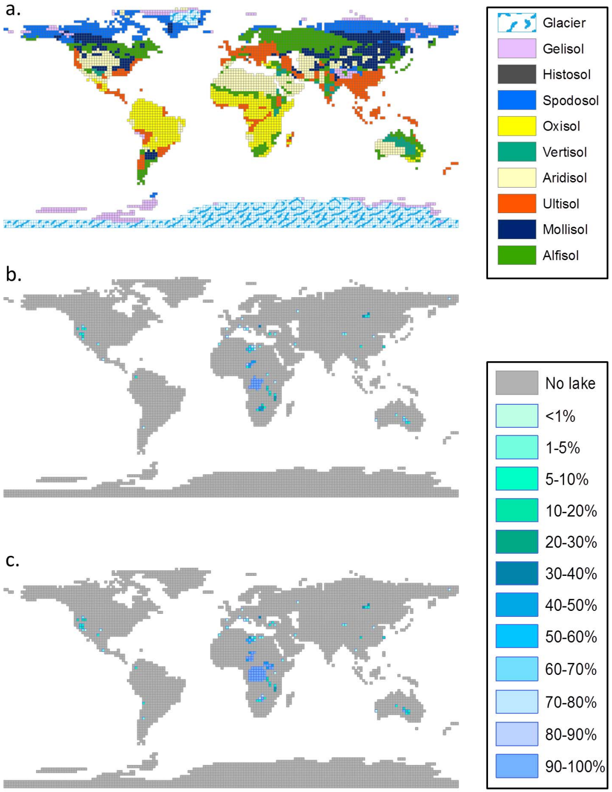

Fig. 2. The reconstructed distribution of **(a)** Late Pliocene soils, **(b)** Late Pliocene dry-lakes scenario and **(c)** Late Pliocene wet-lakes scenario.

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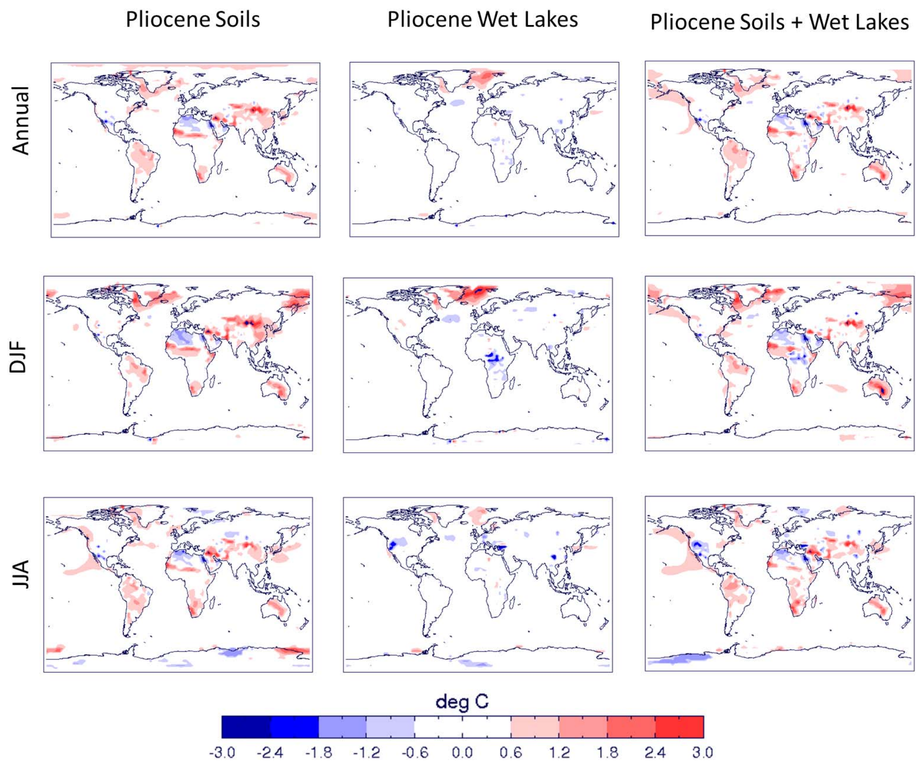

Fig. 3. Mean annual surface air temperature for the soils and lakes experiments.

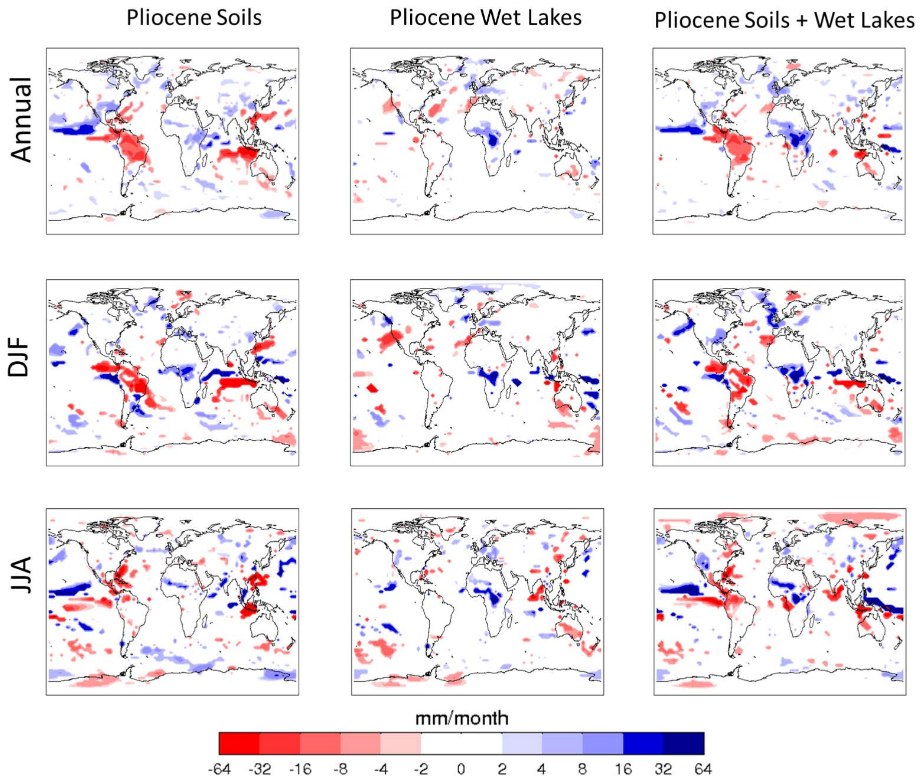

Fig. 4. The mean annual precipitation for the Late Pliocene soils and lakes experiments.

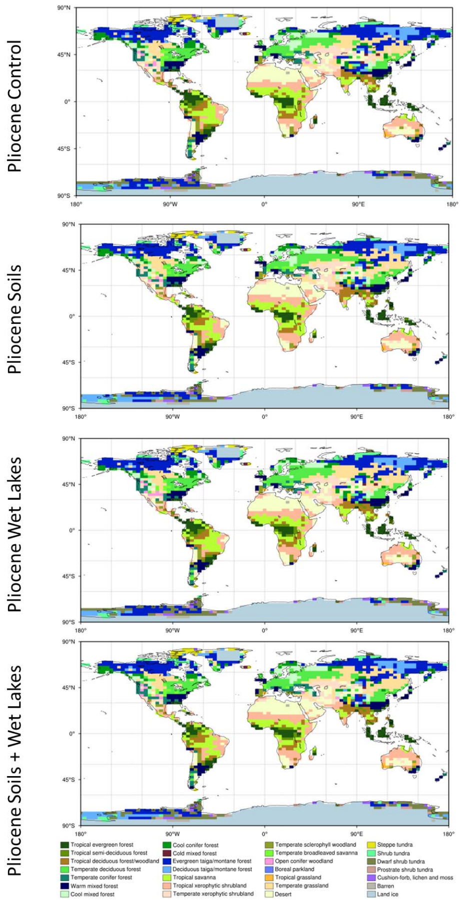

Fig. 5. The predicted biomes for the Late Pliocene soils and lakes experiments.

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