Changes in fire activity since the Last Glacial Maximum: an assessment based on a global synthesis and analysis of charcoal data

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Abstract

Knowledge of historical fire activity tends to be focused at local to landscape scales with few attempts to examine how local patterns of fire activity scale to global patterns. Generally, fire activity varied globally and continuously since the last glacial maximum (LGM) in response to long-term changes in global climate and shorter-term regional changes in climate, vegetation, and human land use. We have synthesised sedimentary charcoal records of biomass burning since the LGM and present global maps showing changes in fire activity for time slices during the past 21,000 years (as differences in charcoal accumulation values compared to pre-industrial). There is strong broad-scale coherence in fire activity after the LGM, but spatial heterogeneity in the signals increases thereafter. In eastern and western North America and western Europe and southern South America, charcoal records indicate less-than-present fire activity from 21,000 to ~11,000 cal yr BP. In contrast, the tropical latitudes of South America and Africa show greater-than-present fire activity from ~19,000 to ~17,000 cal yr BP whereas most sites from Indochina and Australia show greater-than-present fire activity from 16,000 to ~13,000 cal yr BP. Many sites indicate greater-than-present or near-present activity during the Holocene with the exception of eastern North America and eastern Asia from 8000 to ~2000 cal yr BP, Indonesia from 11,000 to 4000 cal yr BP, and southern South America from 6000 to 3000 cal yr BP where fire activity was less than present. Regional coherence in the patterns of change in fire activity was evident throughout the post-glacial period. These complex patterns can be explained in terms of large-scale climate controls modulated by local changes in vegetation and fuel load.

Keywords: palaeoenvironmental reconstruction; biomass burning; palaeofire regimes; charcoal; data-model comparisons

1. Introduction

Fire has direct and important effects on the global carbon cycle, atmospheric chemistry, and in regulating terrestrial ecosystems and biodiversity (Cofer et al. 1997; van der Werf et al. 2004). Uncertainty over the effects of future climate change upon fire regimes, and the importance of vegetation-climate-atmosphere feedbacks has fostered an increasing effort to develop coupled models of vegetation and fire (Prentice et al. 2007) to understand these future changes.

Changes in late-Quaternary fire activity inferred from sedimentary charcoal records provide insights into the coupling and feedbacks between fire and major changes in climate and its boundary conditions or controls (orbital forcing, greenhouse gas concentrations), vegetation and fuel (type and amount), and human activity. Two pioneering charcoal-data syntheses (Haberle and Ledru 2001; Carcaillet et al. 2002) have established that there are inter-hemispheric linkages in palaeo-fire activity on millennial timescales. There has been no attempt, however, to synthesise the palaeo-charcoal records in order to examine the spatial patterns of fire activity at a global scale.

The aim of this paper is therefore to map global patterns of fire activity at key times since the Last Glacial Maximum (LGM, conventionally centred at 21,000 cal yr BP). The global charcoal database used to make these maps constitutes a first step in providing the necessary empirical data for testing the validity of fire models under markedly differing biological and physical conditions than present (Marlon *et al*. in prep). Specifically, we hypothesize that during times when large-scale climate is the dominant control of fire activity, more spatially coherent patterns in fire activity should emerge, at regional or continental scales, overriding the finer scale heterogeneity one might expect from localised anthropogenic influences. Similarly, at times when the large-scale controls (e.g., glacial ice volume and insolation) are less important and anthropogenic fire activity has increased, such as during the middle and late Holocene, we would expect increased spatial heterogeneity in regional to continental scale fire activity. However, this paper does not attempt to assign specific climatic or anthropogenic mechanisms that have controlled fire activity since the LGM, but instead describes for the first time the global patterns of fire activity and offers insights into the dominant large-scale controls.

1.1 Controls on Fire and Charcoal Abundance

The incidence of fire over space and time is influenced by complex interactions between climate (over many scales of variability), fuels (type, amount, and arrangement), and ignition (whether anthropogenic or lightning). At the scale of biomes, the dominant role of climate on fire is demonstrated by e.g., the marked difference in fire frequency between ecosystems of highly humid climates of northern Europe or western Amazonia and climates marked by a prolonged and severe dry season of chaparral or maquis scrub of California or the Mediterranean, savanna regions of subtropical Africa and subtropical South America. Within biomes or ecosystems, fire activity (a reflection of both fire frequency and the amount of biomass burned), varies temporally with changing climate, fuel, and ignition (Pyne et al. 1996).

The fire regime – the frequency, intensity, seasonality, extent and type of fires (Gill 1977) – in a particular region is registered in sedimentary charcoal records as both the total charcoal abundance (which is proportional to the total biomass burned and depositional environment), and when sampling resolution permits, as individual fires that produce peaks in charcoal accumulation or datable fire-related alluvial deposits. Two examples illustrate the utility of charcoal abundance as an indicator of fire activity. In the northwestern USA, a region where fires have remained relatively frequent through time, palaeoecological data show that variations in charcoal abundance are closely associated with changes in the relative abundance of forest (as opposed to tundra and grassland), demonstrating a strong positive relationship between fire as sensed by charcoal abundance and biomass (i.e. fuel load) in this region (Marlon et al. 2006). In the rainforest-savanna ecotone regions, which have experienced a decrease in fire activity since the early Holocene (e.g., Burbridge et al. 2004), fossil charcoal data reveal a negative relationship between fire (i.e. charcoal abundance) and biomass. The contrasting relationship between fire activity and biomass reflects the marked differences in the specific influence of climate and vegetation on fire between these two ecosystems. In both cases, however, total biomass burned is reflected by the overall charcoal abundance. These examples show that fire activity, or the level of biomass burning, is not simply related to a particular vegetation type. Thus, it is necessary to summarize fire activity over time explicitly, which we do here by focusing on overall charcoal abundance.

A number of issues could influence the fidelity of overall charcoal abundance as an indicator of fire activity. Charcoal taphonomy and basin morphometry can have important influences upon charcoal deposition within lake or mire basins (Whitlock and Millspaugh 1996; Marlon et al. 2006). Several studies have suggested that macroscopic charcoal reflects local fires while microscopic charcoal reflects fires on a more regional scale (Clark 1998; Long et al. 1998; Tinner et al. 1998; Carcaillet et al. 2001). Peaks in abundance of macroscopic charcoal could reflect higher energy sediment inputs to a basin (e.g., sudden inwash of coarse, clastic material rather than any change in fire regime: see Thevenon et al. 2003), or rare instances of long-distance transport (Tinner et al. 2006). Comparisons of the age of charcoal peaks with those of known fires and the overall charcoal input with estimates of area burned suggests that despite these issues charcoal deposition in lakes or bogs provides a useful index of overall fire activity (Tinner et al. 1998; Gardiner and Whitlock 2001; Whitlock and Bartlein 2004). For alluvial charcoal records, which are much less common, summed probability distributions for a large (n = ~50-100) sample of radiocarbon dates on fire-related deposits indicate changes in relative fire activity, and the charcoal content, thickness, and depositional processes of these deposits allow inferences on general fire severity (e.g., Meyer et al. 1995; Pierce et al. 2004). Although these various controls on charcoal deposition cannot be ignored when making inter-site comparisons at local or regional scales (e.g., Carcaillet et al. 2002), the dominance of variations in large-scale climate and biome type in controlling the fire regime at a regional- to continental-scale should lead to coherency in observed changes in charcoal abundance on millennial timescales among locations with similar climate, vegetation and human impact.

2. The Global Charcoal Database

The Global Charcoal Database (GCD) contains information about palaeofire regimes in the form of sedimentary charcoal records from sites across the globe since the LGM. Published and unpublished charcoal data were acquired from a network of sites between 70° N and 70° S (http://www.bridge.bris.ac.uk/projects/QUEST_IGBP_Global_Palaeofire_WG/index.html).

Many methods were used for recording changes in charcoal abundance in a sedimentary context, and the database therefore contains a variety of different types of records (e.g., both macroscopic and microscopic charcoal, the latter mostly from pollen-slides) from a variety of site types (e.g., lake, mire, and alluvial-fan sediment records), and with varying temporal resolution and dating control. Therefore, the database includes a large amount of descriptive data (metadata) about both the sites and the charcoal samples. It also contains detailed information on site chronology: the radiocarbon dating technique (AMS or conventional), the sample size, standard deviations, and calibrated ages.

The database currently contains charcoal records from 467 sites (Figure 1), 351 of which are used in this analysis and 30 of which have records back to the LGM (here defined as 21,000 ± 500 calendar yr BP). Records of the mean charcoal value at a site over a 1000-year long interval were extracted for seven time-slices (i.e. 3000, 6000, 9000, 12,000, 15,000, 18,000, and 21,000 cal yr BP); thus fire activity is represented by mean charcoal accumulation over the mapped intervals 3000±500, 6000±500, 9000±500, 12,000±500, 15,000±500, 18,000±500, and 21,000±500 cal yr BP. These values were compared with an estimate of the modern (pre-industrial) fire regime, based on the mean charcoal value for the period 100-1000 cal yr BP. The choice of a 1000-year window to characterize the charcoal record for each time slice reflects the fact that charcoal deposition and accumulation in sediments is intrinsically highly variable (Carcaillet and Richard, 2000) and it was necessary to select a period that would avoid single, anomalous fire events in order to elucidate longer-term (in this case millennial-scale) trends. The 1000-year window technique also allowed us to make use of sites with low sampling resolution and few radiocarbon dates.

2.1 Data Acquisition and Age Models

Charcoal data were provided by the original author or came from the individual charcoal analyst as unpublished data, or from the published literature. Data were extracted from the literature by digitizing the original published figures and using the plotted values to produce tables of charcoal values by depth or by age.

As a consequence of using both published and unpublished data, some of which were produced more than a decade ago, age models based on a consistent calibration had to be developed for each site. Over 3900 radiocarbon dates, calibrated and uncalibrated, from 467 sites were entered into the charcoal database. All radiocarbon dates that were uncalibrated were converted to calibrated years BP using the Fairbanks et al. (2006) calibration curve and program (http://radiocarbon.ldeo.columbia.edu/research/radcarbcal.htm). The mean calibrated age, at one standard deviation, was selected for each radiocarbon date. In many cases, individual charcoal samples were expressed by depth or radiocarbon years and required new calibrated age models. Age calibration and the creation of age models were performed only for records with at least two radiocarbon dates. When the surface samples from sediment cores or soil profiles was established as modern, an age of -50 cal yr BP (2000 AD) was assigned. Considering the multi-centennial resolution used to analyze these records, assigning ages to the surface samples for creating age models had little impact on the final result. In cases where the date of core collection could be established, that date was assigned to the uppermost sample, for example, a core collected in 2003 AD was assigned a core top age of -53 cal yr BP. Age models were constructed using all available calibrated ages, including dated tephra layers, and pollen stratigraphic ages, and were based on four possible age model styles; (1) linear interpolation, (2) a polynomial constrained to pass through zero, (3) an unconstrained polynomial fit, and (4) a cubic smoothing spline (Ripley and Maechler, 2006). The "best fit" age model was selected for each record, based on goodness-of-fit statistics and the appearance of the resulting curve.

2.2 Standardizing Charcoal Data and calculating Anomalies

Charcoal values (e.g., influx, concentration, charcoal/pollen ratios, gravimetrics) can vary by over 10 orders of magnitude among and within sites (Figure 2) because of the broad range of record types, site characteristics, and methodological or analytical techniques. It was therefore necessary to standardise the records to facilitate comparisons between sites and through time. The standardization procedure involves three calculations applied to each site record (see Figure 3): (1) rescaling values using a minimax transformation, (2) homogenisation of variance using the Box-Cox transformation, and (3) rescaling values once more using Z-scores. The minimax transformation rescales charcoal values from a given site record to between 0 and 1 by subtracting the minimum charcoal value found during the record from each charcoal value, and dividing by the range of values:

$$c_i' = \left(c_i - c_{\min}\right) / \left(c_{\max} - c_{\min}\right)$$

where c_i' is the minimax-transformed value of the i-th sample in a particular record, c_i, and $c_{\max}$ and $c_{\min}$ are the maximum and minimum values of the c_i's. The rescaled values were transformed using the Box-Cox transformation:

$$c_i^* = \begin{cases} ((c_i' + \alpha)^{\lambda} - 1) / \lambda & \lambda \neq 0 \\ \log(c_i' + \alpha) & \lambda = 0 \end{cases}$$

where c_i^* is the transformed value, λ is the Box-Cox transformation parameter and α is a small positive constant (here, 0.01) added to avoid problems when c_i' and λ are both zero. The transformation parameter λ is estimated by maximum likelihood using the procedure described by Venables and Ripley (2002). The transformed data were rescaled once more, as Z-scores, so all sites have a common mean and variance (Figure 3e)

$$z_i = (c_i^* - \overline{c}_{(4\text{ka})}^*) / s_{c(4\text{ka})}^*$$

where, $\overline{c}_{(4\text{ka})}^*$ is the mean charcoal value over the interval 4000 to 100 cal yr BP, and $s_{c(4\text{ka})}^*$ is the standard deviation over the same interval.

There is considerable variation in the length of the charcoal records in the database, so a common base period (100-4000 cal yr BP) was used to calculate the mean and standard deviation for each site. The choice of the last 4000 years as a base period represents a compromise between a period long enough to not be dominated by sample-to-sample variability within an individual record while short enough to not exclude a large number of database records from the subsequent analyses. Most of the records in the database (95%) are at least 4000-years long. The base period does not include the last 100 years (i.e. the post-industrial period) because of the intensification of most modern human activities during this part of the fire record. Mean charcoal values, expressed as average Z-scores for a 1000-year window, were calculated for each site at 500-year intervals. Changes in charcoal values through time are expressed as Z-score anomalies (i.e. the difference between the mean Z-score for each 1000-year window and the mean Z-score for the "present", where "present" is defined as the interval 1000 to 100 cal yr BP).

2.3 Creation of 3000-year steps of time-slice maps (1000-year window)

Time-slice anomaly maps of modern (1000 to 100 cal yr BP) mean Z-score minus palaeo mean Z-score were created at 3000-year intervals (Figure 4a-g) from 21,000 cal yr BP to present. The anomalies range from >+1.15, a strong positive anomaly (i.e., significantly more charcoal than at present) to <-1.15, a strong negative anomaly (i.e., significantly less charcoal than at present) and are colour-coded (grey = -0.375 to +0.375, red = > +0.375, blue = <-0.375) to show the strength of the anomaly at each 1000-year time slice.

3.0 Results: Changes in Fire Regimes between LGM and Present

Charcoal records of changes in fire regime during part or all of the past 21,000 years are available from 351 sites (Figure 1). There are relatively few charcoal records available for the LGM and the early phase of the deglaciation. Although there are >200 sites with records for the past 10,000 years (i.e., the Holocene), some regions (e.g., the boreal forest zone of Russia and most arid regions) are only represented by a few sites even in the Holocene epoch. As a result, the interpretation of regional patterns presented here should be considered preliminary. Nevertheless, the maps show broad-scale changes in charcoal abundance through time that can be interpreted as reflecting changes in biomass burning. Here we discuss the spatial patterns of charcoal anomalies at each time step relative to present (Figure 4a) in terms of a spatial hierarchy from global through broad-scale regional to local or landscape-scale patterns.

Interpretations of fire activity at the LGM are constrained by the small number of sites (n=30), although South America, southeast Australia, Europe, and Indonesia are represented. Globally, 57% of charcoal records show less-than-present fire activity. Sites from the mid and high latitudes of South America record lower–than-present fire activity during the LGM, but greater-than-present fire activity is recorded in the southern latitudes of Australia and tropical latitudes of Southeast Asia (Figure 4b). Within these broad regions, however, there is spatial heterogeneity in the change in fire regimes. For example, sites in southern Australia and Tasmania record greater-than-present fire activity whereas adjacent sites to the north reveal less-than-present fire activity. Charcoal records (n = 4) from Indonesia and Papua New Guinea, show both similar-to-modern and strong negative anomalies, or less-than-present fire activity.

There was little change in spatial patterns of fire activity between 21,000 and 18,000 cal yr BP, with 60% of all records showing less than present fire activity (n = 40, global average Z-score anomaly = -1.19) at 18,000 cal yr BP. Charcoal records from Australia and Indonesia indicate that fire activity was generally less than present (Figure 4c). In South America fire activity was less than present in the high and mid latitudes and greater than present at lower latitudes. The relatively few sites in North America, Europe and Africa suggest less-than or similar-to present fire activity.

At 15,000 cal yr BP global fire activity was lower-than-present with 62% of charcoal records (n = 78, global average Z-score anomaly = -0.60) showing less-than-present fire activity (Figure 4d). The northern mid-latitudes (30-60° N) of North America (n = 16) show a consistent pattern of less-than-present fire activity while sites in Europe and Asia show spatial heterogeneity. Sites in Central and South America (n = 25) indicate lower-than present fire activity with the exception of those near the equator and in eastern Brazil, which show greater-than-present fire activity. In Africa, Australia, Indonesia, and Southeast Asia most records (n = 19) indicate similar-to or greater-than-present fire activity. In contrast, sites from New Zealand and two sites from New Guinea show less-than-present fire activity.

There is a significant increase in the number of charcoal records between 15,000 and 12,000 cal yr BP (n = 136 sites). A global pattern of less-than-present fire activity continues at 12,000 cal yr BP for 58% of all records. There are changes in the fire regime between these time intervals in several regions, including e.g., a reduction in fire activity in southeastern Australia (to levels less than present) and an increase in fire activity in extra-tropical latitudes of South America (to levels greater than present). In general, the mapped patterns show more spatial heterogeneity than during earlier periods (Figure 4e), but the globally averaged Z-score anomaly remains lower than present (-0.50). In the low latitudes of South America, areas of eastern Brazil continue to indicate greater-than-present fire activity whereas charcoal records west of the Amazon basin suggest less-than-present fire activity (with the exception of the Lake Titicaca record: Paduano et al., 2003). Positive charcoal anomalies from Indonesia (and eastern Brazil) suggest fire activity was greater than present at 12,000 cal yr BP. Tropical charcoal records from both sides of the Pacific, however, including records from eastern New Guinea, northeastern Australia and from western Colombia, Ecuador and Peru, show less-than-present fire activity. In southeastern Australia, a shift to less-than-present fire activity occurred at most mainland sites, although Tasmanian records continue to indicate greater-than-present fire activity and sites in New Zealand show lower-than-present fire activity. Fire activity in the mid-latitudes of Europe and North America, although increased relative to 15,000 cal yr BP, remained less than present (n = 56, -0.81 average Z-score anomaly). At regional scales, fire activity increased from glacial times at sites in northeastern and in western North America.

The interval between 12,000 and 9000 cal yr BP is marked by a significant change in fire regimes. Broadly considered, the northern extra-tropics and western tropics show increased fire activity and the southern extra-tropics and eastern tropics show a reduction in fire activity between these two intervals. By 9000 cal yr BP, however, the charcoal records (n = 200, -0.01 average Z-score anomaly) indicate a highly heterogeneous pattern of fire activity with 48% of all records showing less-than-present fire activity. Regional summaries of fire activity (Figure 5a and 5b) show greater-than-present fire activity throughout South America and in eastern North America. Mapped patterns of fire activity show spatial heterogeneity in fire activity in western North America and Europe at the sub-continental scale, but at regional scales the records are spatially coherent (Figure 4f). For example, predominantly greater-than-present fire activity occurred in northeastern North America, while lower-than or similar-to present fire activity occurred at sites in central North America. Similarly, greater-than-present fire activity occurred in southern Brazil and lower-than-present fire activity occurred at sites within the Amazon basin. Coherent patterns of less-than-present fire activity also can be seen at larger, sub-continental, scales in Australia and New Zealand at 9000 cal yr BP. Sites in the northern mid-latitudes of Europe show a heterogeneous pattern of fire activity at 9000 cal yr BP.

At 6000 cal yr BP, the charcoal records (n = 266) show continued spatial heterogeneity of fire activity, with 50% of all records showing less-than-present fire activity, but regionally coherent patterns emerge (Figure 4g). In the Northern Hemisphere, regional summaries show greater-than-present fire activity in Central and

Sorth America, less-than-present fire activity in eastern North America, and heterogeneous conditions similar to modern across Europe (Figure 5b). At regional-to-landscape spatial scales, however, positive and negative anomalies in fire activity relative to present appear more spatially coherent. For example, regional patterns of fire across low latitudes (<30°S) of South and Central America indicate greater-than-present fire activity (n = 33, 0.53 average Z-score anomaly) in the neotropics. In the mid and high latitudes of South America (>30°S), fire activity was less than present along the Pacific coast but greater than present east of the Andes. Throughout the eastern tropics, including the low latitudes of Indonesia and eastern New Guinea, fire activity was similar to or less than present at 6000 cal yr BP. In southeastern Australia and New Zealand, fire activity was mostly less than present, similar to conditions at 9000 cal yr BP.

By 3000 cal yr BP, global fire activity was heterogeneous with 46% of all records showing less-than-present fire activity. In general, fire activity was greater than present in the neotropics, central and eastern Europe and less than present in Australia. The mid-latitudes of the Northern Hemisphere suggest a highly heterogeneous pattern of fire activity for 3000 cal yr BP but with generally greater-than-present fire activity in the low latitudes (~10-50°S) of Central and South America and a more heterogeneous pattern in the mid and high latitudes of Patagonia. Less-than-present fire activity is evident from the Eastern Hemisphere, including eastern New Guinea, New Zealand and eastern Australia. Sites in Indonesia and central Asia show increasing heterogeneity by 3000 cal yr BP. Sites throughout the mid- and high-latitudes of North and South America generally indicate a heterogeneous pattern of fire activity, and fewer sites show significant anomalies compared to modern. Examination of the individual charcoal time series suggests that this pattern is related more to the slow rate underlying climatic controls of vegetation and fire than to the particular way in which the data were analyzed (see below).

4.0 Discussion: The Climatic Control of Observed Changes in Fire Regimes

Changes in regional climate have direct effects on fire regimes, through controlling the incidence of ignitions and the likelihood that fires will spread, and indirect effects through changing vegetation type and productivity, and hence available fuel load (Pyne et al. 1996). The major factors governing regional climate changes since the LGM are changes in the seasonal and latitudinal distribution of insolation, the disappearance of the Northern-Hemisphere ice sheets (and concomitant changes in land-sea geography), southern-hemisphere ice caps, changes in sea-surface temperature patterns and variability, and changes in atmospheric composition. All of these factors directly or indirectly (or both) influence regional-scale atmospheric circulation patterns. The LGM, ca 21,000 cal yr BP, represents the global (though not regional) maximum of the extent of the ice sheets (Peltier 2004) and a time when sea level was ca 120m lower than at present and tropical land areas were more extensive than today. Greenhouse gas concentrations (compared to pre-industrial) were low (Raynaud et al. 2003) and atmospheric aerosol loadings were high (Kohfeld and Harrison 2001). Ocean temperatures were, in general, lower than today with the largest changes occurring in high northern latitudes (Schäfer-Neth and Paul 2003). The transition from glacial to interglacial conditions was marked by asynchronous warming in the two hemispheres (Schaefer et al. 2006; Smith et al. 2005), with the Southern Hemisphere leading the Northern Hemisphere by up to two millennia

(Labeyrie et al. 2003). Insolation changes became the major driver by the early Holocene, with regional climates responding to the increased seasonal contrast in insolation in the Northern Hemisphere and the correspondingly decreased seasonal contrast in insolation in the Southern Hemisphere (Berger 1978; Liu et al. 2004). These insolation anomalies changed towards reduced seasonal contrasts in the Northern Hemisphere and stronger seasonal contrasts in the Southern Hemisphere in the last 6000 years. These broad-scale changes in climate forcing can be used to explain much of the observed change in regional fire regimes at orbital timescales (the 21,000 yr precession cycle). Superimposed on these orbital-time scale changes were millennial- and shorter time-scale climate that typically were associated with smaller (spatial) scale anomaly patterns.

Additional time-slice maps at 500-yr intervals that supplement those in Figure 4 (not shown) and the individual charcoal Z-score anomaly time series (not shown) were used to divide the records into continental and regional groups of records with similar histories (Figure 5a). Comparison of these grouped time series with time series of large-scale climate controls (Figure 5b) suggest that the global charcoal record since 21,000 cal yrs ago can be divided into four relatively distinct intervals: 1) a glacial interval (21,000 through 16,000 cal yr BP) when global temperatures were low, it was generally drier than present, and terrestrial biomass was relatively low; 2) a late-glacial interval (15,000 through 12,000 years ago) when global (and particularly Northern Hemisphere) temperature increased, pronounced millennial climate variations were registered, and vegetation exhibited dramatic changes on a global scale (Williams et al. 2004); 3) an early- Holocene interval (from 11,000 through 7000 years ago), when monsoonal regions in both hemispheres were wetter than at present and regions under the influence of the subtropical high pressure system were drier, and 4) a mid-to-late Holocene interval when global climate approached that of the present, and ENSO and human influences on fire regimes became important.

4.1 Interpretation of fire activity patterns during the glacial interval (21,000 through 16,000 cal yrs BP)

Although there are relatively few charcoal records for the LGM and subsequent millennia, they show a consistent pattern of low fire activity (Figure 4b). Indeed the glacial interval is the period of lowest fire activity in the last 21,000 years. This is consistent with the fact that the global climate was generally (but not universally) colder and drier than present, leading to an overall reduction in terrestrial biomass (Francois et al. 2000) and thus a decrease in fuel availability.

At a regional scale, less-than-present fire activity in Patagonia at 21,000 cal yr BP is consistent with reconstructions of regional climates cooler than present (Markgraf 1993; Markgraf et al. 2002). Pollen and lake-level data from the Amazon basin suggests cooler climates during the LGM with average temperatures roughly 4.5-5°C less than present (see Anhuf et al. 2006). Increased ice volume, lowered sea levels, cooler sea-surface temperatures, and decreased atmospheric carbon dioxide, combined with weakened subtropical-high pressure and intensified westerlies, would have contributed to widespread aridity in middle latitudes. In contrast, evidence from the high latitudes of Patagonia (Moreno et al. 1999) suggests the intensification of westerlies resulted in greater-than-present humidity during the LGM. Therefore, cold and wet conditions may have reduced fire activity in the middle and high latitudes of South America.

The charcoal-abundance records from southeastern Australia show a north-south gradient in anomalies of fire activity at 21,000 cal yr BP (Figure 4b), with greater-than-present fire activity to the south and less-than-present fire activity in the north. At the landscape scale, the high fire activity could reflect human activity (Kershaw and Nanson 1993). However, this gradient may also reflect latitudinal gradients in the seasonal cycle of insolation. Average January (austral summer) insolation values at 65°S were similar to present (455 watts m^{-2}) during the LGM (Figure 5b), which promoted greater seasonality in the Southern Hemisphere than during early-Holocene times. High summer insolation may have contributed to relatively dry and warm conditions across the middle latitudes of the Southern Hemisphere. Alternatively, high summer insolation at 65°S (Figure 5b) may have resulted in aridity limiting fuel load and thus contributed to reduced fire activity.

The globally cooler- and drier-than-present climates at 21,000 cal yr BP limited fire activity across the middle and high latitudes of both hemispheres until after 16,000 cal yr BP. The main changes in fire activity after the LGM occurred in the low latitudes of South America and in southeastern Australia. In South America, fire activity increased at sites in southern Brazil while remaining low in western and southern South America. In southeastern Australia, lake level and pollen data suggest enhanced fluvial activity after the LGM (Nanson et al. 2003) and this may help to explain the further decrease in fire activity observed there.

4.2 Interpretation of fire-activity patterns during the deglacial period (ca. 15,000 cal yr BP through 12,000 cal yr BP)

By 15,000 cal yr BP a prominent east-west gradient of charcoal anomalies developed across South America, and there was a significant increase in fire activity throughout Australia and Indonesia (although not Papua New Guinea). In South America, evidence from Lake Titicaca (16-20°S) (Paduano et al. 2003) suggests a rapid climate shift in tropical climates after 17,700 cal yr BP, as fire first appeared but fuels remained limited around the Titicaca basin. The precise timing of tropical climate change and subsequent deglaciation of the central Andes is unclear (Seltzer 2001), and, so the regional controls of fire activity from 11,500 to 21,000 cal yr BP in tropical South America are difficult to identify (Smith et al. 2005). Regional controls of fire activity at 15,000 cal yr BP in South America may be related to their proximity to the oceans and the role of the Andes in reducing moisture advection from the tropical Atlantic (Cook and Vizy 2006). In the mid and high latitudes, late-glacial patterns in fire activity have been attributed to shifts in the position of the westerlies and millennial-scale climate variability (Whitlock et al. 2007; Huber et al. 2003; Moreno 2000). Cool and dry climates in the mid-latitudes likely reduced biomass production resulting in less-than-present fire activity. Lower-than-present sea surface temperatures in the southern Pacific (Lamy et al. 2004) as well as lowered sea level and expanded continental shelves throughout Australasia may have increased continentality and contributed to increased aridity and decreased annual average temperatures.

Regional scale controls of fire activity in southeast Asia, Indonesia, and Australia at 15,000 cal yr BP may be related to lower sea levels (Peltier 1994; 2004)(Figure 5b). Exposed continental shelves were colonized by tropical lowland forest and palynological evidence (Kershaw et al, 2001) suggests greater aridity than during the LGM in the western part of Indonesia than near New Guinea (Hope et al. 2004). Glaciers were likely still present on the highest mountains of New Guinea (Peterson et al. 2002), but increased moisture availability or decreased human activity may explain reduced burning at this time. Haberle and Ledru (2001) suggest that lower land temperatures and the increasing influence of the summer monsoon (Huang et al. 1997) may have contributed to reduced fire activity. Greater-than-present biomass burning 15,000 cal yr BP in southeastern Australia contrasts with the lower-than-present burning in most of South America despite being at similar latitudes. Treeless vegetation was promoted by drier and possibly windier conditions across southeastern Australia following the LGM (Hope et al. 2004). Increased fire activity in Australia 15,000 cal yr BP relative to earlier may have been related to both climate controls and human activity (Black and Mooney 2006; Haberle and David 2004). Fire activity slightly increased in Europe between 15,000 and 12,000 cal yr BP, but remained less than present. Cooler climates and the presence of continental ice sheets in the high latitudes of the Northern Hemisphere may have limited fire activity in northern Europe, but the increasing role of anthropogenic fire for forest clearing may have contributed to increased fire activity at sites in southern Europe.

4.3 Interpretation of fire activity patterns during the early Holocene interval (ca. 11,000 cal yr BP through 7000 cal yr BP)

Dominant influences on global fire activity leading into the early-Holocene interval include the rapidly changing boundary conditions (e.g., Kutzbach et al. 1998) of decreasing ice-sheet size, rising sea-surface temperature and sea level (Peltier 2004), and vegetation changes (Williams et al. 2004; Huntley and Birks 1983), including reforestation of regions formerly covered by glacial ice. Greater-than-present summer insolation resulted in warmer and drier summers in regions of the Northern Hemisphere influenced by stronger-than-present subtropical high pressure. Regional summaries of fire activity suggest increased spatial heterogeneity during this interval with marked shifts in all regions toward either stronger positive or negative anomalies in fire activity (Figure 5a and 5b). Records from North America, Europe and South America show shifts toward increased fire activity while records from Australia show shifts toward decreased burning culminating around 10,000 yr BP. In southern South America and western North America, these patterns have been attributed to the regional changes caused by increased annual and summer insolation (in the North Hemisphere) and increased annual and winter insolation (in the Southern Hemisphere) in the early Holocene (Whitlock et al.,2007; Whitlock and Bartlein,2004). These large-scale changes in the climate systems would have affected regional circulation patterns, including the strength and position of the westerlies, the strength of the monsoons and subtropical highs, and ultimately the duration of the fire season.

In southern Europe, evidence from Lago Piccolo di Avigliana and Lago di Origlio suggests increased fire activity starting from ~10,500 cal yr BP (Finsinger et al. 2006). A non-linear response of vegetation to higher drought stress and fire activity resulted in the expansion of *Corylus* (hazel), which re-sprouts after fire events (Delarze et al. 1992; Tinner et al. 1999) and is more drought-tolerant than other deciduous trees (Huntley 1993; Finsinger et al. 2006).

Increasing fire activity in the Northern Hemisphere and South America can also be compared with records of atmospheric carbon dioxide from Antarctica (Indermühle et al. 1999) (Figure 5b). Increased CO_2 after 12,000 cal yr BP may be related to increasing fire activity in the tropics and high latitudes of South America as well as temperate and boreal ecosystems of the Northern Hemisphere. Recent evidence suggests global fire activity may also contribute to atmospheric methane (van Aardenne et al. 2001; Andreae and Merlet 2001; van der Werf et al. 2007). Methane records from the GISP2 ice core also reveal increased variability around 12,000 cal yr BP (Figure 5b), and have been partly explained by high latitude summer insolation forcing (Brook et al. 1996) and developing boreal peatlands (MacDonald et al. 2006) but there may also be linkages to increased fire activity. In addition to these climate explanations, human populations were increasing in the Americas and may have locally contributed to the changing role of fire activity (Cook 1998). In tropical Central and southern South America, fire activity was also beginning to decrease by 9000 cal yr BP. A record of decreasing atmospheric carbon dioxide from Taylor Dome, Antarctica (Monnin et al. 2001; Indermühle et al. 1999) during the early Holocene may be linked to the reduction in fire activity throughout the Americas, Africa, Indonesia and Australia. Low fire activity during the early Holocene in Indonesia and Papua New Guinea (Haberle and Ledru 2001) and eastern Australia (Black and Mooney 2006) has previously been attributed to a relatively stable climate at that time. Whereas the first agricultural activities, beginning around 10,000 cal yr BP, in the Near East (Gupta 2004) and possibly China may have influenced records of fire activity within those regions.

4.4 Interpretation of fire activity patterns from 6000 cal yr BP to present

The middle to late Holocene was a period of changing large-scale controls of fire activity as summer insolation decreased in the Northern Hemisphere (but increased in the Southern Hemisphere) most glacial ice had disappeared, and sea levels were approaching near-modern position (Figure 5b). The climate system was switching to modern boundary conditions and a shift in the predominant controls of fire activity. In addition, increasing human populations may have had a localized role in modifying the fire regimes in certain locations.

Combined climatic and human controls may have shifted vegetation types (and thus fuel type) and disturbance regimes by 6000 cal yr BP. For example, in Australia, a period of maximum precipitation between 7000 to 5000 cal yr BP (Harrison and Dodson 1993) may have been responsible for reduced fire activity at 6000 cal yr BP. Throughout Indonesia and New Guinea, Haberle and Ledru (2001) report increased fire activity related either to increased variability in El Nino/Southern Oscillation (ENSO) and the related Walker circulation or to the increased role of agricultural activities after 6000 cal yr BP. Black and Mooney (2006) related similar increases to modern ENSO phenomena. Elsewhere, Tinner et al. (1999) report increased fire activities in the European Alps for the period 7000-5000 cal yr BP that resulted from combined effects of intensified land-use activities and centennial-scale shifts to warmer and drier climatic conditions.

By 3000 cal yr BP, dominant controls of fire activity were similar to modern. Despite similar-to-present climate, however, fire activity was greater than present in the mid-latitudes of Eurasia and summer-wet regions of the western United States (Whitlock and Bartlein 2004; Marlon et al. 2006). Progressively decreasing summer insolation in the Northern Hemisphere through the Holocene apparently reduced fire activity by 3000 cal yr BP compared with that at 6000 cal yr BP, but in other regions weakening of early-mid Holocene monsoons led to greater-than-present fire activity (Whitlock and Bartlein 2004). Greater heterogeneity in fire patterns in mid and southern South America at 3000 cal yr BP has been attributed to the onset or strengthening of ENSO and increased human populations (Whitlock et al. 2007). Heavily populated regions of eastern New Guinea, eastern Australia and New Zealand show less-than-present fire activity, possibly a result of ENSO's greater influence in recent millennia. In contrast, greater-than-present fire activity across Eurasia, where Bronze and Iron Age populations used fire as a tool for deforestation, may explain greater-than-present fire activity during the late Holocene. Most records from Indonesia and Australasia show near modern or less-than-present fire activity around 3000 cal yr BP.

5.0 Conclusions

Time-slice anomaly maps of fire activity from the LGM to present illustrate the changing importance of fire as a global phenomenon. These records can be interpreted in terms of changes in biomass burning and imply that climatically-determined changes in fire regimes could have had significant impacts on the global carbon budget through time. The two most important signals shown by the charcoal records, when considered globally, are (a) the monotonic increase in biomass burning between the LGM and present, and (b) the shift from low to high spatial heterogeneity in fire activity ca 12,000 cal yr BP.

The relatively few charcoal records for the LGM show a consistent pattern of low fire activity (Figure 4), characterizing the glacial interval from 21,000 through 16,000 cal yr BP. This pattern is not surprising given that the climate was globally colder and drier than at present resulting in an overall reduction in terrestrial biomass (Francois et al. 2000) and thus a decrease in fuel availability. With the waning of the Northern Hemisphere ice sheets, and the expansion of the terrestrial vegetation, our charcoal-based reconstructions show that fire activity generally increased towards the present (Figure 4a-h, 5a-b).

The charcoal records show an apparent increase in the spatial heterogeneity of the charcoal deposition from the LGM towards the present. This can be explained to some extent by the increase in the number of records over time. Examination of the patterns in regions with comparable densities of sites at 15,000 and 12,000 cal yr BP (i.e. northwestern North America, southern South America, southeastern Australia), however, suggests that the spatial patterns of charcoal anomalies were indeed more homogeneous in late-glacial times than later. The increased spatial heterogeneity may also reflect the transition away from the glacial state: during the glacial, the overall reduction in biomass was a severe constraint on fire regimes but during the later part of the deglaciation, as temperatures rose, regional responses to climate and climate-induced changes in vegetation cover overwhelmed the global signal and spatial heterogeneity increased.

Despite the considerable spatial heterogeneity in fire regimes during the period since ca 12,000 cal yr BP (at the continental and global scales), there is nevertheless regional coherency at sub-continental and regional scales that appear to be explained by direct climate controls and the indirect effects of climate changes on vegetation cover and fuel loading. The dominant controls of fire activity are temporally variable and have been changing on millennial timescales since the LGM. For example, widespread cool dry climatic conditions coupled with reduced biomass were important controls regulating fire activity in the LGM. In contrast, with respect to the Northern Hemisphere, increased seasonality and biomass regulated early Holocene fire activity whereas decreased seasonality, coupled with increased human activity, were important regulators of fire in the late Holocene. Thus, our original hypothesis that spatial coherency reflects large-scale climate control of fire, whilst increased heterogeneity indicates more proximal controls of fire, both climatic and anthropogenic, has not been refuted.

We have focused predominately on the role of climate rather than human intervention in modulating past fire activity, although studies of individual regions suggest that humans may have played a role, especially during the latter part of the Holocene (e.g., Horn 2007). There is a general positive relationship between human population and fire incidence during the late Holocene (Mouillot and Field 2005, and references therein). For example, frequent fires in parts of Scotland during the late Holocene have been attributed to human activity (Tipping and Milburn 2000) as well as to the expansion of fire-prone blanket mire vegetation (Froyd 2006). In southern Scandinavia, microscopic charcoal accumulation rates (Berglund et al. 1991) and macro-charcoal under and within clearing cairns (Lagerås 2000) were related to forest clearings by humans from 6000 cal yr BP, but especially from 3000 cal yr BP. In central and southern Europe, fires were intentionally set to disrupt forests and gain open areas for arable and pastoral farming (Tinner et al. 2005). After disruption of forests by fire, controlled burning was used to maintain open areas for agricultural purposes. Similarly, in Central America, late Holocene fire activity has been closely tied to human activity (Horn 2007). An analysis of the role of human activities, in causing and in suppressing fire during recent millennia, requires a better understanding of changes in fire regime and cultural development than is currently available for most regions of the world.

The palaeofire reconstructions presented here offer a unique opportunity to validate models of the coupled behaviour of vegetation and fire (Marlon et al., in prep). Successful simulation of past changes in fire regimes is an integral part of assessing whether we can predict future changes in biomass burning in a realistic way. This, in turn, has implications for maintaining biodiversity, addressing issues of climate change, and assisting governmental agencies in developing appropriate fire management policies. Model-validation exercises necessarily depend on the quality and quantity of palaeodata available (Kohfeld and Harrison, 2000). While extensive, the current version of the charcoal database has marked spatial heterogeneity in sample site distribution. Some regions such as North America contain a relatively high number of sites whereas many Old World regions are generally less well represented. Additional sampling in regions inadequately represented is necessary to ensure that the spatio-temporal coverage of the current charcoal database is sufficient for meaningful data-model comparison.

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The version of the charcoal database (GCD, V1) used for this paper is available from British Atmospheric Data Center (BADC) (http://badc.nerc.ac.uk/home/index.html) and from the Global Palaeofire Working Group (GPWG) website (http://www.bridge.bris.ac.uk/projects/QUEST_IGBP_Global_Palaeofire_WG).

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Figure Captions:

Figure 1: Inventory of global charcoal records currently used in the analysis (gray dots) and regional delineations (black boxes) where sites were averaged together for regional summaries of fire activity (see Figure 5a).

Figure 2: Scatter diagram for all charcoal concentration (particles/cm^{-3}) values contained within the database. Three types of depositional environments are represented; gray circle represent lake sediment records, open diamonds are from bog sediment records, and dark triangles are from soil charcoal records. All data are plotted by original charcoal units, illustrating the heterogeneity of analytical methods and laboratory techniques used to show charcoal-abundance variations through time. The >10 orders of magnitude represented by charcoal concentration values illustrates the need for standardization of these data.

Figure 3: An example of charcoal standardization performed on all charcoal records contributing to the global paleofire database. The original charcoal abundance (from Millspaugh et al., 2000) values (a) for each record were rescaled (b) to range from 0.0 to 1.0 over the whole of the record, the rescaled values (c) were then transformed using the Box-Cox power transformation to approach normality (d) where possible, with the transformation parameter estimated using the maximum likelihood. The transformed values were then standardized or converted to Z-scores (e) using the mean and standard deviation for each record over the interval (base period) from 4000 to 100 cal yr BP. Anomaly Z-scores, or differences in charcoal values between the "modern", defined as between 1000 to 100 cal yr BP, and the base period (f) were then calculated for each record.

Figure 4: (a) Global map of mean Z-scores of charcoal values for 1000 to 100 cal yr BP illustrates sites that have higher (red) or lower (blue) average charcoal values during the last millennia when compared to the last four millennia. The global anomaly maps (b-h) at 3000-yr time slices, beginning at 21,000 through 3000 cal yr BP, permit comparisons of change in charcoal accumulation relative to present (1000 to 100 cal yr BP). The anomaly maps reveal both the considerable spatial heterogeneity as well as regional coherencies of global charcoal.

Figure 5: Global and regional summaries of average anomaly Z-scores of charcoal values. (a) The number of sites (gray line) contributing to each regional summary (see Figure 1) are compared to the regional average anomaly Z-scores (black line), revealing the potential influence of increasing sites for each regionally averaged time series. Periods within the time slices of positive charcoal anomalies relative to present are shaded gray. Large charcoal anomalies that extend beyond the +2 or -2 are indicated by circled arrows. (b) Regional summaries are grouped by similar latitudes and compared with summer insolation (gray line) at 65°N and S for the high latitude sites and average annual insolation for the circum-equatorial sites (Beger, 1991). Atmospheric carbon dioxide concentrations are shown from Taylor Dome,Antarctica ice core records (Indermühle et al., 1999, 2000; Monnin et al., 2001) and a methane record from GISP2 (Brooks et al.,

1996). Contributions to eustatic sea-level rise (Peltier 2004, Ice-5G) are also shown for comparisons with global charcoal values.

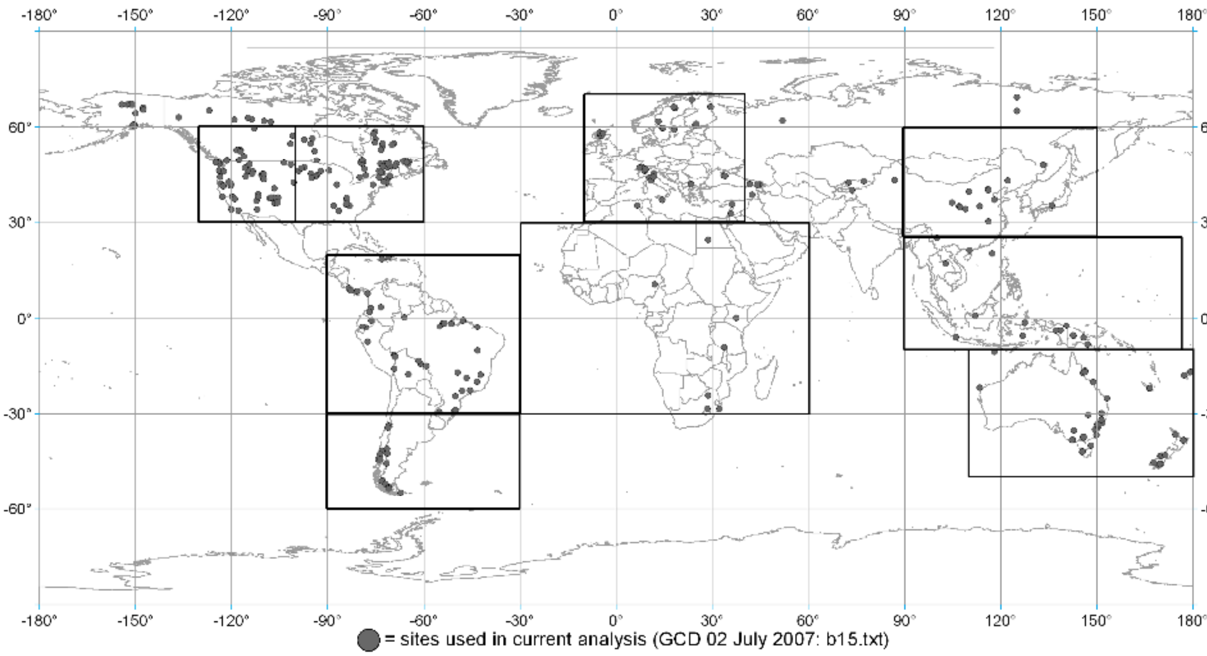

Figure 1

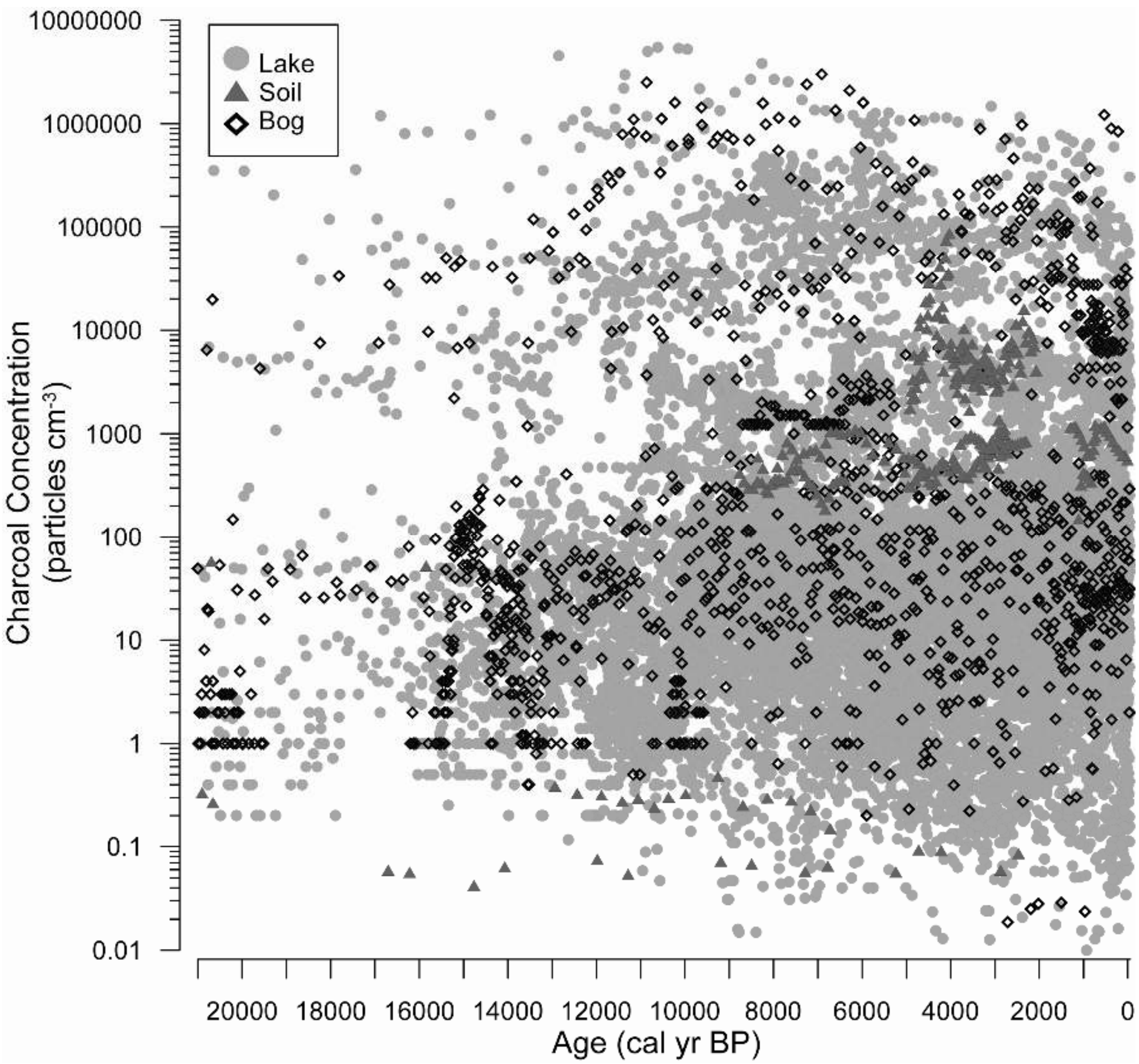
Lake
Soil
Bog
10000000
1000000
100000
10000
1000
100
10
1
0.1
0.01
Charcoal Concentration (particles cm-3)
20000 18000 16000 14000 12000 10000 8000 6000 4000 2000 0
Age (cal yr BP)

Figure 2

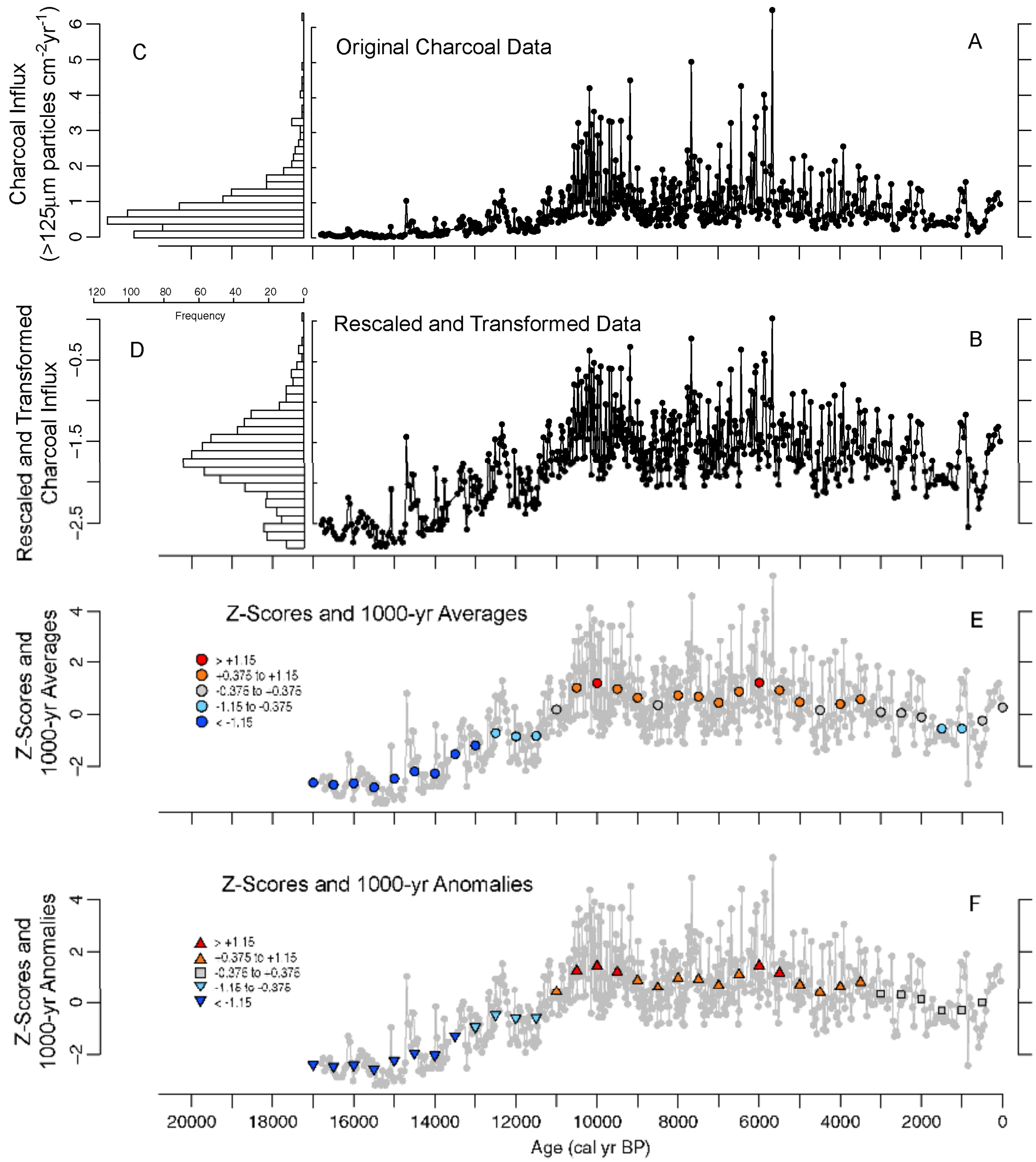
Charcoal Influx
(>125µm particles cm-2yr-1)
C
Original Charcoal Data
A
120 100 80 60 40 20 0
Frequency
Rescaled and Transformed
Charcoal Influx
D
Rescaled and Transformed Data
B
Z-Scores and
1000-yr Averages
Z-Scores and 1000-yr Averages
E
> +1.15
+0.375 to +1.15
-0.375 to -0.375
-1.15 to -0.375
< -1.15
Z-Scores and
1000-yr Anomalies
Z-Scores and 1000-yr Anomalies
F
> +1.15
+0.375 to +1.15
-0.375 to -0.375
-1.15 to -0.375
< -1.15
20000 18000 16000 14000 12000 10000 8000 6000 4000 2000 0
Age (cal yr BP)

Figure 3

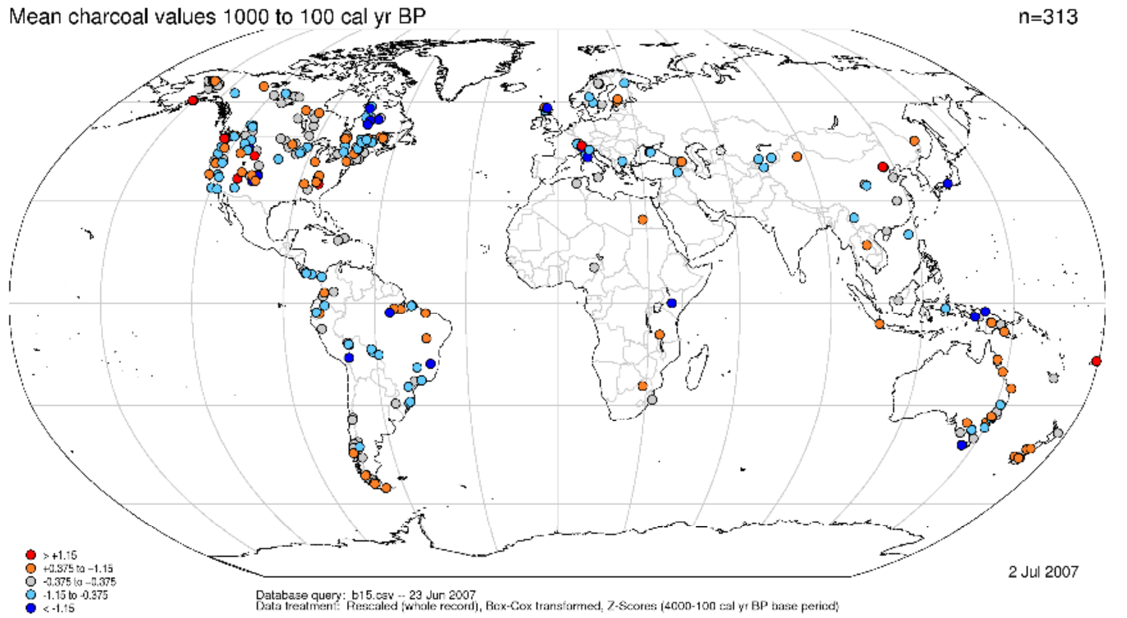

Figure 4a

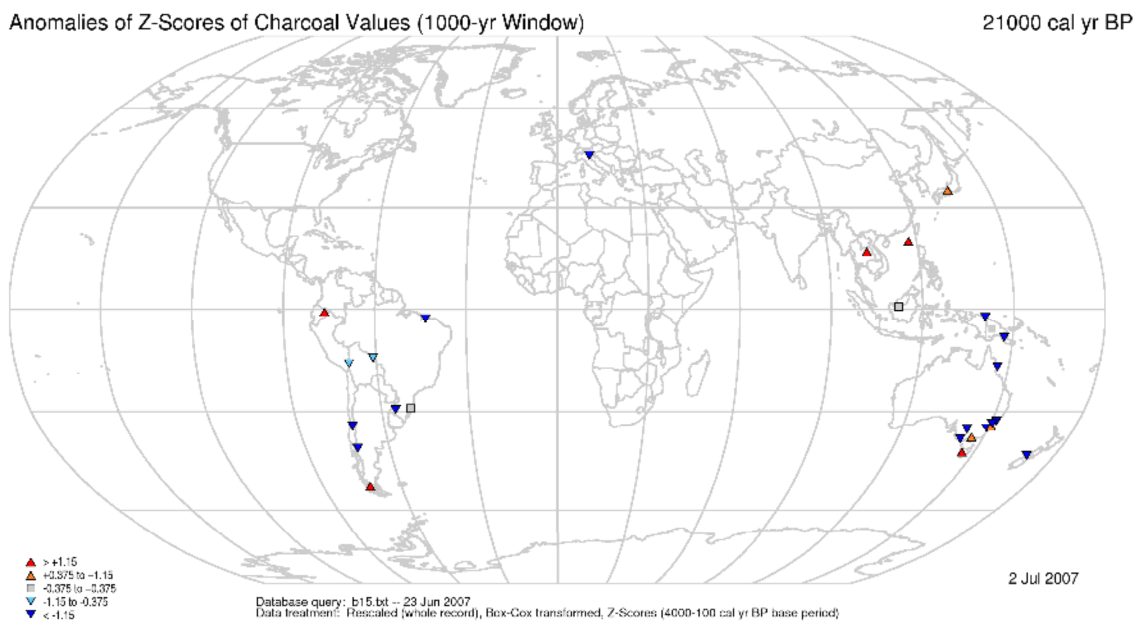

Figure 4b

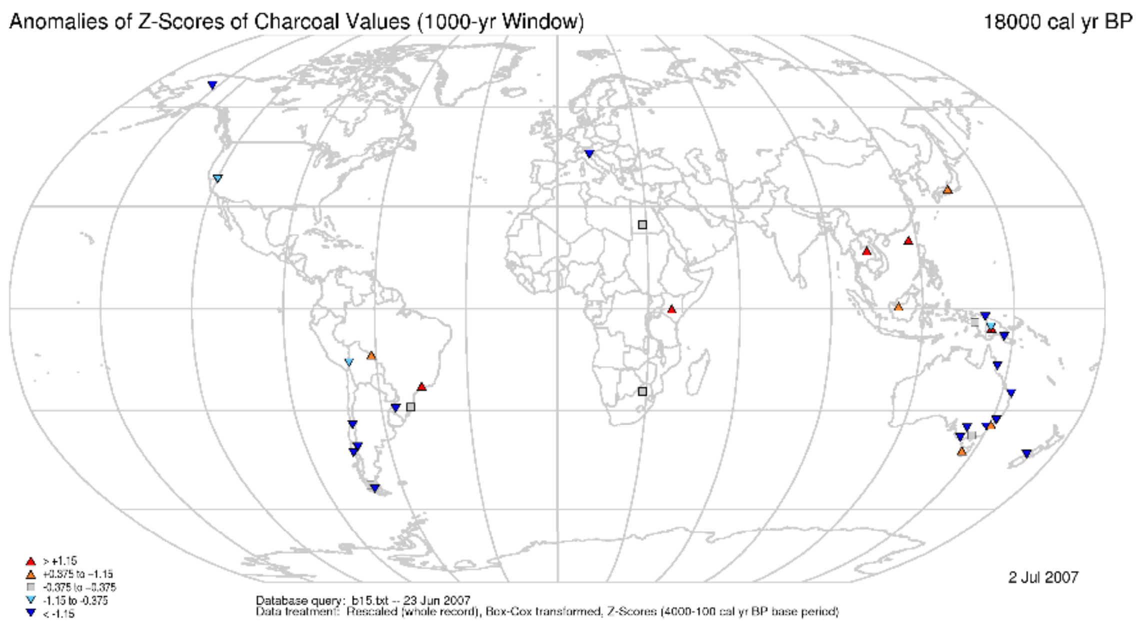

Figure 4c

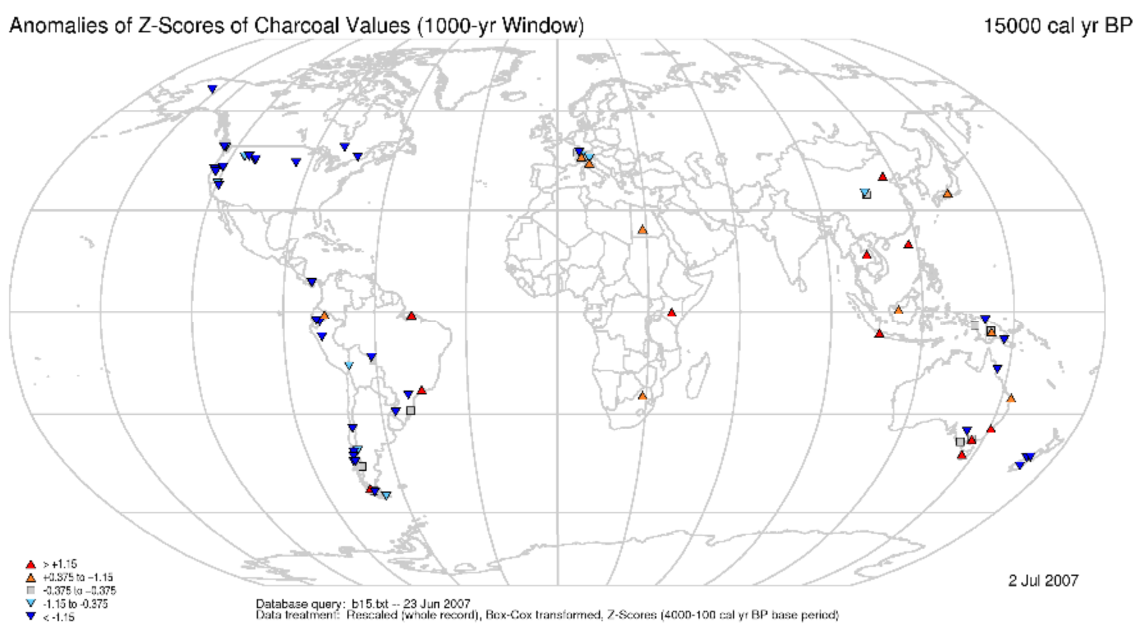

Figure 4d

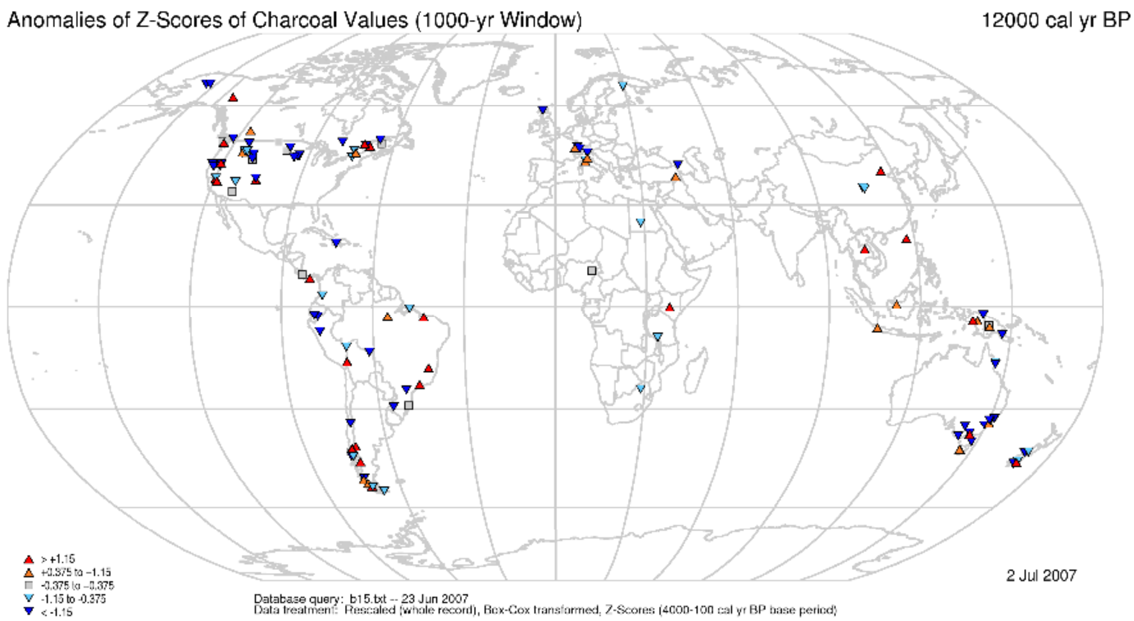

Figure 4e

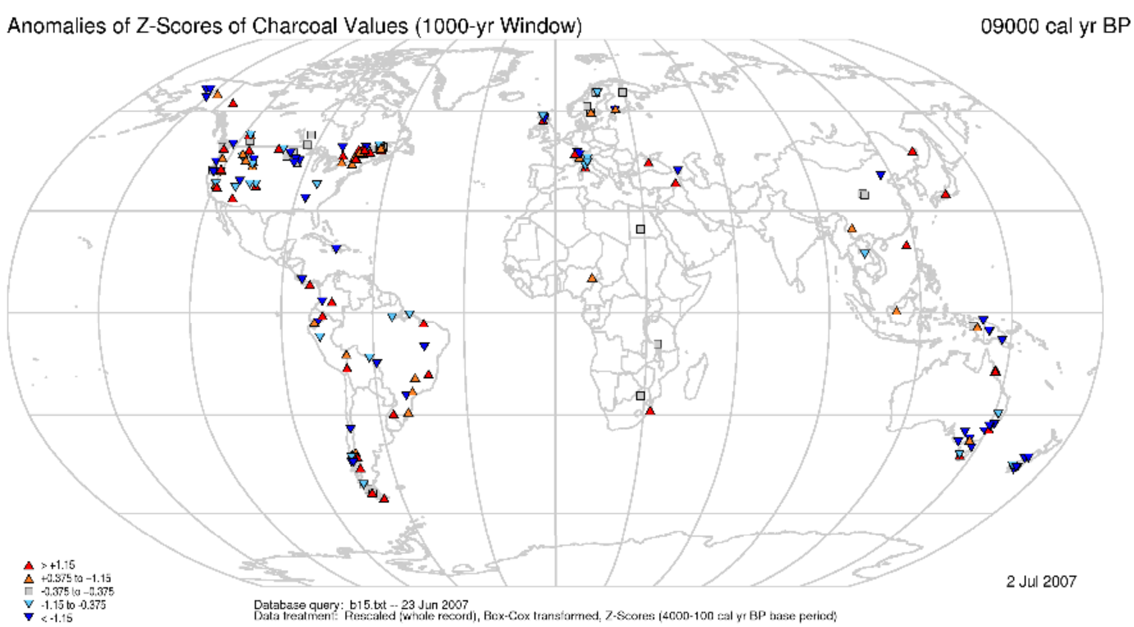

Figure 4f

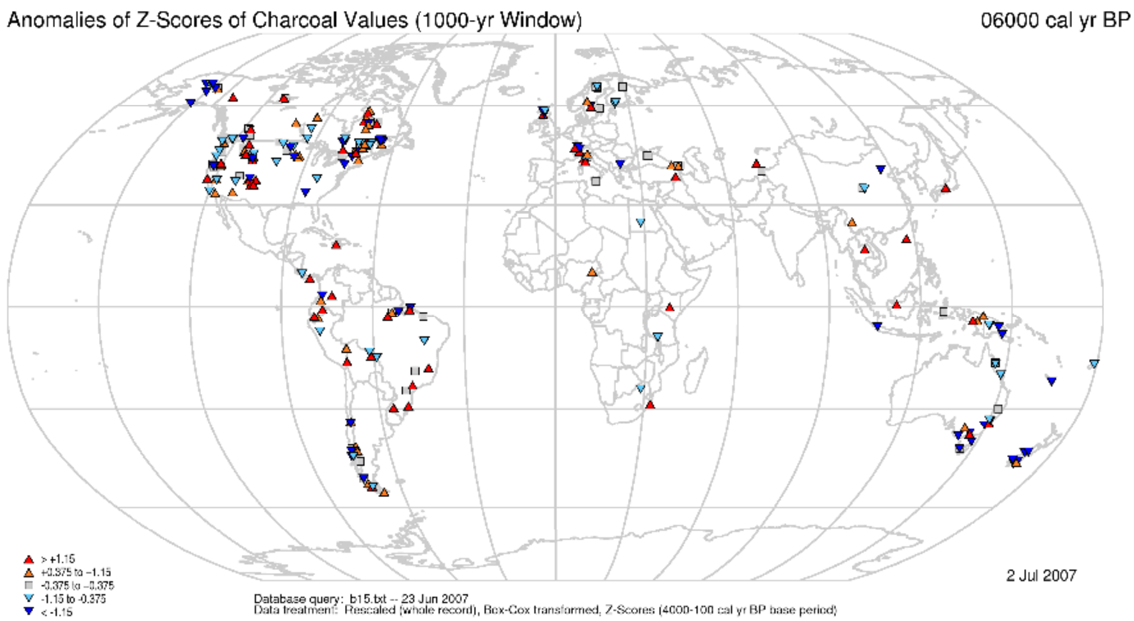

Figure 4g

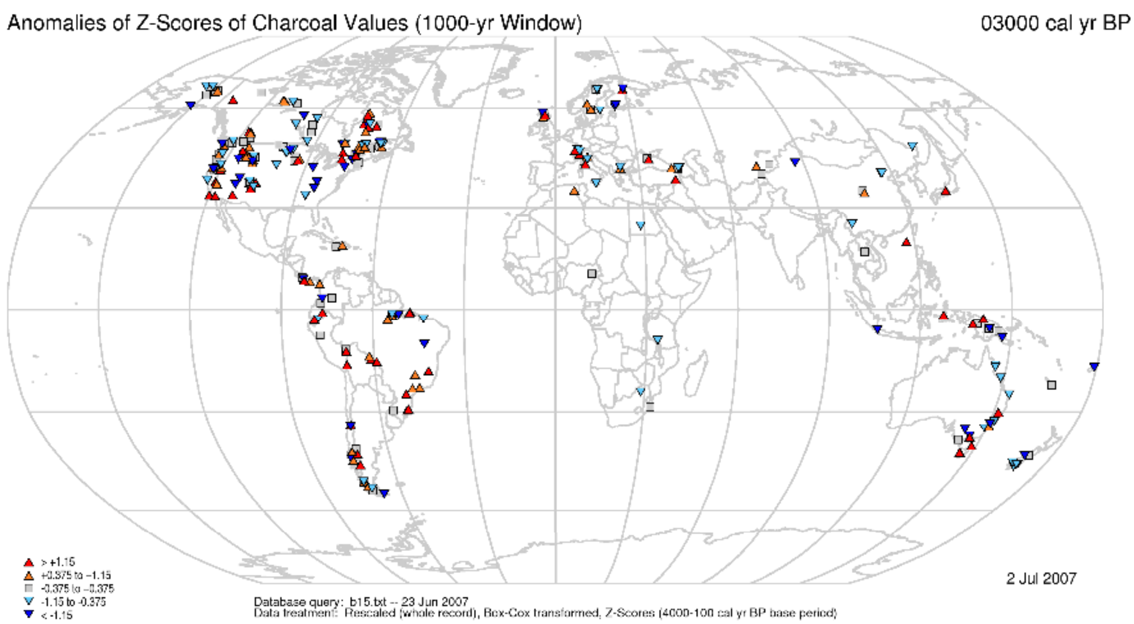

Figure 4h

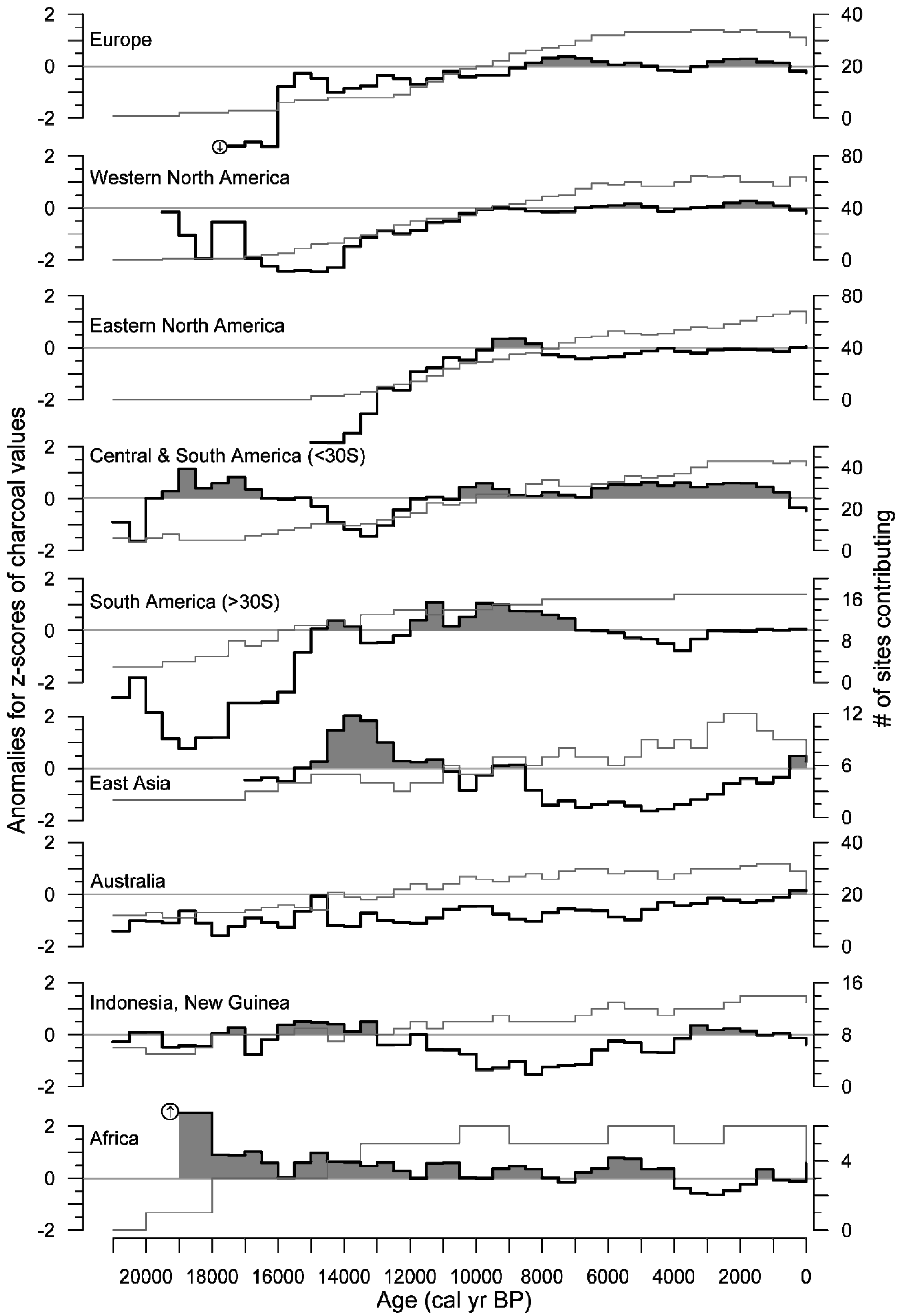
Europe
Western North America
Eastern North America
Central & South America (<30S)
South America (>30S)
East Asia
Australia
Indonesia, New Guinea
Africa
Anomalies for z-scores of charcoal values
# of sites contributing
20000 18000 16000 14000 12000 10000 8000 6000 4000 2000 0
Age (cal yr BP)

Figure 5a

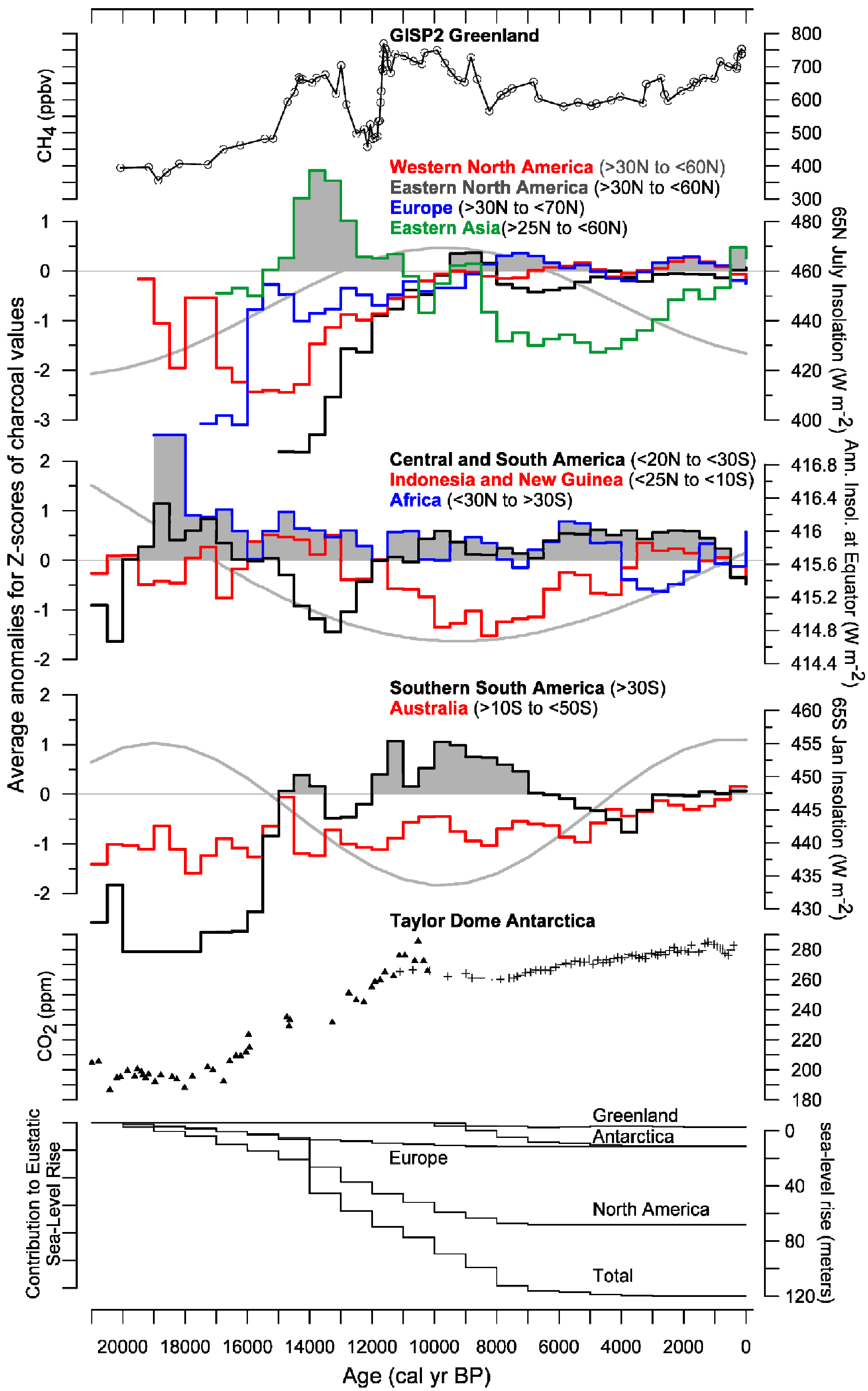
GISP2 Greenland
CH4 (ppbv)
Western North America (>30N to <60N)
Eastern North America (>30N to <60N)
Europe (>30N to <70N)
Eastern Asia(>25N to <60N)
65N July Insolation (W m-2)
Central and South America (<20N to <30S)
Indonesia and New Guinea (<25N to <10S)
Africa (<30N to >30S)
Ann. Insol. at Equator (W m-2)
Southern South America (>30S)
Australia (>10S to <50S)
65S Jan Insolation (W m-2)
Average anomalies for Z-scores of charcoal values
Taylor Dome Antarctica
CO2 (ppm)
Greenland
Antarctica
Europe
North America
Total
Contribution to Eustatic Sea-Level Rise
sea-level rise (meters)
Age (cal yr BP)

Figure 5b