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Fire and ecosystem change in the Arctic across the Paleocene–Eocene Thermal Maximum

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ABSTRACT

Fire has been an important component of ecosystems on a range of spatial and temporal scales. Fire can affect vegetation distribution, the carbon cycle, and climate. The relationship between climate and fire is complex, in large part because of a key role of vegetation type. Here, we evaluate regional scale fire–climate relationships during a past global warming event, the Paleocene–Eocene Thermal Maximum (PETM), in order to understand how vegetation influenced the links between climate and fire occurrence in the Arctic region. To document concurrent changes in climate, vegetation, and fire occurrence, we evaluated biomarkers, including polycyclic aromatic hydrocarbons (PAHs), terpenoids, and alkanes, from the PETM interval at a marine depositional site (IODP site 302, the Lomonosov Ridge) in the Arctic Ocean. Biomarker, fossil, and isotope evidence from site 302 indicates that terrestrial vegetation changed during the PETM. The abundance of the C_{29} *n*-alkanes, pollen, and the ratio of leaf-wax *n*-alkanes relative to diterpenoids all indicate that proportional contributions from angiosperm vegetation increased relative to that from gymnosperms. These changes accompanied increased moisture transport to the Arctic and higher temperatures, as recorded by previously published proxy records. We find that PAH abundances were elevated relative to total plant biomarkers throughout the PETM, and suggest that fire occurrence increased relative to plant productivity. The fact that fire frequency or prevalence may have increased during wetter Arctic conditions suggests that changes in fire occurrence were not a simple function of aridity, as is commonly conceived. Instead, we suggest that the climate-driven ecological shift to angiosperm-dominated vegetation was what led to increased fire occurrence. Potential increases in terrestrial plant biomass that arose from warm, wet, and high CO_2 conditions were possibly attenuated by biomass burning associated with compositional changes in the plant community.

1. Introduction

Many climate modeling studies predict increases in wildfire activity in future decades associated with globally warming climates and shifting hydrologic patterns. Even so, mechanisms controlling fire patterns are complex and the primary controls are not always clear (Hessl, 2011). Today, increased atmospheric CO_2 concentrations, higher temperatures, and longer dry seasons are associated with increases in fire activity in the western USA (Westerling, 2006). However, shifts in vegetation (e.g., type, abundance, structure, and continuity) can override the influence of warmer and drier conditions (Higuera et al., 2014). In addition, most empirical evidence, which is also the basis of many models, covers centen-

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Abbreviations: carbon isotope excursion, CIE; cyclization of branched tetraether, CBT; dichloromethane, DCM; glycerol dialkyl glycerol tetraether, GDGT; mass spectrometer, MS; mean annual temperature, MAT; methylation of branched tetraether, MBT; Paleocene–Eocene Thermal Maximum, PETM; polycyclic aromatic hydrocarbon, PAH; pristane, Pr; phytane, Ph; total lipid extract, TLE; total organic carbon, TOC.

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nial scales (or less), and may not readily translate to climate–vegetation–atmospheric CO_2 relationships recorded in the paleorecord on 1000 to 10,000 yr scales (Hessl, 2011). Records of fire occurrence during past major warming events, such as the Paleocene–Eocene Thermal Maximum (PETM), can potentially elucidate fire dynamics during abrupt and extreme warming, and provide insights relevant to anticipating climate, vegetation, and fire associations under future climate scenarios.

The PETM was a geologically abrupt period of global warming that occurred approximately 55.5 million yrs ago (Westerhold et al., 2012). This climatic event is widely invoked as a geologic analog for modern climate change, even though modern carbon release (∼10 Pg C/yr) may be 10 times faster (Cui et al., 2011). The hyperthermal event is marked by a negative carbon isotope excursion (CIE), signifying a major perturbation to the carbon cycle (McInerney and Wing, 2011, and references therein). At least 3000 Pg of ^{13}C-depleted carbon was released into the atmosphere over ∼10,000 yrs and global temperatures rose ∼5–8 °C over ∼170,000 yrs (Cui et al., 2011; McInerney and Wing, 2011; Peterse et al., 2012; Sluijs et al., 2006; Weijers et al., 2007; Wing et al., 2005). Concurrently, there were dramatic shifts in vegetation and precipitation patterns around the world (Kraus and Riggins, 2007; Pagani et al., 2006; Wing et al., 2005; Wing and Currano, 2013).

For example, in the Bighorn Basin, Wyoming, USA, where there has been extensive plant fossil research, flora shifted considerably during the PETM (McInerney and Wing, 2011; Wing and Currano, 2013). Plants that are typically adapted to intermediate moisture levels (particularly conifers) decreased, and thermophilic and dry-tolerant species (particularly Fabaceae (legumes)) surged in abundance (Wing and Currano, 2013). Hence, the western USA flora during the PETM was most similar to dry tropical forests.

Despite some regional variations, generally flora expanded toward higher latitudes, such as was observed in the Bighorn Basin (Wing and Currano, 2013). In the Arctic, pollen counts and biomarkers indicate that angiosperm abundance increased at the expense of gymnosperms (Schouten et al., 2007; Sluijs et al., 2006), while moisture transport increased, as suggested by changes in the δD of *n*-alkanes (Pagani et al., 2006).

Boucsein and Stein (2009) analyzed characteristics of organic particles, or macerals, in Arctic Ocean sediments (Integrated Ocean Drilling Program (IODP) site 302) from the late Cretaceous to the Eocene. Based on changes in the proportion of inertinite (regarded as an indicator of fire occurrence) relative to other terrigenous and aquatic macerals, the authors suggested that greater inputs of burned vegetation were deposited in the marine sediments during the Paleocene relative to the PETM and early Eocene.

Moore and Kurtz (2008) examined graphitic black carbon, a combustion byproduct, from two IODP sites: site 1210 (Shatsky Rise) and the Bass River section (New Jersey Margin). At Shatsky Rise, black carbon concentrations were below detection (<0.5 ppm), while at the New Jersey Margin, there was no clear pattern in black carbon flux at the onset or during the CIE. Carbon isotope analyses of black carbon revealed a ∼3.5‰ negative CIE, which linked burned material to PETM biomass, rather than burning of older Paleocene peat or coal (Moore and Kurtz, 2008).

Collinson et al. (2009) linked a shift in fire regime to changes in vegetation composition across the PETM in England. Late Paleocene samples, from the Cobham Lignite Bed in southern England, were dominated by charcoal associated with episodic fires and by fern spores, which suggested a low diversity, fire-prone community mainly composed of ferns and woody angiosperms. The PETM vegetation was characterized by a loss of ferns, an increase in wetland plants, and decreased fire occurrence. This study highlights the importance of vegetation (e.g., composition and fire-prone species) in determining fire propensity. Given the global geographic and compositional changes in PETM vegetation, which are often linked to precipitation and temperature patterns, predictions of fire occurrence are not easily extrapolated from changes in the quantity of biomass and aridity.

The concept of biomass and aridity as key fire drivers has its roots in fire history reconstructions of the past decades to 21,000 yrs, mainly derived from sedimentary charcoal and tree ring fire scar analyses. These reconstructions provide information regarding fire frequency, fire extent, and the timing of past fires in relation to climate (Daniau et al., 2012; Margolis and Balmat, 2009). The records reveal complexity and that multiple factors influence the relationship between fire occurrence and climate. But overall and in simplified terms, wet periods allow for the buildup of biomass (fuel) and dry periods facilitate the burning of vegetation (fuel availability). Increased precipitation can result in opposite effects on the susceptibility to fire depending on the initial wetness of the environment. In relatively wet environments that are likely not limited by fuel abundance, precipitation increases fuel moisture and dampens fire occurrence; in dry environments that are fuel-limited, precipitation increases the amount of fuel and increases the ecosystems tendency toward fire (Daniau et al., 2012).

The length of wet and dry periods can also have different effects on fire occurrence depending on fuel type. Holocene fire frequency records in the western USA indicate that enhanced seasonality and anomalously wet years followed by anomalously dry years promoted fire conditions for vegetation with annual fuel production, such as grass (Margolis and Balmat, 2009). Other studies have suggested that extended dry periods led to widespread fires, such as the 1997 Indonesian fires that spread wildly during the long El Niño dry season, likely because heavier fuels (e.g., branches and logs) respond to humidity changes more slowly than finer fuels (e.g., grass and small twigs) (Page et al., 2002). Alternatively, during long-term droughts, fire occurrence can decrease if there is insufficient biomass to burn (Flannigan et al., 2009).

Changes in vegetation type can modify the link between climate and fire by affecting, for example, the abundance, structure, and moisture content of fuels (Higuera et al., 2014). In ecosystems with dense, continuous vegetation, fire occurrence is limited by climatic conditions that facilitate the drying of fuels. In contrast, in systems with low biomass abundance or discontinuous fuels, fire occurrence can be limited by the scarcity of burnable materials, even if climate conditions may have been conducive for fire (Higuera et al., 2014).

From the analysis of a global compilation of charcoal records covering the last 21,000 yrs, Daniau et al. (2012) found an overall increase in fire occurrence with increased temperature. Such findings tend to influence studies of ancient climate, and authors often postulate that hotter and drier conditions likely increased fire occurrence (Secord et al., 2010; Wing et al., 2005).

Pyrogenic carbon is a continuum of combustion products generated as solid residue or volatiles, ranging from slightly charred material to soot (Knicker, 2011; von Lützow et al., 2006). Polycyclic aromatic hydrocarbons (PAHs), which are part of this continuum, are byproducts of combustion released as volatiles and in association with particles. In the sedimentary record, changes in PAH concentrations are usually interpreted to indicate changes in fire occurrence, with more PAHs linked to increased fire occurrence (e.g., Marynowski and Simoneit, 2009; Denis et al., 2012). Aromatic structures tend to make pyrogenic carbon, including larger PAHs (≥5 rings), relatively resistant to degradation in soil environments and marine sediments (Knicker, 2011; von Lützow et al., 2006). For example, charcoal, another byproduct of fire, has a relatively long residence time in modern soils, estimated on the order of 500–10,000 yrs, and in marine sediments with oxygen exposure, 10,000–20,000 yrs (Knicker, 2011; von Lützow et al., 2006).