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Disentangling the roles of late Miocene palaeogeography and vegetation – Implications for climate sensitivity

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ABSTRACT

The impact of rising CO_2 on future climate remains uncertain but the evidence for high CO_2 in the palaeorecord suggests that past climates could provide a potentially quantifiable indication of climate in a high-CO_2 world. One such past time period is the late Miocene (11.6–5.3 Ma), for which CO_2 reconstructions indicate higher levels than those of preindustrial, and similar to the present atmospheric level (~400 ppm). The late Miocene palaeorecord suggests a much warmer and wetter Northern Hemisphere than preindustrial. However, vegetation feedbacks are an important component of the climate system and vegetation distribution reconstructions from the palaeorecord have been shown to be very different to the present vegetation distribution. We examine the roles that different vegetation and palaeogeography play in climate sensitivity for the late Miocene and consider the implications for potential future climate change. To do this we use coupled atmosphere-ocean-vegetation simulations of late Miocene and potential modern climates forced by three different CO_2 concentrations with vegetation perturbation experiments and make quantitative comparisons to the palaeorecord. Optimal regions to target late Miocene palaeodata acquisition for the purposes of informing about future climate include North America, northern Africa, Australia, Paraguay and southern Brazil, and northeastern Asia. These regions are those which the model results predict to be most sensitive to CO_2 forcing, but where the local temperature response to CO_2 forcing is similar between the simulated potential modern and late Miocene climates. The model results suggest that climate sensitivity to CO_2 forcing is directly affected by the palaeogeographic configuration and that the inferred climate sensitivity for doubled CO_2 is 0.5–0.8 °C higher for the late Miocene than we might expect for future climate because of differences in synergy. The greater land mass at high northern latitudes during the late Miocene and the differences in vegetation distribution predictions that result, combined with differences in ocean circulation and the effect of sea ice, make the late Miocene boundary conditions more sensitive to CO_2 forcing than the modern boundary conditions.

1. Introduction

Reconstructions of late Miocene (11.6–5.3 Ma) CO_2 range from 144 to 1350 ppm but most data suggest CO_2 levels were between preindustrial (280 ppm) and modern (400 ppm) concentrations (Demicco et al., 2003; Freeman and Hayes, 1992; Kurschner et al., 2008; Kurschner et al., 1996; Pagani et al., 1999a,b, 2010; Pearson and Palmer, 2000; Tripati et al., 2011; Zhang et al., 2013; and see Fig. 1 of Bradshaw et al., 2012). The palaeorecord also suggests that, for regions with abundant late Miocene data (in southern Europe and in central and southern Asia), the climate was generally hotter and/or wetter than today (Bruch et al., 2007; Eronen et al., 2010; Pound et al., 2012; Pound et al., 2011; Utescher et al., 2011; and see Figs. 7 and 11 of Bradshaw et al., 2012). The fact that the late Miocene climate was warmer and wetter than today is consistent with the fact that our modern climate has not yet reached equilibrium with our present atmospheric CO_2 concentration (Stocker et al., 2013), However, there could also be underlying differences in climate sensitivity between these two time periods due to differences in the continental and orographic configuration.

In order to use past warm climates to infer potential future climate change, it is important to establish the dependence of feedbacks (and therefore climate sensitivity) on the background climate state (Rohling et al., 2012). Consistent intercomparisons that separate out understanding of climate dynamics due to CO_2 forcing from other potential contributors such as paleogeography (continental positions, ocean gateways and continental ice extent), and associated feedbacks, are therefore essential. Previous work using extensive model-data comparisons suggests that CO_2 rather than paleogeography was the primary driver of late Miocene warmth (Bradshaw et al., 2012) but did not separate out the effects of vegetation. This study focuses on the role of vegetation in determining late Miocene climate and how palaeogeographic differences might affect the vegetation distribution and the sensitivity to CO_2 forcing. We show that palaeogeography is very important in the

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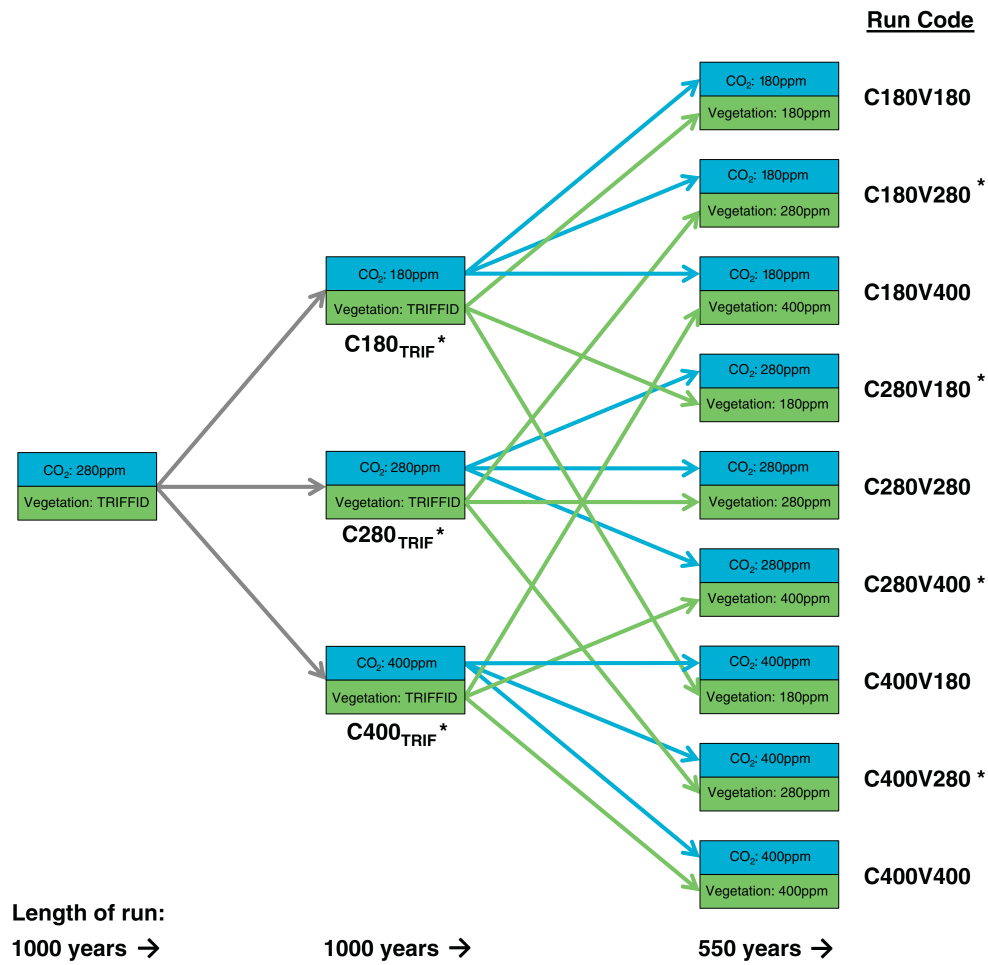

Fig. 1. Schematic showing the evolution of the late Miocene and potential modern GCM runs used in this study. All of the runs have been conducted with late Miocene boundary conditions; the asterisks indicate which of the run combinations have also been conducted with modern boundary conditions. For clarity the reader is referred to the online version of this paper where a colour version of this figure is provided.

determination of temperature because it impacts both sensitivity to CO_2 forcing directly through differences in heat capacity, and indirectly through the distribution of high latitude vegetation and the combination of feedback mechanisms.

2. Description of the Models and Experiment Design

2.1. Description of the climate model HadCM3L and the dynamic vegetation model TRIFFID

The general circulation model (GCM) used in this work is HadCM3L (Cox et al., 2000), the low ocean resolution (2.5° latitude by 3.75° longitude) version of the fully coupled atmosphere-ocean model HadCM3 (Gordon et al., 2000; Pope et al., 2000). The atmosphere component has 19 vertical levels and the ocean component has 20 vertical levels and the model is run without the requirement for flux adjustments. Full details of the GCM and comparison to modern observations are given in Appendix B Section 1.1 of Bradshaw et al. (2012).

The interactive global vegetation model coupled to HadCM3L is the Top-down Representation of Interactive Foliage and Flora Including Dynamics (TRIFFID) model, a full description of which is given in Cox (2001) and Hughes et al. (2004). TRIFFID calculates areal coverage, leaf area index and canopy height for five defined plant functional types (PFTs): broadleaf tree, needleleaf tree, C_3 grass, C_4 grass and shrub, all of which can co-exist within the same model grid box. The vegetation model is competitive and hierarchical based on height, so natural vegetation will tend towards trees if the conditions are suitable. Each PFT responds differently to climate and CO_2 forcing (e.g. C_3 and C_4 grasses use different photosynthetic pathways), and also impact differently on the physical properties of the land surface (i.e. possessing different aerodynamic roughness lengths and albedo properties). In using the TRIFFID model in a paleo context it is inherently assumed that modern vegetation characteristics are appropriate for the late Miocene and this of course may not be a good assumption. However, allowing vegetation distributions to alter with, and feed back to, the climate is a better test of the dependence of climate sensitivity to vegetation distribution than keeping the vegetation fixed at the modern distribution. More details of the TRIFFID model and comparison to modern observations are given in the Supplementary Information.

2.2. Experimental Design

In this study, simulations have been conducted for late Miocene boundary conditions under different CO_2 concentrations and comparisons are made with potential modern climates for the same CO_2 concentrations. The modern climates are derived using TRIFFID-simulated natural vegetation rather than prescribing the true modern vegetation distribution in order to exclude anthropogenic land-use changes associated with agriculture and urban areas. The continental positions and orographic boundary conditions for the late Miocene simulations are those from Markwick (2007) and are described in detail in Bradshaw et al. (2012). The boundary conditions for the potential modern simulations are those of the UK Met. Office and also described in Bradshaw et al. (2012). The major differences in the late Miocene boundary