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Marine Isotope Stage 11: Palaeoclimates, palaeoenvironments and its role as an analogue for the current interglacial

Ian Candy *, Danielle C. Schreve, Jennifer Sherriff, Gareth J. Tye

Department of Geography, Royal Holloway, University of London, Egham, Surrey TW20 0EX, United Kingdom

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A B S T R A C T

Interglacials of the Quaternary Period are currently the focus of a great deal of attention within the scientific community. This is primarily because they play a vital role in distinguishing between "natural" and "human" climate change in the current interglacial and in understanding how the Holocene would evolve in the absence of anthropogenic greenhouse warming. In this respect, Marine Isotope Stage 11 (MIS 11, ca 410,000 yr BP) is one of the key interglacial stages of the past 450,000 yr. The pattern of insolation variability that occurs during MIS 11 matches that which occurs in the Holocene more closely than in any other warm stage of the past half a million years. In addition there is now an extensive range of evidence for MIS 11 palaeoclimates and palaeoenvironments from marine, ice core, lacustrine and terrestrial sequences. The aim of this paper is to provide a comprehensive review of the current state of our understanding of MIS 11. This is the first paper to provide a detailed review of MIS 11 that incorporates the wide range of marine, ice core, long lacustrine and terrestrial records that have been generated over the last ten years since the last major overview. Crucially, it is the first review of MIS 11 that incorporates a detailed synthesis of the high-resolution terrestrial sequences of western and central Europe. This paper, therefore, provides a holistic integration of a diverse range of proxies and archives to provide a detailed understanding of the expression of MIS 11 in the Earth system. In particular the review focuses on: (1) the climatic background of MIS 11, (2) the robustness of the identification of MIS 11 in a diverse range of sequences, (3) the climatic structure of MIS 11, (4) the magnitude of warmth that occurred in this warm stage, (5) MIS 11 sea level magnitude and variability, (6) the duration of MIS 11, (7) evidence for abrupt climatic events within the interglacial of MIS 11 and (8) precipitation patterns and trends during this interglacial. The paper concludes by considering how useful MIS 11 is as an analogue for Holocene climates and compares it with other proposed analogues, such as MIS 19, with particular reference to the "early anthropogenic" hypothesis.

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* Corresponding author.
E-mail address: ian.candy@rhul.ac.uk (I. Candy).

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1. Introduction

Interglacial episodes of the Quaternary Period (the past 2.6 million years) have received a large amount of attention over the past twenty years (Kukla et al., 1997; Droxler et al., 2003a; Tzedakis et al., 2009a; Tzedakis, 2010). This interest stems from the fact that interglacial episodes have the potential to act as analogues for the current warm interval (see Droxler and Farrell, 2000; Tzedakis et al., 2009a). Consequently, the study of interglacials offers the potential to: (1) understand how the climate of the current interglacial may have evolved without human intervention, (2) investigate the long-term stability of interglacial climates, for example assessing whether abrupt climatic events are common, and routinely characterise the climates of warm episodes and (3) understand the impact of these climates on ecological and geomorphic systems. Two interglacials have received the greatest attention; namely Marine Oxygen Isotope sub-stage (MIS) 5e (the last interglacial, ca 125,000 yr BP (Kukla et al., 1997; Rioual et al., 2001; Kukla et al., 2002)) and MIS 11 (ca 410,000 yr BP (see Berger and Loutre, 2002; Droxler et al., 2003b and references therein; Tzedakis, 2010).

MIS 5e, being the most recent pre-Holocene interglacial, is well-represented in marine (Shackleton, 1969; Martinson et al., 1987; Oppo et al., 2006), ice-core (Dansgaard et al., 1993; Petit et al., 1999; EPICA, 2004; Jouzel et al., 2007) and terrestrial sediment sequences from a range of locations across the globe (see Kukla et al., 2002 for a review). Consequently, deposits of this interglacial offer the potential to reconstruct its climatic history at a high resolution. This is particularly true for ice core records. In the case of the Greenland ice cores, MIS 5e is the only pre-Holocene interglacial that is represented (Dansgaard et al., 1993), whilst in Antarctica, the section of core relating to MIS 5e, being relatively young, has undergone less compression, and is therefore recorded at a higher resolution than any other pre-Holocene interglacial (Petit et al., 1999; Jouzel et al., 2007).

The interest in MIS 11 reflects the fact that it is widely suggested to be the most appropriate climate analogue for the Holocene (Droxler and Farrell, 2000; Loutre and Berger, 2003; Droxler et al., 2003a and references contained therein; Tzedakis, 2010). This suggestion is based upon the observation that the pattern of incoming solar insolation that occurred during MIS 11 matches that of the Holocene more closely than that of any other interglacial in the past 500,000 yr (Berger and Loutre, 2002, 2003; Loutre and Berger, 2003). As the pattern of incoming insolation will partly control the duration, structure and degree of warmth that occurs during an interglacial, the marine, ice-core and terrestrial sediment records of MIS 11 can allow us to investigate the characteristics of an interglacial comparable to the Holocene but unaffected by human impacts. Despite the fact that constructing high-resolution climate records for the more recent MIS 5e is more straightforward than for MIS 11, MIS 5e has limited application as a Holocene climate analogue because its insolation pattern bears little resemblance to that of the Holocene (Fig. 1) (Berger and Loutre, 2002, 2003; Loutre and Berger, 2003).

A major review of MIS 11 was published ten years ago (Droxler et al., 2003b). Although much of the material contained in this volume is still relevant, a new review of MIS 11 is timely for two reasons. Firstly, because over the past decade there has been a significant increase in the number of continuous temperature reconstructions that extend back to MIS 11 and beyond, including the Antarctic EPICA Dome C temperature record of the past 800,000 yr BP (EPICA, 2004; Jouzel et al., 2007) and many sea surface temperature (SST) records (Rodrigues et al., 2011; Becquey and Gersonde, 2002; Kandiano and Bauch, 2003; Liu and Herbert, 2004; de Abreu et al., 2005; de Garidel-Thoron et al., 2005; Lawrence and Herbert, 2005; Medina Elizalde and Lea, 2005; Lawrence et al., 2010; Kandiano and Bauch, 2007; Martrat et al., 2007; Crundwell et al., 2008; Lawrence et al., 2009; Stein et al., 2009; Herbert et al., 2010; Kandiano et al., 2012). These new records allow us to understand the climatic history of MIS 11 in much greater detail than has previously been possible. Secondly, earlier reviews of MIS 11 focussed primarily on marine records with little attention paid to terrestrial records (although see Rousseau et al., 1992; Rousseau, 2003; Kukla, 2003). Therefore, our understanding of how the climates of MIS 11 are expressed in palaeoecological and geomorphic systems has previously been limited.

This review paper has three main aims. The first is to summarise the background controls that drive the climate of MIS 11 and to discuss the archives that record important climatic information of this warm episode. As well as discussing long palaeoclimatic records (e.g. EPICA Dome C), this review is novel in that it integrates with the exceptionally detailed terrestrial record of western Europe, primarily the British Quaternary record. Consequently, the rationale for correlating terrestrial deposits of this region to MIS 11 is also discussed. The second aim is to summarise the key climatic characteristics of MIS 11 as expressed in the range of archives that are currently available; these include the climatic structure of MIS 11,the magnitude of warmth achieved during MIS 11, sea level history during MIS 11, the duration of the MIS 11 interglacial, the precipitation regime of MIS 11 and evidence for abrupt climate change during MIS 11. Finally the review concludes with a discussion of the issues of using MIS 11 as a Holocene analogue and its relative merits over other suggested analogues such as MIS 19.

2. Stratigraphy and nomenclature of warm stages and interglacials

Before the climatic characteristics of MIS 11 are discussed, it is important to define some of the stratigraphic nomenclature that is regularly used when discussing interglacials (Hays et al., 1976; Imbrie et al., 1984; Shackleton, 1987). The stratigraphic framework of the Quaternary Period is now routinely based upon the $\delta^{18}O$ record of planktonic/benthic foraminifera from deep marine sediments (Imbrie et al., 1984; Martinson et al., 1987; Lisiecki and Raymo, 2005), a record that serves primarily as a proxy for changes in global ice volume (Shackleton, 1967, 1987). The marine $\delta^{18}O$ sequence is divided into a series of warm and cold isotopic stages based upon the deviation of the $\delta^{18}O$ signal away from the mean of the dataset (Imbrie et al., 1984; Martinson et al., 1987). Periods of time characterised by $\delta^{18}O$ values that are depleted, relative to the mean value, record episodes of reduced global ice volume and are referred to as “warm” isotope stages. These stages are given odd numbers with the current warm stage being MIS 1. Periods of time characterised by $\delta^{18}O$ values that are enriched, relative to the mean value, record periods of increased global ice volume and are referred to as “cold” isotope stages. These stages are given even numbers, with the last glacial maximum being MIS 2.

It is important to note that the term “warm stage”, as represented by MIS 5, 7, 9 and 11, is not synonymous with the term interglacial (see Shackleton, 1969; Martinson et al., 1987; Tzedakis et al., 2009a). Warm stages are of relatively long duration, ca 60,000 yr, and contain numerous episodes of warm and cold climate, see Fig. 2 (Imbrie et al., 1984). The term interglacial has been defined in many ways (West, 1977), however, its clearest definition was developed in western and