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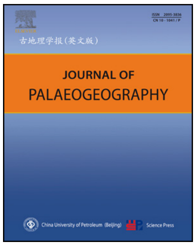

Modeling the Middle Jurassic ocean circulation

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ABSTRACT

We present coupled ocean–sea-ice simulations of the Middle Jurassic (~165 Ma) when Laurasia and Gondwana began drifting apart and gave rise to the formation of the Atlantic Ocean. Since the opening of the Proto-Caribbean is not well constrained by geological records, configurations with and without an open connection between the Proto-Caribbean and Panthalassa are examined. We use a sea-floor bathymetry obtained by a recently developed three-dimensional (3D) elevation model which compiles geological, palaeogeographical and geophysical data. Our original approach consists in coupling this elevation model, which is based on detailed reconstructions of oceanic realms, with a dynamical ocean circulation model. We find that the Middle Jurassic bathymetry of the Central Atlantic and Proto-Caribbean seaway only allows for a weak current of the order of 2 Sv in the upper 1000 m even if the system is open to the west. The effect of closing the western boundary of the Proto-Caribbean is to increase the transport related to barotropic gyres in the southern hemisphere and to change water properties, such as salinity, in the Neo-Tethys. Weak upwelling rates are found in the nascent Atlantic Ocean in the presence of this superficial current and we discuss their compatibility with deep-sea sedimentological records in this region.

1. Introduction

Earth's climate is a complex system which evolves under the action of internal dynamics of highly coupled subsystems (ocean, atmosphere, ice masses, land surface, *etc.*) and external factors (Saltzman, 2002; and references therein), such as the astronomical forcing (changes in solar luminosity, Earth's orbit and tilt) and the tectonic forcing (plate tectonics, volcanic activity). We are interested in investigating how the ocean circulation (whose relaxation time is of the order of 100–1000 years) responds to changes in plate tectonic setting of ocean basins and land masses (which act on very long time-scales of the order of 10 My). Given the large difference between the ocean and tectonic time-scales, the tectonic forcing can be considered as a constant during the ocean response time and we look for equilibrium states of ocean currents for given different tectonic configurations. This method allows us to find the main regions of upwelling and downwelling (where organic activity is maximum), anoxic regions (*e.g.*, stagnant circulation caused by the presence of barriers to deep circulation), overturning cells and gyre patterns for a given geological period, and to evaluate the model results against palaeoclimate records.

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We use an ocean general circulation model (OGCM) coupled to the sea-ice component, while the contributions of other internal subsystems, which affect the interface between the ocean and the atmosphere and can be described by fast-response variables, are included as specified monthly averaged boundary conditions at the ocean surface. This is a first-order approximation which does not account for possible feedbacks between the averaged components and the dynamical ones, and which reduces internal variability. We will relax this approximation in further studies.

In this paper, we present the results of global ocean–sea-ice simulations conducted using the Massachussetts Institute of Technology (MIT) general circulation model (Marshall et al., 1997a, 1997b). For this first study, we have chosen the Middle Jurassic (Callovian) Epoch (~165 Ma). We plan to investigate other geological intervals in a systematic way by applying the methods discussed in the present paper. A main improvement with respect to previous studies of the Jurassic ocean circulation (Bjerrum et al., 2001; Dera and Donnadieu, 2012) is the bathymetry model, which is based on reconstructions of oceanic realms, in particular of Panthalassa (Flores-Reyes, 2009; Vérard et al., 2015a, 2015b; and see Section 2).

The Callovian–Oxfordian transition is an interesting geological period since it records perturbations in the carbonate deposition pattern and cooling of seawater temperature whose causes are still debated (Donnadieu et al., 2011). Pangaea breakup started in the Early Jurassic by rifting between Laurasia and Gondwana, resulting in the formation of the Central Atlantic and its connection with the Neo-Tethys (see Fig. 1). While an Early Jurassic (Toarcian) opening of the Central Atlantic is now well constrained (*e.g.*, Kneller et al., 2012; Labails et al., 2010), rifting and breakup between North and South America is still controversial. A number of plate tectonic models place the Proto-Caribbean breakup in the Early Jurassic (*e.g.*, Stampfli and Borel, 2004), while others opt for prolonged crustal extension between the Americas and breakup by the early Late Jurassic (*e.g.*, Pindell and Kennan, 2009). A first marine Proto-Caribbean passage may have been opened in the Middle Jurassic, but the oldest clearly Proto-Caribbean ocean crust is only of early Late Jurassic age (Baumgartner, 2013; Pindell and Kennan, 2009). Here, we examine both the configurations with and without an open connection between the Proto-Caribbean and Panthalassa.

In the literature, several examples of comparisons between the results of atmospheric general circulation models (AGCM) and geological and phytogeographical data can be found for the Jurassic (Moore et al., 1992; Sellwood and Valdes, 2008; Sellwood et al., 2000; Valdes, 1993). In these papers, ocean dynamics are not included explicitly or described by simplified models, such as mixed layer models (Moore et al., 1992), since the aim was to find the dynamical equilibrium between the atmosphere and a given orography. In the present paper, we will discuss the results of numerical simulations which explicitly follow the ocean dynamics.

The role of the ocean in the Jurassic climates has been investigated in the past (Chandler et al., 1992; Rind and Chandler, 1991). The ocean has been found to be an important dynamical component, the treatment of which likely explains different model predictions, in particular at high latitudes. Typically, atmospheric CO_2 concentrations in the Jurassic are taken to be between 1 and 7.5 times pre-industrial values (Moore et al., 1992; Rees et al., 2000; Sellwood and Valdes, 2008; Valdes, 1993). The effect of increased concentrations of CO_2 in the atmosphere is to warm tropical regions as well as high latitudes. In order to obtain a reduced meridional temperature gradient, which is characteristic of warm climates, different mechanisms need to be considered. Since the Jurassic simulations with specified sea-surface temperatures warmer than the present-day values were found in energy balance without requiring high atmospheric CO_2 concentrations (Chandler et al., 1992), it was suggested that warm Jurassic climates can be produced by an enhanced poleward heat transport through the ocean. This hypothesis has, however, been questioned by the Late Jurassic

Fig. 1 – Palaeo-Digital Elevation Model of the Earth at ~165 Ma applied on the plate tectonic model developed at the University of Lausanne (UNIL) (© Shell Global Solutions International, 2013; version 2010 of the UNIL Plate Model). Abbreviations are: NAm: North America; SAm: South America; Ant: Antarctica; Aus: Australia; G: Greenland; I: Iberia; A: Adria; T: Taurus; AT: Alpine Tethys; BN: Bangong-Nujiang; ES: Elise Sea. Mollweide projection.