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Climate at high-obliquity

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ABSTRACT

The question of climate at high obliquity is raised in the context of both exoplanet studies (e.g. habitability) and paleoclimates studies (evidence for low-latitude glaciation during the Neoproterozoic and the "Snowball Earth" hypothesis). States of high obliquity, ϕ, are distinctive in that, for $\phi \geqslant 54^\circ$, the poles receive more solar radiation in the annual mean than the equator, opposite to the present day situation. In addition, the seasonal cycle of insolation is extreme, with the poles alternatively "facing" the Sun and sheltering in the dark for months.

The novelty of our approach is to consider the role of a dynamical ocean in controlling the surface climate at high obliquity, which in turn requires understanding of the surface winds patterns when temperature gradients are reversed. To address these questions, a coupled ocean–atmosphere–sea ice GCM configured on an Aquaplanet is employed. Except for the absence of topography and modified obliquity, the set-up is Earth-like. Two large obliquities ϕ, 54° and 90°, are compared to today's Earth value, $\phi = 23.5^\circ$.

Three key results emerge at high obliquity: (1) despite reversed temperature gradients, mid-latitudes surface winds are westerly and trade winds exist at the equator (as for $\phi = 23.5^\circ$) although the westerlies are confined to the summer hemisphere, (2) a habitable planet is possible with mid-latitude temperatures in the range 300–280 K and (3) a stable climate state with an ice cap limited to the equatorial region is unlikely.

We clarify the dynamics behind these features (notably by an analysis of the potential vorticity structure and conditions for baroclinic instability of the atmosphere). Interestingly, we find that the absence of a stable partially glaciated state is critically linked to the absence of ocean heat transport during winter, a feature ultimately traced back to the high seasonality of baroclinic instability conditions in the atmosphere.

1. Introduction

Exoplanets, including those that have the potential to harbor life, are expected to have a range of obliquities. The reasoning is based both on the range of obliquities of the terrestrial planets of our own Solar System as well as predictions for exoplanets. The obliquity of Mars has been shown to vary chaotically, ranging from zero to nearly sixty degrees (Laskar and Robutel, 1993; Touma and Wisdom, 1993). Venus has an obliquity close to 180°, and therefore a retrograde rotation (Carpenter, 1964; Shapiro, 1967). While measurements of exoplanet obliquity are unlikely to be possible (but c.f. Carter and Winn, 2010 for a specialized case), the final states of exoplanet obliquity evolution will be affected by gravitational tides and thermal atmospheric tides, core–mantle friction (Correia and Laskar, 2011; Cunha et al., 2014), and collisions with other planets or planetesimals. A large Moon is also thought to play a stabilizing role on obliquity variations, however it depends on the planet's initial obliquity (Laskar et al., 1993). The tidal evolution depends on a planet's distance to its host star, which for habitable zones changes for different star type. While a number of publications have addressed the influence of obliquity on climates of Earth-like planets none have considered a dynamic ocean (Gaidos and Williams, 2004; Spiegel et al., 2009; Cowan et al., 2012; Armstrong et al., 2014).

If obliquity exceeds 54°, polar latitudes receive more energy per unit area, in the yearly mean, than do equatorial latitudes and undergo a very pronounced seasonal cycle, a challenge for the development of life (Fig. 1 and further discussion below). A key aspect with regard to habitability is to understand how the atmosphere and ocean of this high obliquity planet work together to transport energy meridionally, mediating the warmth of the poles and the coldness of the equator. How extreme are seasonal temperature fluctuations? Should one expect to find ice around the equator?

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Additional motivation for the study of climate at high obliquity is found in Earth's climate history which shows evidence of large low-latitude glaciations during the Neoproterozoic (∼700–600 Myr ago). An interpretation is that Earth was completely covered with ice at these periods, the so-called "Snowball Earth" hypothesis (Kirschvink, 1992; Hoffman et al., 1998). This hypothesis raises challenging questions about the survival of life during the long (∼10 Myr) glacial spells and requires an escape mechanism out of a fully glaciated Earth (see Pierrehumbert et al., 2011, for a review). An alternative to the "Snowball Earth" state is that Earth was in a high obliquity configuration with a cold equator and warm poles. The interpretation is then that large ice caps existed in equatorial regions while the poles remained ice-free. From a climate perspective (leaving aside other difficulties, see Hoffman and Schrag (2002)), it is unclear if such a climate state can be achieved in the coupled system. Recent work showed that the existence of large stable ice caps critically depends on the meridional structure of the ocean heat transport (OHT): sea ice caps extend to latitudes at which the OHT has maxima of convergence (Rose and Marshall, 2009; Ferreira et al., 2011). To address such questions, one needs to consider dynamical constraints on the ocean circulation and understand the pattern of surface winds.

High values of obliquity particularly challenge our understanding of climate dynamics because the poles will become warmer than the equator and we are led to consider a world in which the meridional temperature gradients, and associated prevailing zonal wind, have the opposite sign to the present Earth, and the equatorial Hadley circulation exists where it is cold rather than where it is warm.

The problem becomes even richer when one considers the dynamics of an ocean, should one exist. The volume and surface area of a planet's ocean is not known a priori and is expected to be highly variable from planet to planet due to the stochastic nature of delivery of volatiles to a planet during its early phase. While the surface area of an ocean contributes to a planet's surface climate (see a series of arguments in Abe et al., 2011; Zsom et al., 2013; Kasting et al., 2013; Seager, 2014) investigating ocean surface area is beyond the scope of this paper. A deep Earth-like ocean, on the other hand, allows for a system of 3-dimensional ocean currents that is able to transport large amount of heat and mitigate harsh climates, like the Gulf Stream and Meridional Overturning Circulation (MOC) do on our present-day Earth (e.g. Seager et al., 2002; Ferreira et al., 2010). A central question for the ocean circulation is then: what is the pattern of surface winds at high obliquities?, for it is the winds that drive the ocean currents and MOC. How do atmospheric weather systems growing in the easterly sheared middle latitude jets and subject to a global angular momentum constraint, combine to determine the surface wind pattern. Should one expect middle latitude easterly winds? If not, why not?

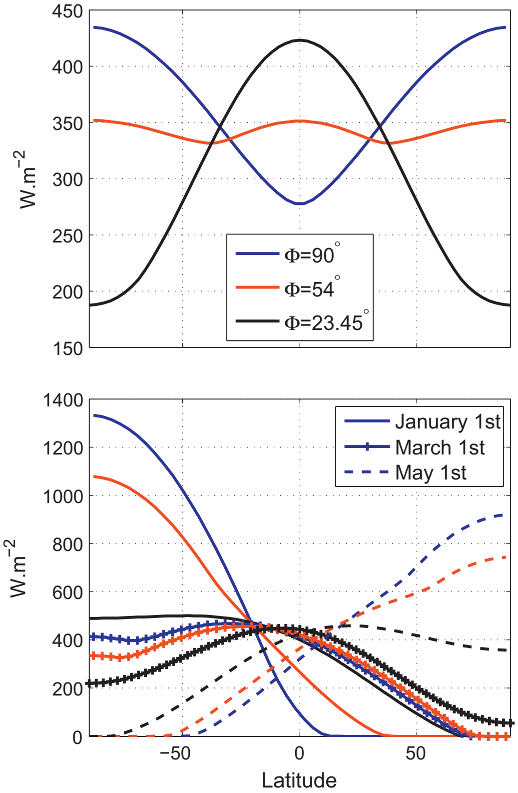

Fig. 1. Top-of-the-atmosphere incoming solar radiation (W m^{-2}) for obliquities of 90° (blue), 54° (red) and 23.45° (black): (top) annual mean and (bottom) daily mean on January 1st (solid), March 1st (dotted), and May 1st (dashed). A zero eccentricity is assumed. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Here, possible answers to some of these questions are sought by experimentation with a coupled atmosphere, ocean and sea–ice General Circulation Model (GCM) of an Earth-like Aquaplanet: i.e. a planet like our own but on which there is only an ocean but no land. The coupled climate is studied across a range of obliquities (23.5, 54 and 90°).

The novelty of our approach is the use of a coupled GCM in which both fluids are represented by 3d fully dynamical models. To our knowledge, previous studies of climate at high-obliquity only employed atmosphere-only GCM or atmospheric GCM coupled to a slab ocean (e.g. Jenkins, 2000; Donnadieu et al., 2002; Williams and Pollard, 2003). There, the ocean is treated as a "swamp" without OHT or with a prescribed OHT or with a diffusive OHT. Other studies are based on Energy Balance Models (EBM, see North et al. (1981, for a review) in which dynamics is absent and all (atmosphere + ocean) transports are represented through a diffusive process (e.g. Williams and Kasting, 1997; Gaidos and Williams, 2004; Spiegel et al., 2009).

In our simulations, the OHT is realized as part of the solution. Our approach allows us to document the ocean circulation at high-obliquity and to explore, in a dynamically consistent way, the role of the ocean in setting the climate. We present some of the descriptive climatology of our solutions and how they shed light on the deeper questions of coupled climate dynamics that motivate them. We focus on understanding the ocean circulation and its forcing. This leads us into a detailed analysis of the mechanisms responsible for the maintenance of surface winds. We notably elucidate the conditions for baroclinic instability and storm track development in a world with reversed temperature gradients. Our analysis of the atmospheric dynamics and energy transports are also a novelty of this study.

We use an Aquaplanet set up, a planet entirely covered with a 3000 m-deep ocean. The previous studies mentioned above used present-day and neoproterozoic continental distributions. One might be concerned by the absence of topographical constraints in our Aquaplanet. Fig. 2 however illustrates that the energy transports simulated in Aquaplanet at $\phi = 23°$ compare favorably with present-day observed transports (in terms of shape, magnitude and partitioning between ocean and atmosphere – see further discussion in Marshall et al. (2007)). That is, the main features of the ocean and atmosphere circulations of our present climate are well captured in an Aquaplanet set-up. Although continental configurations can influence the climate state and are indeed important to explain some aspects of present and past Earth's climate (Enderton and Marshall, 2009; Ferreira et al., 2010), such a level of refinement is not warranted for a first investigation of the coupled system at high obliquity.