Title

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Permalink

https://escholarship.org/uc/item/4z79f096

Journal

PLOS Climate, 3(7)

ISSN

2767-3200

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Publication Date

2024-07-02

DOI

10.1371/journal.pclm.0000436

Orbital eccentricity and Earth's seasonal cycle

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We argue that Earth's orbital eccentricity should be given due consideration as an annual cycle forcing in its own right in studies of Earth's seasonal cycle.

There are two sources of seasonality arising from Earth's orbit around the Sun. Earth's axial tilt (hereafter the ***tilt effect***) produces a seasonal cycle of insolation at a given latitude because of the angle that the surface makes to the sun's incoming rays. Earth's orbital eccentricity (***distance effect***) provides an annual variation in the solar flux because of the varying distance between the Earth and Sun.

In practice, it is assumed that the tilt effect dominates the Earth's seasons. Earth Science textbooks note that the distance effect is negligible since Earth's orbital eccentricity is relatively small (e ~ 0.0167, meaning that the Earth-Sun distance at aphelion is ~1.67% longer than the mean) and the solar flux changes only by ~7% between aphelion and perihelion. This assumption extends to the research literature on the seasonal cycle, where the relative roles of tilt versus distance is rarely addressed except in a handful of studies [1-3]. As a result, there is a curious gap in our understanding of how Earth's seasonal climate responds to orbital eccentricity.

However, orbital eccentricity produces seasonal radiative changes that are comparable in magnitude to transient climate forcings commonly considered in climate studies. The decrease in insolation absorbed by the Earth at aphelion (relative to the annual mean) is ~8 W/m^2. This can be compared to the peak radiative forcing resulting from shorter-lived volcanic eruptions like Pinatubo (-3.2W/m^2) [4] resulting from increased reflection by aerosols. Moreover, while the annual cycle of insolation is dominated by tilt at most latitudes (Fig 1a,b), near the equator the annual cycle of insolation is dominated by the distance effect (though the tilt effect does produce a large semiannual cycle) (Fig 1c). For atmospheric circulation and related climate quantities, their seasonal cycle can depend on nonlocal insolation; if we were to use the globally-averaged insolation as a measure, its annual cycle comes entirely from the distance effect (Fig 1d).

Our argument is motivated by a recent study by the authors and collaborators [5] on the seasonal cycle of the Pacific cold tongue. The Pacific cold tongue is a region of the eastern equatorial Pacific where the sea surface temperature is colder relative to its surroundings and is climatically important as the epicenter of the El Nino -Southern Oscillation. It has an annual cycle of temperature with the warm season in boreal spring and cold season in boreal fall [6] with its origins attributed to the tilt effect. However, Chiang et al. [5] showed that the cold tongue in coupled model simulations in fact possessed two distinct annual cycles: one driven by the tilt effect and in accord with prevailing theory, and another driven by the distance effect. Moreover, the distance effect amplitude was found to be around 1/3 that of the tilt effect, which is not negligible.

The above result demonstrates that a proper evaluation of the annual cycle requires explicitly considering the relative roles of the tilt and distance effects. This determination is not possible from observational data, but the contributions from each can be decomposed from model simulations spanning the calendar timing of perihelion [5].

New climate physics are revealed by separately considering the tilt and distance effects on regional climate. Chiang et al. [5] found that the distance effect annual cycle of the cold tongue was driven by coupled ocean-atmosphere dynamics distinctly different from the annual cycle arising from tilt. Moreover, the two cycles of insolation have different spatiotemporal characteristics, and as such the Earth will respond differently to each influence. We know how the annual cycle of the Earth's general circulation responds to the tilt effect - it generates an interhemispheric contrast that then drives seasonal changes in the Hadley circulation and extratropical westerlies. Our hypothesis thus poses this question: what is the equivalent picture for the distance effect annual cycle?

Our argument has profound implications for the concept of seasonality. Seasonality refers to periodic and generally predictable behavior over the course of a calendar year. However, the superposition of the tilt and distance effects (assuming the two amplitudes are comparable) can lead to a wholesale change in the seasonality of a region over precessional timescales, since the year defined by the distance effect (the Anomalistic year, from perihelion to perihelion) is slightly longer (by ~25 minutes currently) than the year defined by the tilt effect (the Tropical year, from solstice to solstice) [2]. Beaufort and Sarr [7] found a gradual and consistent transition in the seasonality of tropical ocean surface temperature with the timing of perihelion in simulations with high orbital eccentricity (e~ 0.054), evidencing the important role that orbital eccentricity can play in seasonality[1]. These effects are not just limited to the deep

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[1] Beaufort and Sarr [7] goes on to propose the concept of 'eccentriseasons' which they define as "as seasons occurring at low latitude in response to the cycles of the Earth-Sun distance".

tropics: Chiang and Broccoli [8] showed that the distance effect can account for an appreciable fraction of the annual cycle for features as poleward as the southern hemisphere westerlies.

Our hypothesis also has implications for paleoclimate. While paleoclimate studies on orbital timescales generally do account for eccentricity variations, it typically only considers how the annual mean (or fixed seasonal) quantity varies over thousands of years. However, mechanisms of paleoclimate changes are often seasonally-dependent, a prime example being the role of northern hemisphere summer insolation on glacial-interglacial cycles [9]. If the nature of the seasons change, so must their influence on paleoclimate. We thus argue that how eccentricity impacts the seasonal cycle of specific regions is critical to the understanding of paleoclimate changes.

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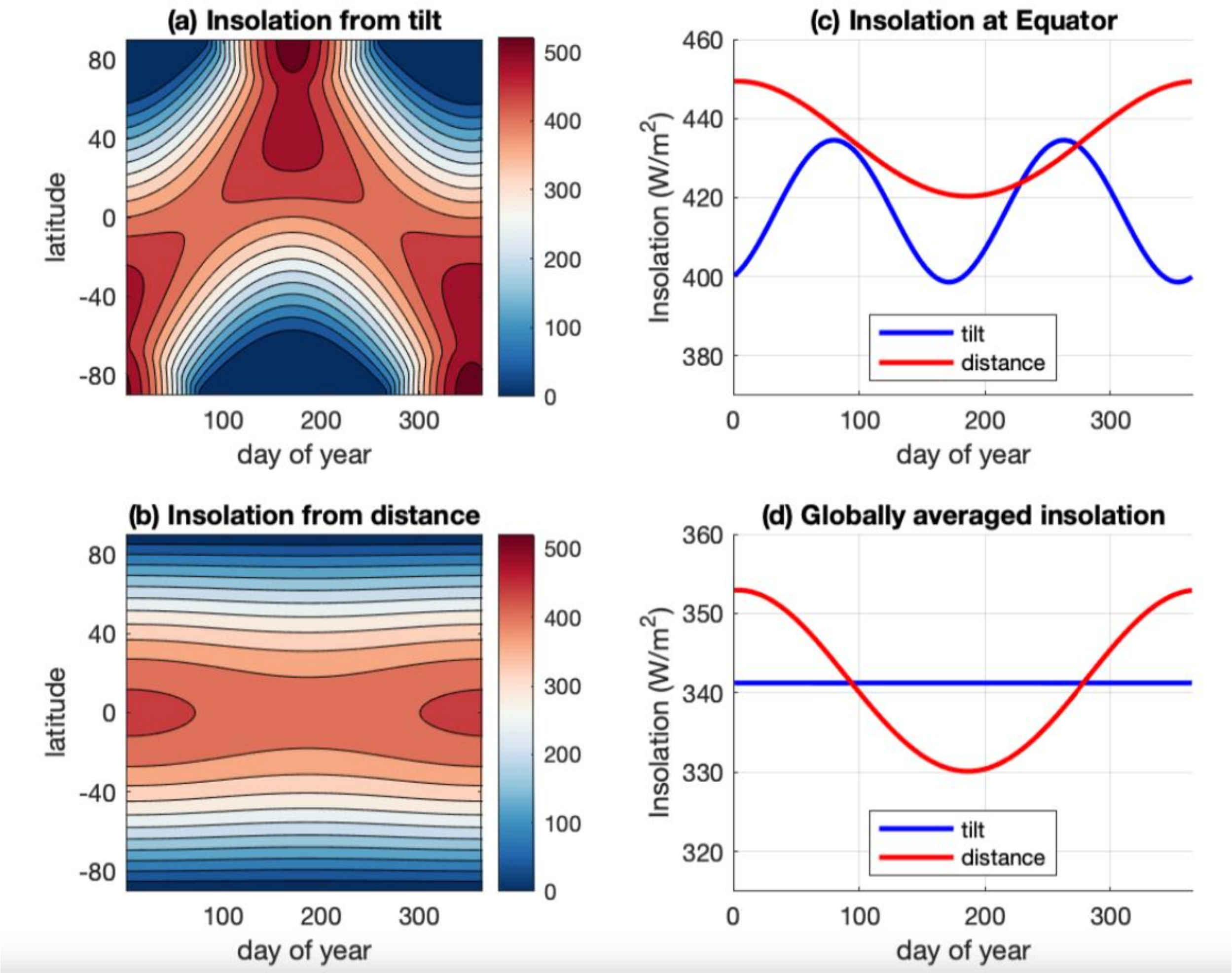

Figure 1. Comparison between the tilt and distance effect on the seasonality of daily-averaged incoming solar radiation (insolation). (a) Insolation resulting from the tilt effect; (b) insolation resulting from the distance effect; (c) insolation at the equator from tilt (blue line) and distance (red line); and (d) globally averaged insolation from tilt (blue line) and distance (red line). Insolation calculated using the code from Huybers and Eisenmann [10], using pre-industrial orbital parameters stated in Erb et al. [11]: *e* = 0.0167, obliquity = 23.439°, and longitude of perihelion = 102.932°. For calculating the insolation from tilt, eccentricity was set to zero in the calculation; and for the insolation from distance, obliquity was set to zero.