



Research Article

An assessment of the Pliocene as an analogue for our warmer future

Lauren E. Burton^{a,*}, Arthur M. Oldeman^b, Alan M. Haywood^a, Julia C. Tindall^a,
Aisling M. Dolan^a, Daniel J. Hill^a, Anna von der Heydt^{b,c}, Michiel L.J. Baatsen^b

^a School of Earth and Environment, University of Leeds, Woodhouse Lane, Leeds, West Yorkshire LS2 9JT, UK

^b Institute for Marine and Atmospheric Research Utrecht (IMAU), Department of Physics, Utrecht University, 3584 CC Utrecht, the Netherlands

^c Centre for Complex Systems Studies, Utrecht University, 3584 CE Utrecht, the Netherlands



ARTICLE INFO

Editor name: Dr. Storelvmo Trude

Keywords:

Climate change
Palaeoclimate
Pliocene
Analogy
Climate modelling

ABSTRACT

The Pliocene has been considered a possible palaeoclimate analogue for over four decades and is often referred to as the “best” analogue for the end-of-century future. Using elements of a newly proposed palaeoclimate analogy framework, we critically assess the Pliocene as an analogue for our warmer future using data from the Pliocene Model Intercomparison Project (PlioMIP) and Shared Socioeconomic Pathway (SSP) scenarios from the Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC). Three future intervals are considered: near term (2021–2040), medium term (2041–2060), and long term (2081–2100).

The strength of the Pliocene as an analogue is found to be highly dependent on a number of factors, including the climate variable and the spatial and temporal scales of interest. Warming under medium emission scenarios (SSP2-4.5 and SSP3-7.0) by the end of this century is found to be the most analogous to the Pliocene, though there is significant variation both between models and between regions on the level of analogy. While increases in Pliocene surface air temperature are found to be analogous to some future scenarios, changes in precipitation are less analogous between the Pliocene and projected futures, particularly in terms of the spatial patterns of change. Using sensitivity experiments, we show that the regions of greatest difference between the Pliocene and projected future(s) are largely attributable to non-CO₂ Pliocene boundary conditions, such as reduced land ice and closed Arctic Ocean gateways.

1. Introduction

1.1. Palaeoclimate analogy

As the need to mitigate and adapt to anthropogenic climate change becomes more urgent, it is paramount to use all available lines of evidence to better understand, and consequently prepare for, our warmer future. Though the future is unknowable, it is possible to turn to periods in Earth's geologic history to better understand the dynamics of the climate system in a warmer than present world (e.g., Jiang et al., 2005; Jansen et al., 2007; Haywood et al., 2011; Burke et al., 2018).

The concept of palaeoclimate analogy extends from the keystone theory of uniformitarianism, proposed by James Hutton (Hutton, 1795) and later popularised in Charles Lyell's *Principles of Geology* (Lyell, 1830). The theory postulates that ‘the present is the key to the past’, i.e., that we can learn about Earth's past from processes occurring today. Given our understanding of unchanging physical laws and constants,

this concept can also be reversed to mean that we can gain insights of our (unknowable) future from Earth's past (e.g., Budyko, 1982; Chandler et al., 1994; Haywood et al., 2009; Tierney et al., 2020).

Though the concept was proposed far earlier, Haywood et al. (2011) presented the first explicit effort to define what constitutes a palaeoclimate analogue with criteria including increased atmospheric CO₂ concentrations (relative to the pre-industrial (PI) period); comparable climate sensitivity; and climate change not being attributable to changes in palaeogeography. From these criteria, Haywood et al. concluded that there is no satisfactory palaeoclimate analogue. After all, despite the variability seen within the 4.6 billion years of Earth's climatic history, it is highly unlikely that any time in geologic history is a perfect replica of today's climate, or the near-term future (e.g., Chandler et al., 1994; Jansen et al., 2007; Haywood et al., 2011; Tierney et al., 2020). This reinforces the need to better explore and understand a variety of past climates, as different climates will share different similarities and dynamics and therefore provide different insights.

* Corresponding author.

E-mail address: L.E.Burton@leeds.ac.uk (L.E. Burton).

<https://doi.org/10.1016/j.gloplacha.2025.104860>

Received 24 July 2024; Received in revised form 26 April 2025; Accepted 26 April 2025

Available online 28 April 2025

0921-8181/© 2025 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

Palaeoclimate analogy has most often been considered in terms of the similarity of the global mean state response, particularly by comparing the global mean surface air temperature (SAT) anomaly to that of future climate projections (e.g., Jansen et al., 2007; Haywood et al., 2011). This focus is understandable given its relative ease of calculation and utility for comparison to, and preparation for, projected future warming. However, to fully assess the level of analogy between two climate states one should also consider the level of analogy of the dominant climate forcings, and the analogy of the underlying physical mechanisms and processes (Crowley, 1990; Burton et al., 2023; Oldeman et al., *in review*).

1.2. A new palaeoclimate analogy framework

The newly proposed palaeoclimate analogy framework of Oldeman et al. (*in review*) aims to overcome some of the limitations in considerations of palaeoclimate analogy to date by outlining five key steps that should be followed when assessing analogy (Fig. 1):

- 1) Clearly stating the aim and the relevance of assessing analogy;
- 2) Considering how feasible it is to assess analogy given current data and methodologies;
- 3) Clearly describing the data and methods used to assess analogy;
- 4) Assessing the confidence in the conclusions drawn;
- 5) Communicating strengths and limitations of the assessment.

In addition to the five steps, the framework also emphasises the need to consider the type of analogy/analogies being assessed. Four types of analogy are suggested:

- Response analogy

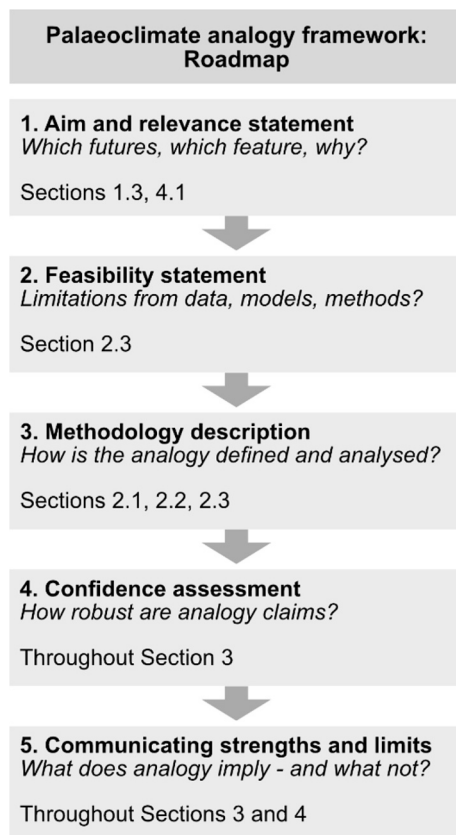


Fig. 1. Roadmap of the Oldeman et al. (*in review*) palaeoclimate analogy framework and which sections address each step. Adapted from Oldeman et al. (*in review*).

- Forcing analogy
- Process analogy
- Rate of change analogy

Specifying the type of analogy being assessed is particularly important given that the first three steps of the framework are dependent upon it, and it also encourages researchers to consider the interrelatedness between types of analogy. For example, if the global annual mean SAT response is deemed analogous, is there an associated analogy in global scale forcing, underpinned by analogous processes, at an analogous rate? Despite the range of climates and contributing factors throughout Earth's history, it is likely impossible that an exact analogue for present or future climate change exists in the geological record, so understanding and, importantly, communicating these limitations of analogy are crucial to the progression of palaeoclimate analogy research.

Additionally, the definition of 'analogy' will, and should, differ depending on the goal of the research itself; different methods may be required to assess analogy in global mean SAT response compared to those required to assess analogy in e.g., tipping dynamics or changes in the El Niño Southern Oscillation (Oldeman et al., *in review*). What is important is to have a clear and well-communicated definition that can be easily compared to other research and/or adapted to further research. How 'good' an analogy is is wholly dependent on this definition, and on the research questions being asked.

The application of this palaeoclimate analogy framework will enable researchers to more critically consider the concept of palaeoclimate analogy, in turn allowing both the palaeo- and future climate communities to understand the strengths and limitations and garner the potential impact from this area of science. Historically, conclusions have been drawn based on a loose, or even undefined, concept of analogy, which limits their robustness and associated level of confidence and consequently their potential impact. If the aim and relevance of the analogy assessment is clearly defined (step one of the Oldeman et al. framework), more useful and more impactful conclusions will follow.

Practically, if an analogue was to be found through the application of this framework, it has the potential to inform policy and adaptation decisions. The framework encourages researchers to consider, and clearly state, the spatial and temporal limitations of their conclusions, meaning that conclusions of analogy could be drawn on local, regional, or global scales. If a study found, for example, an analogue for precipitation response over the UK for the end-of-21st century it might be possible to suggest parts of the UK where flooding adaptation is most required, and it might also be possible to explore the processes behind that precipitation response in the warmer-than-present Pliocene world. An underlying advantage of exploring, and fully utilising, palaeoclimate analogues in addition to future climate simulations is that palaeoclimate model simulations can be compared to geological information, which detail how the environment actually changed. Palaeoclimate data-model comparison efforts also highlight how some models are better matched to geological data, which might also in turn indicate the models that are more accurately simulating future climate change under a given scenario.

1.3. The Pliocene as a palaeoclimate analogue?

The Pliocene has been posed as a palaeoclimate analogue for over four decades, though some early discussions (e.g., Budyko, 1982) do not explicitly use the term 'analogue'. More recently, the Pliocene has been referred to as one of the "best" analogues for near-term future climate change (e.g., Haywood et al., 2011; Hill, 2015; Burke et al., 2018). As well as its cited similarity in warming to the end of the 21st century, the Pliocene is also favoured as an analogue candidate because it is the most recent period of sustained warmth above PI levels, has similar-to-modern atmospheric CO₂ concentration (~400 ppm) and similar-to-modern continental configuration; "In many respects, from continental distribution to vegetation types, [the Pliocene] is more similar to our

future than any other warm period of the past” (Chandler et al., 1994, p. 217).

Budyko (1982) is one of the first to suggest the need to look back in Earth’s history to answer questions around future climatic conditions given increasing atmospheric CO₂ concentration due to the burning of fossil fuels. Since that time, atmospheric CO₂ concentration has risen from ~340 ppm to ~420 ppm (NOAA Global Monitoring Laboratory, 2024). Though not using the term ‘analogue’, Budyko (1982) predicted that increases in atmospheric CO₂ would lead to the thermal regime of the 2020s approaching that of the Pliocene. Similarly, Zubakov and Borzenkova (1988) present the “Climatic Optimum” of the Pliocene (defined as 4.3–3.3 million years ago (Ma)) as a palaeoclimate analogue of the mid-21st century due to predicted increases in atmospheric CO₂ concentration and global mean SAT. In both of these cases, the foundation of the analogy lies with the comparable CO₂ concentration, with consequent similarity in SAT increase.

Soon after these initial proposals, Crowley (1990, 1991) presents the first critique of the Pliocene as a palaeoclimate analogue, and of the palaeoclimate analogue concept as a whole. Crowley (1990) attempts to answer the question of whether there are any satisfactory geologic analogues for a future greenhouse warming and suggests that the Early Pliocene (defined as 3–5 Ma) is not a satisfactory analogue because reduced ice sheet cover would not occur in the near future (though “satisfactory” or “near future” are never explicitly defined), and possible differences in palaeogeography (particularly in the Tibetan Plateau and the Central American Isthmus region). The critique implies that past warm periods, including the Pliocene, must be a perfect replica of present and/or near-term future conditions in order to learn useful lessons for our understanding of future climate change. The result is the suggestion that future discussions of palaeoclimate analogues should be restricted to processes only, and that the use of the term ‘analogue’ for past warm time intervals be abandoned. Though suggesting that higher CO₂ concentrations may have been primarily responsible for warmer Pliocene temperatures (hence being comparable in terms of both forcing and consequent SAT response), this message of caution is echoed in Crowley (1991), which explicitly states that “[the Pliocene] should not be cited as a direct analog[ue] for a future greenhouse warming” (p. 275) due to the differences in the transient state of future warming compared to the (semi-)equilibrium state of the Pliocene.

Since these foundational papers, Pliocene modelling efforts have evolved to better consider past-for-future research questions. Earlier efforts (e.g., Chandler et al., 1994; Haywood et al., 2000; Jiang et al., 2005) culminated in the Pliocene being presented as a possible analogue for the future in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report: Jansen et al. (2007) state that the Mid-Pliocene (defined as ~3.3–3.0 Ma) provides an “accessible example of a world that is similar in many respects to what models estimate could be the Earth of the late 21st century” (p. 440).

From 2008, research about the Pliocene and its possible utility as an analogue for the future flourished with the development of the Pliocene Model Intercomparison Project (PlioMIP), a working group of the Palaeoclimate Model Intercomparison Project (PMIP). A summary of Pliocene climate and its similarities to the near-term future was presented in a Special Issue of *Philosophical Transactions of the Royal Society A* in 2009, ‘The Pliocene. A vision of Earth in the late twenty-first century?’ (see Dowsett et al., 2009; Lunt et al., 2009; Salzmann et al., 2009). Specific experiments with a past-for-future agenda are proposed in the experimental designs of PlioMIP2 (Haywood et al., 2016) and PlioMIP3 (Haywood et al., 2024), including CO₂ sensitivity experiments. Such experiments have allowed for more detailed comparisons of large-scale features of Pliocene and future climates (Haywood et al., 2020), as well as assessments of the role of CO₂ forcing in the Pliocene given its dominance in driving anthropogenic climate change (Burton et al., 2023).

A keystone paper in more recent years, Burke et al. (2018) present the first quantitative comparison of possible palaeoclimate analogue

candidates, using an ensemble of three models (HadCM3, GISS and CCSM). They compare December, January and February (DJF) and June, July and August (JJA) SAT and total monthly precipitation for terrestrial gridpoints in six geo-historical periods (the Early Eocene (~50 Ma), mid-Pliocene (3.3–3.0 Ma), Last Interglacial (129–116 thousand years ago (ka)), mid-Holocene (6 ka), PI (~1850), and ‘historical’ (1940–1970)) to two future scenarios (Representative Concentration Pathway (RCP) 4.5 and RCP8.5) for each decade from 2020 to 2280. The Pliocene is found to be the best analogue for the remainder of this century under both RCP4.5 and RCP8.5, though the climate most closely resembles the Eocene by 2140 under RCP8.5; RCP4.5 is described as “a Pliocene commitment scenario” (p. 13,289). Despite this conclusion, the Pliocene is the closest analogue for only 37 % of terrestrial grid cells in 2280 under RCP4.5 and 22 % under RCP8.5 (peaking at ~40 % in 2080; Burke et al., 2018), so it might be possible to describe the Pliocene as the “best” analogue, but this does not necessarily imply that it is a good analogue.

Another recent keystone paper, Tierney et al. (2020) showcase the ways in which past climates can inform our understanding of future climate change. Beyond having comparable atmospheric CO₂ concentration to modern and near-term future under low- to medium-emission scenarios (e.g., Shared Socioeconomic Pathway (SSP) 2–4.5), the Pliocene is highlighted in two ways. The first focuses on the way in which the Pliocene can provide insights into the processes that drive destabilisation of the ice sheets; a refined understanding of threshold behaviour in ice sheets will improve projections of future sea level rise. The second considers how past warm climates like the Pliocene can provide insights into regional hydroclimate and the response of subtropics to higher CO₂ concentrations. Future projections generally simulate drying in the subtropics, but the Pliocene suggests that this drying may be a transient feature that would not persist in equilibrium with higher CO₂ forcing (e.g., Burls and Fedorov, 2017; Ibarra et al., 2018; Feng et al., 2022). This highlights the importance of timescales when considering palaeoclimate analogy; the Pliocene, or any other analogue candidate, may look more, or less, analogous depending how far into the future one considers as the system approaches equilibrium.

The focus of the Pliocene-for-future analogy typically remains on SAT response to CO₂ forcing but is used generally as motivation for wide-ranging research, with more literature discussing (to varying levels of detail) the level of analogy of processes operating within the climate system (e.g. those affecting hydroclimate (Sun et al., 2018; Bernett et al., 2021; Menemenlis et al., 2021; Feng et al., 2022; Han et al., 2023), large-scale circulation (e.g., Corvec and Fletcher, 2017; Abell and Winckler, 2023; Weiffenbach et al., 2023; Weiffenbach et al., 2024), and ENSO (Pontes et al., 2022; Oldeman et al., accepted)). Consideration is also being given to processes operating within specific regions (e.g. in the Arctic (de Noijer et al., 2020; Behera et al., 2021), in the Pacific Ocean (Abell and Winckler, 2023; Grant et al., 2023), and the Coral Triangle (Harrison et al., 2023)), highlighting how the level of analogy between the Pliocene and the future can differ spatially (see also Burton et al., 2023).

There evidently are similarities between the climate of the Pliocene and of the future, and it is naturally tempting to want to use our understanding of the Pliocene to better understand the workings of the climate system as anthropogenic greenhouse gas emissions continue to warm the Earth. However, it is paramount to remember that the Pliocene is a “possible yet imperfect” analogue (Robinson et al., 2008, p. 501) and the message of caution first urged by Crowley (1990, 1991) should be heeded to avoid drawing and promoting inaccurate conclusions.

In this paper, we assess the Pliocene as a specific example of a palaeoclimate analogue by applying elements of the palaeoclimate analogy framework proposed by Oldeman et al. (in review). Per step one of the framework, the relevance of this assessment is that the Pliocene is often referred to as an analogue for the end of the 21st century, and that the vast majority of these references do not include a critical assessment of ‘analogy’. We consider how analogous Pliocene SAT and precipitation

change are to a range of future climate change scenarios in the near-term (2021–2040), medium-term (2041–2060), and long-term (2081–2100) future presented in the IPCC Sixth Assessment Report (AR6), at a global scale and in terms of the annual mean and boreal winter (December, January, February; DJF) and boreal summer (June, July, August; JJA) seasons. As recommended in the Oldeman et al. framework, we also contextualise this response analogy and explore forcing analogy by considering the role of CO₂ forcing vs. non-CO₂ forcing in driving SAT and precipitation change. We discuss the strengths and limitations of using the Pliocene as a palaeoclimate analogue, with the overall aim of making this area of research more useful and impactful when preparing for future climate change.

2. Methods

2.1. Pliocene climate data

The Pliocene climate is assessed using data from PlioMIP2 (see Haywood et al., 2016; Haywood et al., 2020). PlioMIP2 comprises an ensemble of 17 models, with results on the large-scale features and climate sensitivity presented in Haywood et al. (2020); results for HadGEM3 are presented separately in Williams et al., 2021; see Section S1). All 17 models are considered in this paper. All model groups use standardised boundary conditions for the core Pliocene control experiment (Eoi⁴⁰⁰), derived from the U.S. Geological Survey (USGS) fourth Pliocene Research, Interpretation and Synoptic Mapping (PRISM4) reconstruction (Dowsett et al., 2016). The boundary conditions include spatially complete gridded data-sets for land-sea distribution, topography and bathymetry, vegetation, soils, lakes and land ice cover at 1° x 1° of latitude-longitude. Readers are referred to Haywood et al. (2016) and Haywood et al. (2020) for further details.

To reduce the effect of variability and to allow for more accurate Pliocene-for-future assessment, PlioMIP2 focuses on Marine Isotope Stage (MIS) KM5c (3.205 ± 0.01 Ma), a warm interglacial with similar-to-modern orbital forcing (Haywood et al., 2013). When we refer to the “Pliocene” in this paper, we are specifically referring to MIS KM5c.

The nomenclature for PlioMIP2 follows the form Ex^c, where c is the atmospheric concentration of CO₂ in ppm, and x is either, both or neither of Pliocene orography (represented by ‘o’, which also includes fixed vegetation, lakes, soils) and Pliocene ice sheets (represented by ‘i’). In this paper we consider the full Pliocene control experiment (Eoi⁴⁰⁰), the PI control experiment (E²⁸⁰), and a PI experiment with Pliocene-equivalent CO₂ concentration (E⁴⁰⁰).

Climate forcings in the Pliocene are assessed using the FCO₂ method of Burton et al. (2023). This method uses the Eoi⁴⁰⁰, E²⁸⁰ and E⁴⁰⁰ PlioMIP2 experiments, and shows the proportion of climate change that is driven by CO₂ forcing (an FCO₂ value close to 1 represents change very strongly driven by CO₂ forcing, whereas an FCO₂ value close to 0 represents change very strongly driven by non-CO₂ forcing). For this forcing analysis a subset of 7 models (CCSM4-UoT, CESM2, COSMOS, HadCM3, IPSLCM5A2, MIROC4m and NorESM1-F) is considered for the annual mean and a subset of 6 models (CCSM4-UoT, CESM2, COSMOS, HadCM3, MIROC4m and NorESM1-F) is considered for the seasonal analysis, comprised of the only models to have run the required E⁴⁰⁰ experiment. Sensitivity experiments show that the impact of this reduced ensemble for the seasonal analysis is negligible. Readers are referred to Burton et al. (2023) for full details on the FCO₂ methodology.

2.2. Future climate data

The ‘future’ is presented using SSP scenarios from Phase 6 of the Coupled Model Intercomparison Project (CMIP6), included in IPCC AR6. Four SSPs are considered: SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5. These illustrative scenarios represent different pathways of future warming (see Section TS1.3.1 in Arias et al., 2021). The SSP itself is denoted by the number immediately following “SSP” (i.e., 1, 2, 3, or 5),

and the second component (i.e., 2.6, 4.5, 7.0, or 8.5) refers to the approximate increase in radiative forcing (in W m⁻²) in 2100 compared to PI. SSP1-2.6 is therefore the lowest emission scenario considered here, and SSP5-8.5 is the highest emission scenario.

Each scenario is considered for three intervals: near-term (2021–2040), medium-term (2041–2060) and long-term (2081–2100). These near-term, medium-term and long-term intervals are used consistently as in IPCC AR6 and data is sourced from the IPCC Working Group I (WGI) Interactive Atlas (hereafter referred to as “IPCC Atlas”; Gutiérrez et al., 2021a, Gutiérrez et al., 2021b; Iturbide et al., 2021a). Data from the IPCC Atlas is not available beyond 2100. For full technical details on the IPCC Atlas readers are referred to Iturbide et al. (2021a, 2021b). Anomalies are calculated relative to the CMIP6 1850–1900 historical run (hereafter referred to as “CMIP6 PI” where appropriate). When calculating anomalies, we consider the annual mean, boreal winter (DJF) mean and boreal summer (JJA) mean of each interval.

The size and composition of the model ensemble differs depending on the climate variable and SSP selected. For SAT (Section 3.1.1 and Section 3.1.2), the ensemble size is 32 for SSP1-2.6, 34 for SSP2-4.5, 30 for SSP3-7.0 and 34 for SSP5-8.5. For total precipitation (Section 3.2.1 and Sect 3.2.2), the ensemble size is 31 for SSP1-2.6, 32 for SSP2-4.5, 28 for SSP3-7.0 and 33 for SSP5-8.5 (see Table Atlas.SM.2 in Gutiérrez et al., 2021c). Individual model data for CNRM-CM6-1 was not available for SAT or precipitation so this model is excluded in Section 3.1.3 and 3.2.3; CESM2-WACCM is also excluded in the DJF and JJA analysis in Section 3.2.3 (but is included in the annual mean analysis) as monthly data was not available.

2.3. Assessing analogy between Pliocene and future climates

In this paper we focus on SAT and total precipitation. Though we understand and advocate the importance of assessing a range of climate variables when considering analogy, SAT and total precipitation are directly comparable variables between the PlioMIP2 and CMIP6 data-sets, and also have a large impact on society under anthropogenic climate change. As more data becomes available (particularly higher temporal resolution data in the PlioMIP simulations), comparing climate extreme variables such as maximum temperature and precipitation would also be highly valuable. The methods we use in this paper can be applied to any climate variable so long as the necessary data is available.

The criteria for and definition of analogy is dependent upon the variable(s) of choice, available data, and methodology (Oldeman et al., in review). Four methods in which analogy can be assessed are presented, each of which may lead to different conclusions of analogy. Firstly, we calculate the difference (Δ) between Pliocene and future SAT and precipitation change using

$$\Delta = (Eoi^{400} - E^{280}) - (SSP - PI) \quad (1)$$

where Eoi⁴⁰⁰ is the PlioMIP2 Pliocene control run, E²⁸⁰ is the PlioMIP2 PI control run, SSP is any of the four SSP scenarios, and PI is the CMIP6 1850–1900 historical run (hereafter referred to as “CMIP6 PI”).

Secondly, *t*-test statistics are presented alongside SAT results and are calculated for both the (area-weighted) global mean and by individual grid cell. Thirdly, for both SAT and precipitation, the (area-weighted) global mean root mean squared error (RMSE) is also calculated and presented alongside Δ values. And fourthly, the interquartile range (IQR) of the Pliocene ensemble is compared to the IQR of each future projection ensemble (see Section 3.1.3 and Section 3.2.3).

It is worth noting that the E²⁸⁰ (PlioMIP2 PI control) run is different to the CMIP6 PI run. The E²⁸⁰ ensemble presented here comprises the 17 models in the PlioMIP2 ensemble (those presented in Haywood et al. (2020) in addition to HadGEM3 (Williams et al., 2021)), compared to a larger ensemble which collectively displayed a greater feedback to forcing for the CMIP6 PI (Gutiérrez et al., 2021a; Gutiérrez et al., 2021b; Iturbide et al., 2021a; Arias et al., 2021). The decision was made to keep

the respective PlioMIP2 and CMIP6 PI bases, rather than select a single one, for internal consistency. For the global annual mean SAT, the CMIP6 PI is 0.36 °C warmer than E²⁸⁰ (0.40 °C warmer in DJF and 0.31 °C warmer in JJA), though regional differences range within $\pm \sim 4$ °C. For the global annual mean total precipitation, the CMIP6 PI is 0.09 mm d⁻¹ wetter than E²⁸⁰ (0.08 mm d⁻¹ wetter in DJF and 0.09 mm d⁻¹ wetter in JJA). Readers are referred to [Section S2](#) for further details.

Ideally, an analogy assessment would be conducted with the same models to negate the impact of different model versions and parameterisations. In this case, we decided to use the full CMIP6 and PlioMIP2 ensembles since the ensembles are relatively large (at least 17 models per ensemble) and the overlap of models is relatively small (only two PlioMIP2 models (CESM2 and IPSL-CM6A-LR) conducted the CMIP6 experiments included here). Though the ensembles differ, a benefit of using ensembles is having a greater number of realisations to compare. It would be possible for future research to apply the same methodology to a single model, or to an ensemble with identical members, to further explore these implications.

In accordance with steps two and three of the [Oldeman et al. \(in review\)](#) framework, we have clearly described the methods used to assess analogy, and these relatively simple methods and ease of data availability ensure that the assessment is feasible. As further (model or geological proxy) data becomes available and/or is incorporated, both the feasibility (step three) and confidence in the assessment (step four) is likely to improve.

3. Results

3.1. Surface air temperature

3.1.1. Annual mean

The level of analogy in the annual mean SAT response between the Pliocene and the future is highly dependent on what ‘future’ is considered ([Fig. 2](#)). In the near term (left column in [Fig. 2](#)), the Pliocene is warmer than all SSP scenarios (with the exception of central Antarctica where all scenarios are ~ 5 °C warmer than the Pliocene).

Differences between the SSP scenarios begin to emerge in the medium term (central column in [Fig. 2](#)) and the number of regions that are warmer in the future than in the Pliocene begins to increase in the highest emission scenario (SSP5-8.5), to include parts of Australia, central Africa, northern North America, the Indian subcontinent, and northeastern China ([Fig. 2k](#)).

The increased warming in the medium term relative to the near term means that the Pliocene is generally more comparable to the medium-term future than the near-term future. In terms of annual mean SAT, however, the long-term future (right column in [Fig. 2](#)) is overall the most analogous to the Pliocene. According to Δ , the long-term SSP2-4.5 projection is the most analogous to the Pliocene of all twelve futures considered, with a global mean anomaly of 2.93 °C compared to the Pliocene anomaly of 3.29 °C ([Fig. 2f](#)). The global mean t -test results support this conclusion, with the long-term SSP2-4.5 projection the only projection to not be statistically different to the Pliocene ($t(16) = 1.46$, $p = 0.15$). That most future projections are statistically different to the Pliocene shows that the Pliocene is, at best, partially analogous rather than perfectly analogous. Though the most analogous in terms of global mean Δ and t -test, the RMSE between the Pliocene and both the long-term SSP2-4.5 and SSP3-7.0 projections is 2.58. The greater degree of

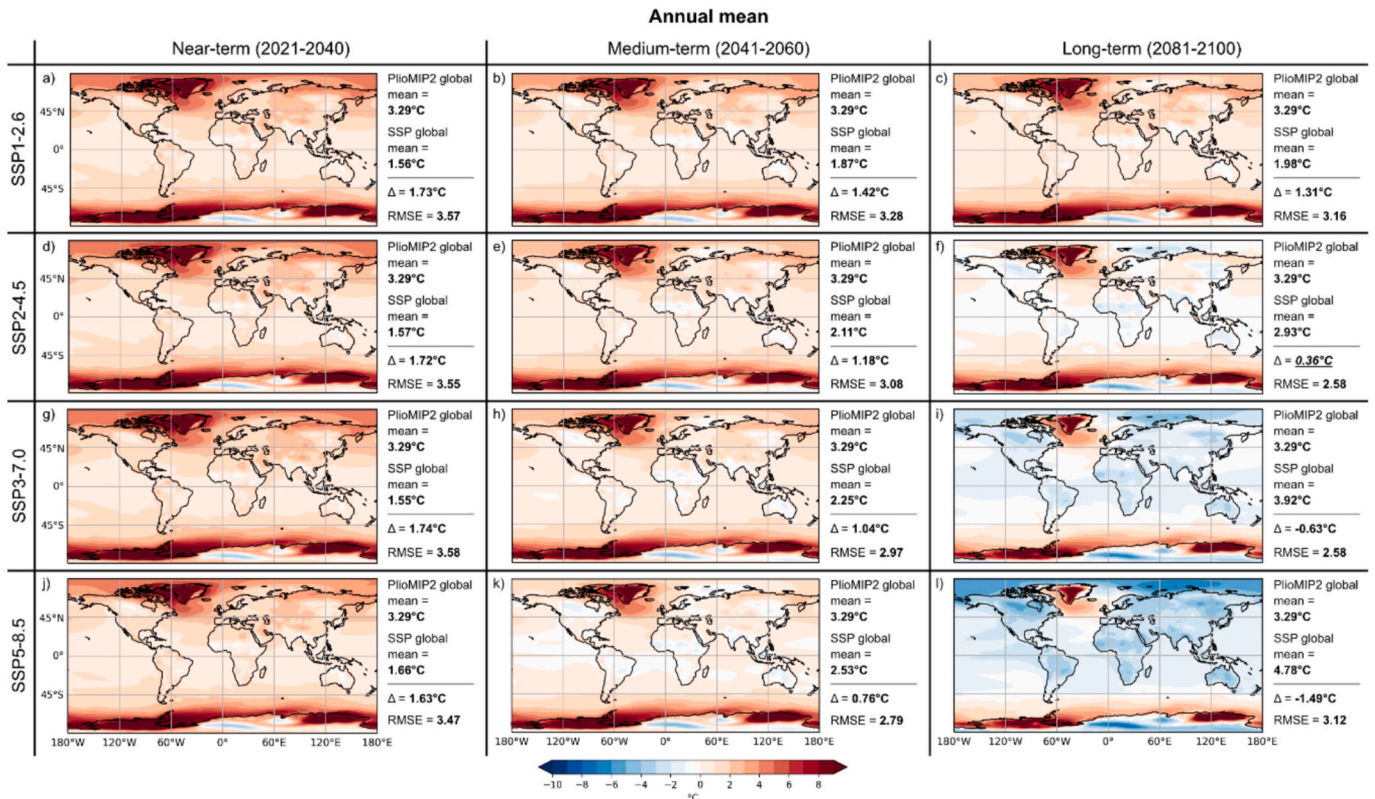


Fig. 2. Δ in annual mean Pliocene and SSP SAT per eq. 1. Each row represents a different future interval, and each column represents a different future interval. Red shading indicates where the Pliocene is warmer than the future, and blue shading represents where the future is warmer than the Pliocene. Global mean anomalies, RMSE and Δ per eq. 1 are also shown. The smallest Δ is underlined and italicised. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

warming in SSP3-7.0 and SSP5-8.5 mean that they become warmer than the Pliocene, with global mean anomalies of 3.92°C ($t(16) = -2.15$, $p = 0.037$) and 4.78°C ($t(16) = -4.64$, $p = 2.68 \times 10^{-5}$), respectively. So, though the long-term SSP2-4.5 global mean appears the most analogous to the Pliocene, the level of warming in the Pliocene falls between that of the long-term SSP2-4.5 and SSP3-7.0 projections for the time intervals considered here.

There is also notable spatial variation in Δ between SSP scenarios and future intervals, so conclusions of analogy may, and should, differ upon the region(s) of interest. Even in the (most analogous) long-term SSP2-4.5 scenario, there are notable regions with large, statistically significant differences (see Section S3), including parts of Antarctica and Greenland which have a Δ exceeding 10°C . This variation can largely be explained by non- CO_2 Pliocene boundary conditions, particularly the reduction of the extent and volume of the ice sheets, equivalent changes of which are not projected over the timescales considered here (see Section 3.1.4.).

3.1.2. Seasonal means

As in the annual mean, the global mean warming in DJF in the long-term SSP2-4.5 projection (Fig. 3f) is the most analogous to the Pliocene in terms of global mean Δ , with values of 3.07°C and 3.12°C , respectively. Global mean t -test results also indicate that the long-term SSP2-4.5 projection is also the most analogous ($t(16) = 0.22$, $p = 0.83$), and the medium-term SSP5-8.5 projection is also not statistically different from the Pliocene ($t(16) = 2.00$, $p = 0.051$). However, the RMSE value for the medium-term SSP5-8.5 projection is smaller (RMSE = 2.44 for the medium-term SSP5-8.5 projection compared to RMSE = 2.49 for the long-term SSP2-4.5 projection), again highlighting that the choice of methodology affects the conclusions drawn. As in the annual mean, even in these two most analogous scenarios there are notable regions where

significant differences are seen between the Pliocene and future (vivid shading in Fig. 3; Section S3).

The spatial patterns of Δ between the Pliocene and future projections are comparable in DJF (Fig. 3) to the annual mean (Fig. 2), with some notable exceptions:

- Warming is generally reduced in DJF compared to the annual mean off the Antarctic coastline, indicating the effect of the reduced Antarctic ice sheet in the Pliocene (see Section 3.1.4.).
- Depending on the scenario the Hudson Bay is $\sim 8\text{--}20^\circ\text{C}$ warmer in the future than the Pliocene, relating to the different boundary conditions between the Pliocene (where the Bay is land) and the modern (where it is water).
- The Δ between the Pliocene and the future increases in the northern high latitudes, particularly in the long term. Under SSP5-8.5 in the long term, the atmospheric concentration of CO_2 would be significantly higher than that of the Pliocene and consequently sees temperature anomalies $\sim 8\text{--}10^\circ\text{C}$ greater than in the Pliocene (Fig. 3l). This leads to greater sea ice loss under SSP5-8.5 and associated sea-ice-albedo feedbacks.

The spatial pattern of the difference between Pliocene and future warming in JJA (Fig. 4) is an amplification of what is seen in the annual mean: Greenland and coastal Antarctica are over 10°C warmer in the Pliocene than in future projections (with some parts exceeding 20°C Δ), suggesting the particular impact of changes to the ice sheets in the JJA period (Weiffenbach et al., 2024; see Section 3.1.4.).

Unlike in the annual mean and the DJF period, in JJA the global mean long-term SSP3-7.0 projection (Fig. 4i) is the most analogous to the Pliocene. This is true across multiple methods, with a Δ value of -0.36°C and a RMSE value of 2.91. The global mean t -test results also

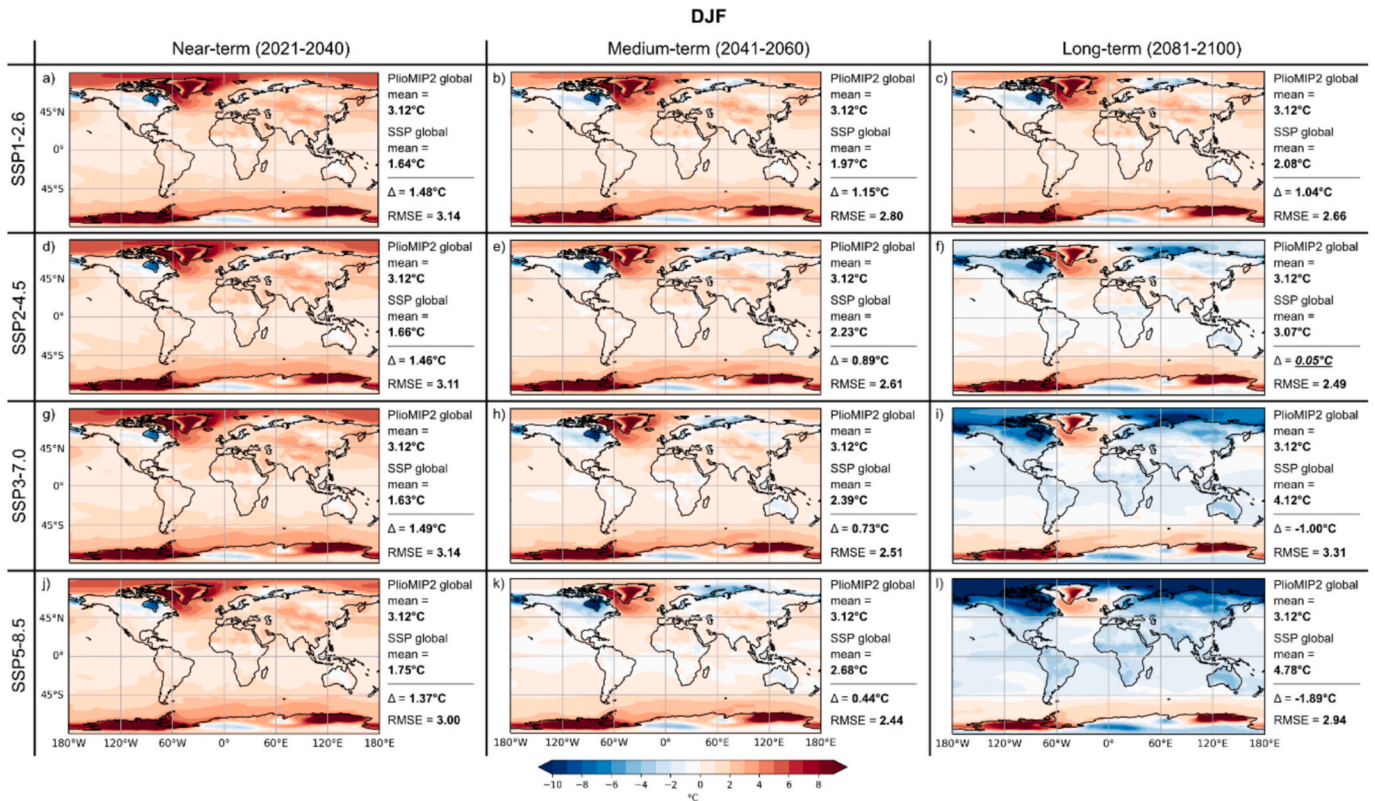


Fig. 3. Δ in DJF Pliocene and SSP SAT per eq. 1. Each row represents a different SSP scenario, and each column represents a different future interval. Red shading indicates where the Pliocene is warmer than the future, and blue shading represents where the future is warmer than the Pliocene. Global mean anomalies, RMSE and Δ per eq. 1 are also shown. The smallest Δ is underlined and italicised. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

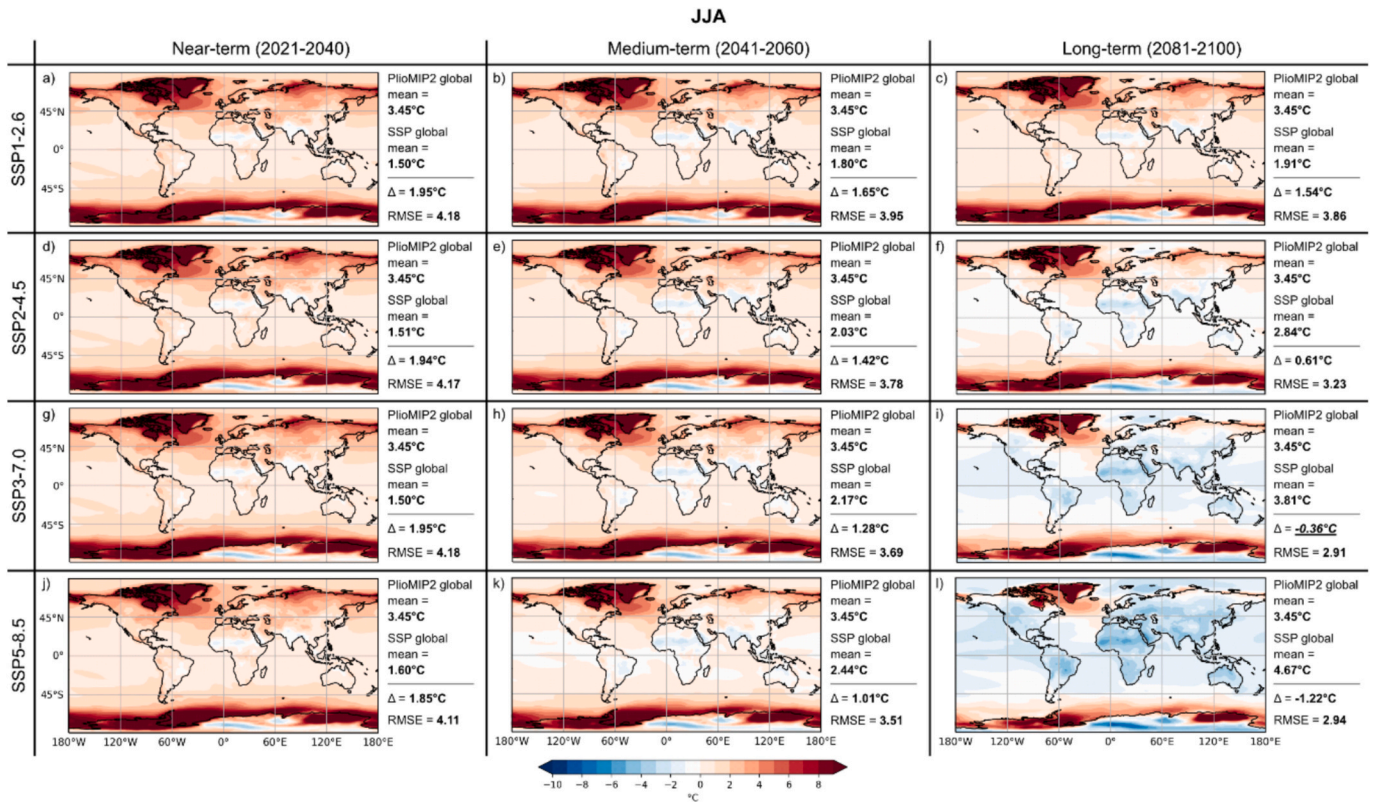


Fig. 4. Δ in JJA Pliocene and SSP SAT per eq. 1. Each row represents a different SSP scenario, and each column represents a different future interval. Red shading indicates where the Pliocene is warmer than the future, and blue shading represents where the future is warmer than the Pliocene. Global mean anomalies, RMSE and Δ per eq. 1 are also shown. The smallest Δ is underlined and italicised. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

indicate that this is the only JJA projection to not be statistically different to the Pliocene ($t(16) = -1.16$, $p = 0.25$). This is the only occasion where the closest analogue is warmer in the future than in the Pliocene, indicating that, in the long term (2081–2100), the most analogous future to the Pliocene is between SSP2-4.5 and SSP3-7.0 (being closer to SSP2-4.5 in the annual mean and DJF, and closer to SSP3-7.0 in JJA).

These results show that the level of analogy between the Pliocene and future projections is highly dependent on the ‘future’ that is chosen. It is also clear how the level of analogy differs both spatially (with some regions (e.g., ice regions) appearing less analogous than others; Section S2) and temporally (either seasonally, and/or how far into the future is considered).

3.1.3. Ensemble spread

Though comparing the global means and spatial patterns can be insightful, it does not account for the uncertainty seen between different models. Understanding the model spread is also useful when assessing the level of analogy between the Pliocene, or any other time period, and the future because it can increase or decrease the robustness of the analogy.

Fig. 5 shows a comparison of the individual model spread in SAT change in the Pliocene and the twelve ‘futures’ considered here. The overall range is larger in the PlioMIP2 ensemble than in most future projections, though the model spread increases with the level of emissions and duration into the future (i.e., the long-term SSP5-8.5 projection has a greater spread than the near-term SSP1-2.6 projection).

This data provides additional context for the comparison of global mean values (blue dots in Fig. 5). Considering the model ensembles, rather than just the multi-model mean, the long-term SSP2-4.5 projection is consistently the most analogous to the Pliocene for SAT change.

The annual mean $E_{oi}^{400} - E_{280}$ IQR (purple shading in Fig. 5a) fully captures the IQR of the long-term SSP2-4.5 projection (Fig. 5a). The median (orange lines in Fig. 5) of the long-term SSP3-7.0 and medium-term SSP5-8.5 projections also fall within the $E_{oi}^{400} - E_{280}$ IQR, while the median for the medium-term SSP3-7.0 projection falls just outside of the $E_{oi}^{400} - E_{280}$ IQR.

The medians of four projections fall within the $E_{oi}^{400} - E_{280}$ IQR for the DJF period (Fig. 5b): SSP2-4.5 in the medium term, SSP2-4.5 in the long term, SSP3-7.0 in the medium term, and SSP5-8.5 in the long term. For the JJA period (Fig. 5c), the medians of three projections fall within the $E_{oi}^{400} - E_{280}$ IQR: SSP2-4.5 in the long term, SSP3-7.0 in the long term, and SSP5-8.5 in the medium term. In JJA, we have shown that the global mean anomaly of the long-term SSP3-7.0 projection is most analogous to that of the Pliocene, but the long-term SSP2-4.5 projection is also well captured by the PlioMIP2 $E_{oi}^{400} - E_{280}$ range.

By looking at the $E_{400}^{400} - E_{280}^{400}$ and $E_{oi}^{400} - E_{400}^{400}$ IQRs, it is possible to see the relative contribution of CO₂ forcing and non-CO₂ forcing to the overall Pliocene SAT anomaly ($E_{oi}^{400} - E_{280}^{400}$), respectively (see also Section 3.1.4). The $E_{400}^{400} - E_{280}^{400}$ IQR (green shading in Fig. 5) captures all near-term futures but is exceeded in the medium- to long term, especially for higher emission scenarios. This highlights the need to understand and account for the level of analogy in terms of relevant climate forcing(s), as well as the overall response.

3.1.4. Response to forcing

The comparable (global mean) temperature response is one of the most commonly cited reasons for drawing analogy between the Pliocene and the future. However, studies very rarely explicitly assess the level of analogy in the forcing of this temperature response, meaning that the temperature response may be comparable but driven by different forcings. Using the FCO₂ method of Burton et al. (2023), hatching in Fig. 6

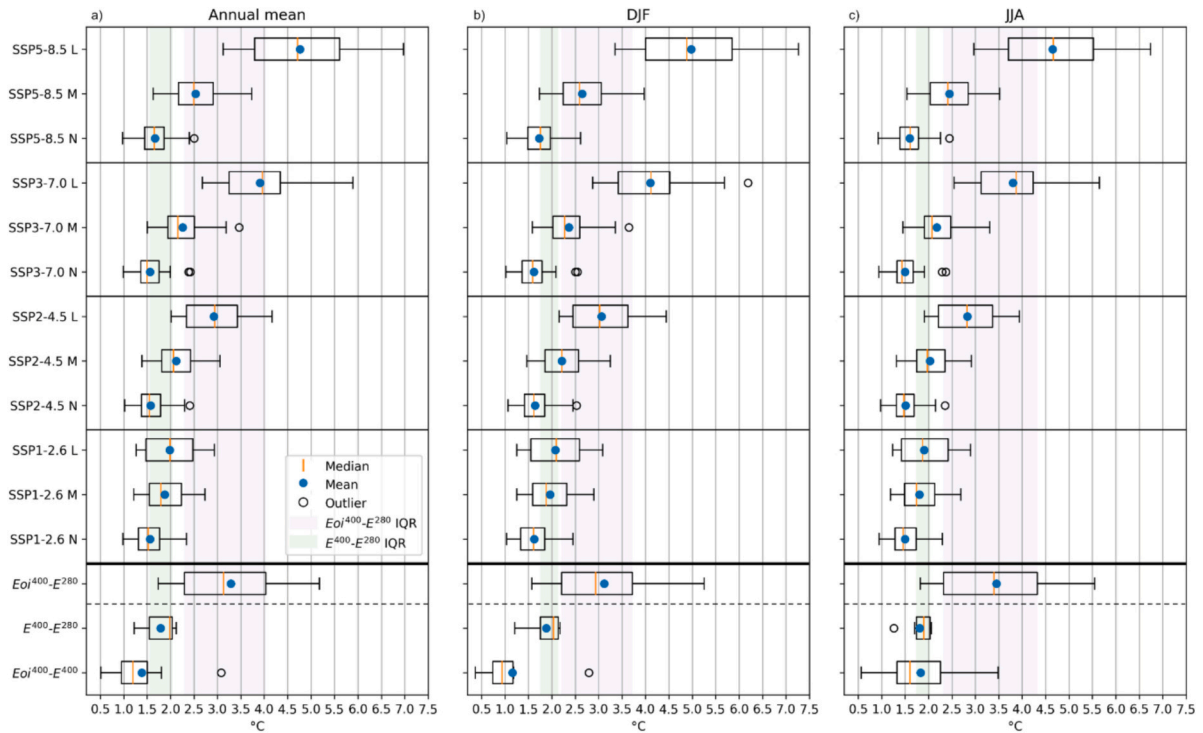


Fig. 5. Comparison of annual mean (a), DJF (b), and JJA (c) Pliocene SAT $Eoi^{400} - E^{280}$ anomaly to near-term ('N'), medium-term ('M'), and long-term ('L') SSP scenarios. The $E^{400} - E^{280}$ and $Eoi^{400} - E^{400}$ anomalies are also included, which show the relative contribution of CO₂ forcing ($E^{400} - E^{280}$) and non-CO₂ forcing ($Eoi^{400} - E^{400}$) to the overall Pliocene anomaly ($Eoi^{400} - E^{280}$). In each case, the box represents the interquartile range (IQR) of each dataset. The tails represent the outermost data points within $1.5 \times$ the IQR; data points outside this (outliers) are represented by open black circles. The median of each dataset is represented by a vertical orange line in each box, and the mean is represented by a blue circle. The purple shading extends the $Eoi^{400} - E^{280}$ IQR for ease of comparison between the various future scenarios, and the green shading similarly extends the $E^{400} - E^{280}$ IQR. The outlier in the annual mean and DJF for $Eoi^{400} - E^{400}$ is CESM2, and outlier in JJA $E^{400} - E^{280}$ is NorESM1-F. All outliers in the SSP simulations are either CanESM and/or KACE1-0-G. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

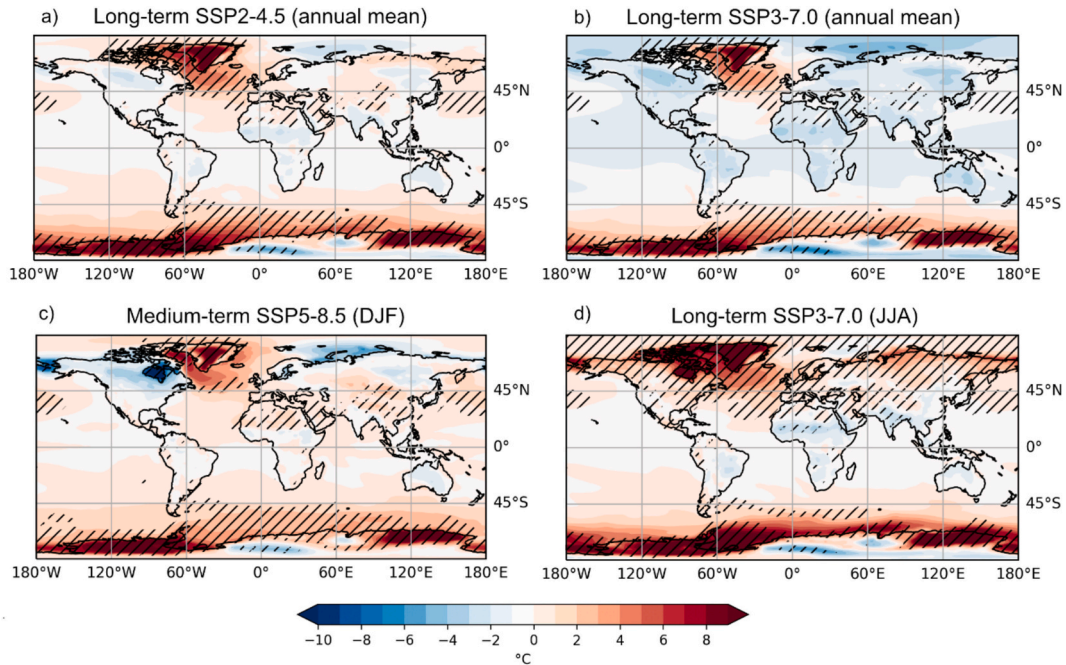


Fig. 6. Δ in annual mean, DJF, and JJA Pliocene and projected future SAT change per eq. 1. The projected futures shown are those with the lowest RMSE values for the annual mean (a, b), DJF (c) and JJA (d) respectively (i.e. Fig. 2f (a), Fig. 2i (b), Fig. 3k (c), and Fig. 4i (d)). Hatching denotes regions that are predominantly driven by non-CO₂ forcing per the FCO₂ method, i.e., where FCO₂ < 0.5 (see Burton et al., 2023); these regions broadly overlap the least analogous regions in terms of SAT change (darkest colours). Note that the FCO₂ ensemble size is 7 for the annual mean, and 6 for DJF and JJA (see Section 2.1).

denotes regions where non-CO₂ forcing (such as changes to orography, vegetation, and ice sheets) predominantly drive Pliocene SAT change on the Δ seen in Fig. 2, Fig. 3, and Fig. 4. The scenarios with the lowest RMSE values for the annual mean, DJF, and JJA are presented (annual mean long-term SSP2-4.5 (Fig. 6a) and SSP3-7.0 (Fig. 6b) projections; DJF medium-term SSP5-8.5 projection (Fig. 6c); and JJA long-term SSP3-7.0 projection (Fig. 6d)). Regions of the largest Δ are often found in regions that are predominantly forced by non-CO₂ forcing (hatching in Fig. 6), a pattern that is particularly evident in the annual mean (Fig. 6a).

Though the FCO₂ method itself cannot provide exact details of the non-CO₂ forcing, the location of the region(s) of low FCO₂ (FCO₂ < 0.5) can provide some insight. For example, low FCO₂ is seen in regions of vegetation change, such as parts of the Arctic and the Sahara which underwent a greening during the Pliocene (Myers-Smith et al., 2020; Salzmann et al., 2008).

Additionally, regions of low FCO₂ over Greenland and Antarctica indicate the effect of reduced ice sheets on Pliocene SAT; the reduction in the Pliocene Antarctic ice sheet is seen to impact surface warming and circulation in the Southern Ocean (Weiffenbach et al., 2024). The Pliocene is seen to be >10 °C warmer than the long-term SSP2-4.5 projection in these regions. Though ice melt is projected in the future, the reduction of land ice is not included in SSP projections and is also not similar (enough) to the Pliocene ice extent on the timescales considered here.

As the magnitude and spatial pattern of Δ change seasonally, so too does the dominant forcing in the Pliocene. For example, the Δ in SAT in the Hudson Bay, Baffin Bay and Labrador Sea can be explained by the different boundary conditions in the Pliocene relative to the modern day. This consequently acts to increase the Atlantic Meridional Overturning Circulation (AMOC), which suppresses sea ice cover and further

amplifies the warming (Weiffenbach et al., 2023; de Nooijer et al., 2020).

The role of non-CO₂ forcing means that, particularly for lower emission scenarios (e.g., SSP1-2.6), the Pliocene may become more analogous on longer timescales than are considered here as the Earth system equilibrates to this non-CO₂ forcing and associated feedbacks.

3.2. Total precipitation

3.2.1. Annual mean

As with SAT, the level of analogy between annual mean Pliocene and future precipitation change is dependent on which SSP and future interval is considered (Fig. 7). Though the global mean precipitation change in the Pliocene is somewhat comparable in most future scenarios, there are significant spatial differences in the pattern of precipitation change. In terms of the global mean, the Pliocene is wetter than all future projections except the long-term SSP5-8.5 projection (Fig. 7).

Though the Δ in precipitation change between the Pliocene and the future is greatest in the near-term (left column of Fig. 7), the RMSE is relatively consistent between different scenarios, ranging between 0.31 (medium-term SSP5-8.5 projection) and 0.40 (long-term SSP5-8.5 projection). There are multiple regions where the Pliocene precipitation change is significantly greater than projected future change (blue shading in Fig. 7), including central Africa and the Arabian Peninsula. The increased precipitation in the Pliocene in this region can be related to changes in vegetation and the presence of large lakes, which increased evapotranspiration and precipitation (see Section 3.2.4). Additionally, increased precipitation over regions with reduced land ice (e.g., Greenland and parts of Antarctica) is related to the fact that SATs are elevated, increasing precipitation potential. Regions that are wetter in the future than in the Pliocene (brown shading in Fig. 7) are limited to

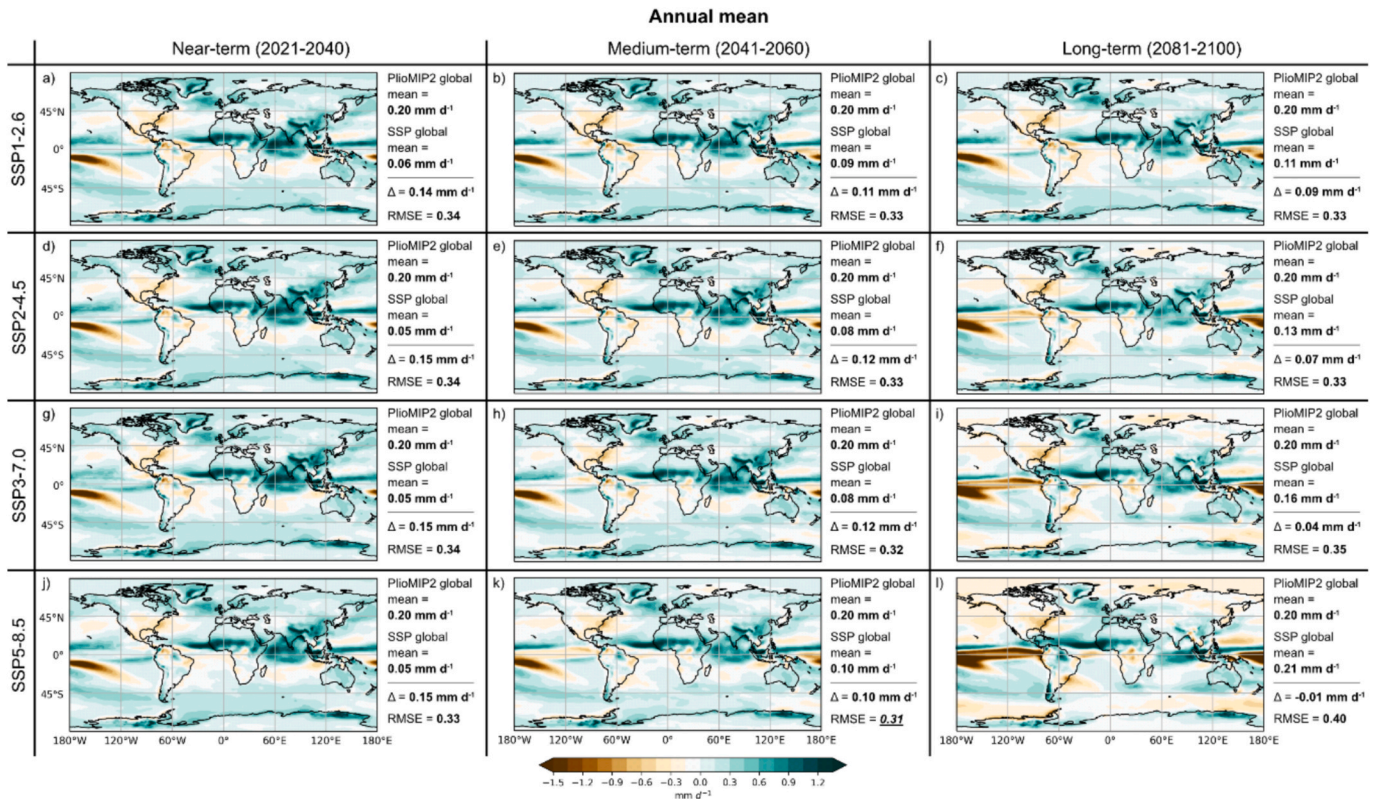


Fig. 7. Δ in annual mean Pliocene and SSP precipitation per eq. 1. Each row represents a different SSP scenario, and each column represents a different future interval. Blue shading indicates where the Pliocene is wetter than the future, and brown shading represents where the future is wetter than the Pliocene. Global mean anomalies, RMSE and Δ per eq. 1 are also shown. The smallest RMSE is underlined and italicised. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

subtropical regions, specifically the southern tropical Pacific Ocean, southern North America, and the southern tropical Atlantic Ocean.

The global means become slightly more comparable in the medium-term and RMSE is marginally reduced, though there are still large spatial differences in some regions. The medium-term SSP5-8.5 projection (Fig. 7k) has the lowest RMSE (0.31) of all scenarios included.

The long-term projections display the largest variation in RMSE between SSPs and, though the SSP5-8.5 projection has the most comparable global mean anomaly overall (PlioMIP2 anomaly of 0.20 mm d^{-1} compared to CMIP6 anomaly of 0.21 mm d^{-1} , i.e. therefore the smallest Δ), it displays the largest RMSE (0.40). The RMSE results further highlight the significant spatial differences in the pattern(s) of precipitation change, which limit conclusions of analogy.

3.2.2. Seasonal means

The spatial patterns and magnitude of change in DJF (Fig. 8) are generally comparable to the annual mean. In terms of the global mean anomaly, the long-term SSP3-7.0 (0.18 mm d^{-1} increase) and SSP5-8.5 (0.22 mm d^{-1} increase) projections are most comparable to the Pliocene (0.19 mm d^{-1} increase), but as in the annual mean, also display the highest RMSE values (0.42 and 0.48, respectively) due to the significant differences in the spatial patterns of precipitation change (Fig. 7i, l). The most analogous projections per the RMSE are the near- and medium-term SSP5-8.5 projections, which both show a value of 0.36.

The regions of greatest Δ between Pliocene and future precipitation are generally seen in the subtropics, with the exception of the Labrador Sea and North Atlantic which are notably wetter in the Pliocene due to differences in boundary conditions (see Section 3.2.4).

Precipitation change is least comparable to the Pliocene in JJA, where the highest RMSE values are consistently seen; values range from 0.48 (medium-term SSP5-8.5 and long-term SSP1-2.6 projections) to

0.59 (long-term SSP5-8.5 projection). Based on the RMSE values, the most comparable projections to the Pliocene for JJA are the medium-term SSP5-8.5 (Fig. 9k) and long-term SSP1-2.6 (Fig. 9c) projections, with the medium-term SSP5-8.5 projection having the lowest RMSE value for the annual mean (0.31), DJF (0.36), and JJA (0.48).

The region of precipitation increase in the Pliocene over central Africa and the Arabian Peninsula seen in the annual mean (Fig. 7) appears to be a seasonal signal from JJA, likely associated with the enhancement of the African, Indian, and East Asian summer monsoons (Haywood et al., 2020). An enhancement of these monsoon systems is also projected in the long-term (2081–2100) future scenarios considered in this paper, although contrasting projections within the ensemble limit the confidence (Douville et al., 2021). Though small in absolute values, there is also a relatively large change over eastern and western Antarctica and Greenland in JJA.

Though the global mean values of precipitation change may be relatively comparable between the Pliocene and certain futures, this analysis (including RMSE values) highlights that there are significant differences in the spatial pattern(s) of precipitation change between the Pliocene and projected futures, both in the annual mean and DJF and JJA seasons. This emphasises the importance of not overstating conclusions of analogy and of understanding the (spatial) limitations; we can conclude that some regions may be analogous in terms of precipitation change for some futures, but as a global picture of hydrological cycle change the Pliocene is not a good analogue.

3.2.3. Ensemble spread

There is a large model spread when considering Pliocene precipitation change (Fig. 10), which again emphasises the uncertainty in the results and the need for caution when assessing analogy. This range is larger in the Pliocene than in the future projections considered, though,

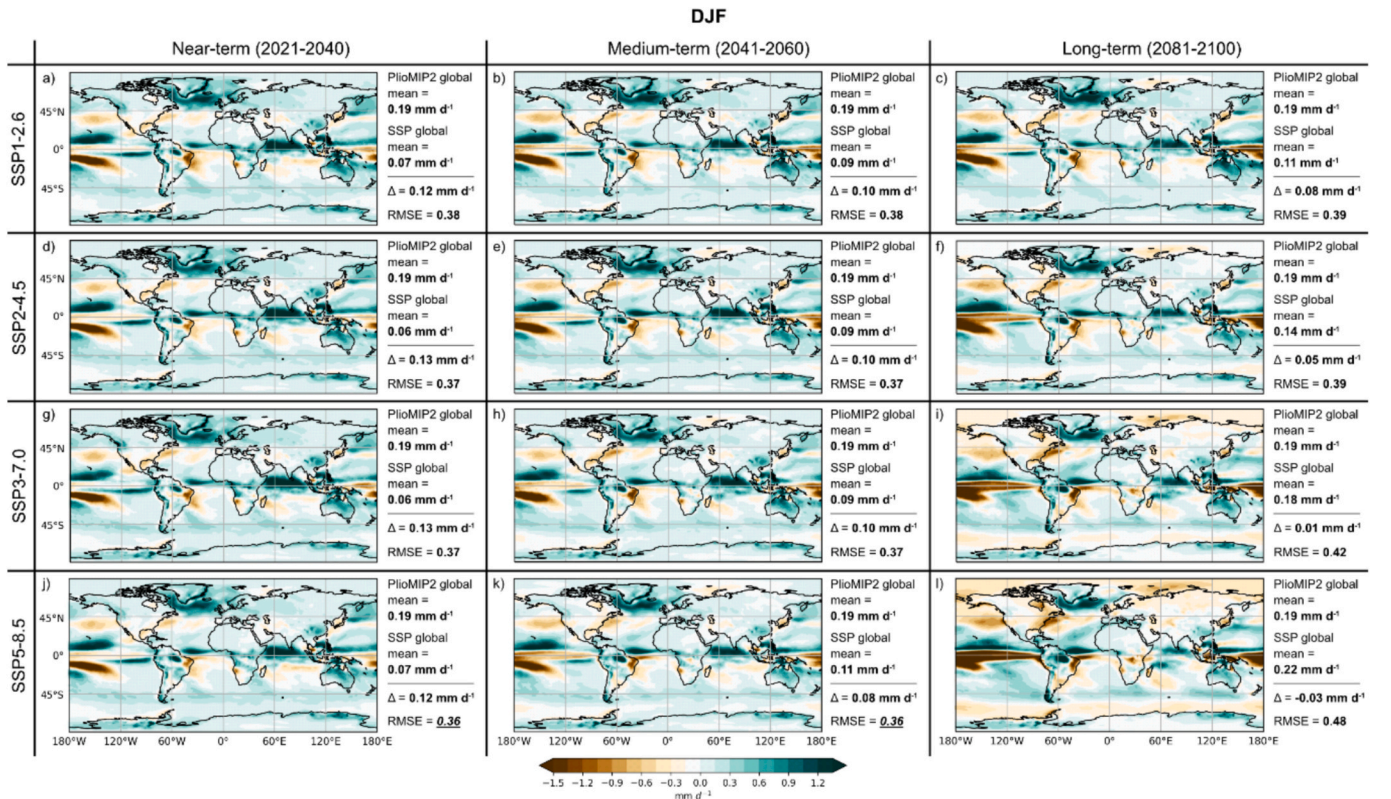


Fig. 8. Δ in DJF Pliocene and SSP precipitation per eq. 1. Each row represents a different SSP scenario, and each column represents a different future interval. Blue shading indicates where the Pliocene is wetter than the future, and brown shading represents where the future is wetter than the Pliocene. Global mean anomalies, RMSE and Δ per eq. 1 are also shown. The smallest RMSE is underlined and italicised. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

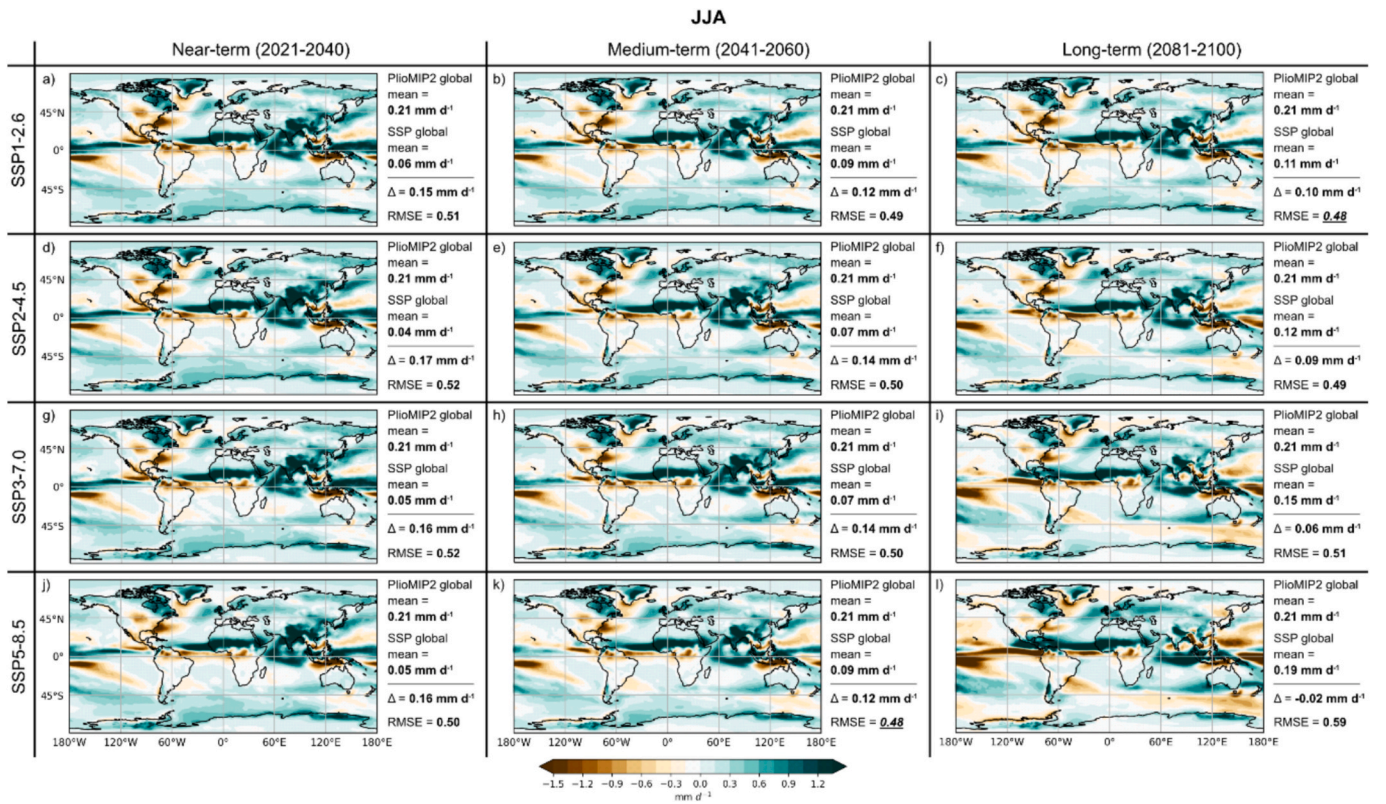


Fig. 9. Δ in JJA Pliocene and SSP precipitation per eq. 1. Each row represents a different SSP scenario, and each column represents a different future interval. Blue shading indicates where the Pliocene is wetter than the future, and brown shading represents where the future is wetter than the Pliocene. Global mean anomalies, RMSE and Δ per eq. 1 are also shown. The smallest RMSE is underlined and italicised. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

as with SAT, the level of model spread and uncertainty increases further into the future and with higher emission scenarios (Fig. 10).

Comparing the model ensembles in this way makes it even more clear how the choice of ‘future’ affects the level of analogy. The annual mean $E_{oi}^{400} - E^{280}$ IQR (purple shading in Fig. 10a) captures the mean (blue dot) and median (orange line) of the long-term SSP3-7.0 and SSP5-8.5 projections; the long-term SSP5-8.5 has a very similar IQR to $E_{oi}^{400} - E^{280}$, but we have shown that there is significant spatial variation (Fig. 7). In DJF, the long-term SSP3-7.0 projection is most central to the $E_{oi}^{400} - E^{280}$ IQR (purple shading in Fig. 10b), with the long-term SSP2-4.5 and SSP5-8.5 falling at the lower and upper ends, respectively. In JJA, the long-term SSP5-8.5 projection is most central to the $E_{oi}^{400} - E^{280}$ IQR (purple shading in Fig. 10c), with the long-term SSP3-7.0 projection also partially captured at the lower end.

Despite these comparable global mean values and ranges, the significant spatial differences in precipitation change between the Pliocene and projected futures (Figs. 6, 7, 8) is not represented. Additionally, by comparing the $E_{oi}^{400} - E^{400}$ and $E^{400} - E^{280}$ ranges, it is clear that a significant proportion of Pliocene precipitation change is driven by non- CO_2 forcing, which is less analogous to the end of the 21st century (Section 3.2.4).

3.2.4. Response to forcing

The spatial pattern of forcings attributable to precipitation change is more complex than for SAT. CO_2 is responsible for 51 % of the global mean Pliocene precipitation increase, but non- CO_2 forcing is predominant in driving the spatial patterns of precipitation change (Burton et al., 2023). Akin to Fig. 6, hatching in Fig. 11 denotes regions where non- CO_2 forcing predominantly drives Pliocene precipitation change (per the FCO₂ method of Burton et al., 2023), overlaying the Δ presented in Fig. 7, Fig. 8 and Fig. 9. The scenarios with the lowest RMSE for the

annual mean, DJF and JJA are presented (annual mean medium-term SSP5-8.5 projection (Fig. 7k); DJF medium-term SSP5-8.5 (Fig. 8k) and near-term SSP5-8.5 (Fig. 8j) projections; and JJA medium-term SSP5-8.5 (Fig. 9k) and long-term SSP1-2.6 (Fig. 9c) projections).

Regions where the Pliocene is wetter than the future (blue shading in Fig. 11) are generally predominantly forced by non- CO_2 forcing (hatching in Fig. 11). Though the absolute change is relatively small, this includes Antarctica and Greenland, where the reduction in extent and volume of the ice sheets leads to an increase in precipitation, and northern Africa, where a reduction in the equator-to-pole temperature gradient weakens the Hadley circulation (e.g., Haywood et al., 2020).

Conversely, regions where the future is significantly wetter than the Pliocene (brown shading in Fig. 11) are generally forced by CO_2 (no hatching in Fig. 11), which is consistent given that atmospheric concentrations of CO_2 under SSP5-8.5 are projected to be greater by 2100 than in the Pliocene. An exception to this is the southern tropical Pacific, where precipitation change is likely related to shifts in atmospheric circulation such as the South Pacific Convergence Zone, Intertropical Convergence Zone and Walker circulation (e.g., Han et al., 2021).

These conclusions are less robust than for SAT given the uncertainty in and complexity of the spatial patterns seen (see also Burton et al., 2023). It is also worth highlighting here that the future scenarios in this paper do not consider vegetation or ice sheet changes, so Pliocene precipitation change may be more analogous to longer-term future projections which would include the equilibrated responses of vegetation and ice sheets to elevated CO_2 concentrations. Further research is needed to explore this effect. Given that (anthropogenic) CO_2 forcing is the dominant driver of climate change today (Eyring et al., 2021), the FCO₂ results here reinforce the finding that the Pliocene is not a good analogue for the global-scale future hydrological cycle.

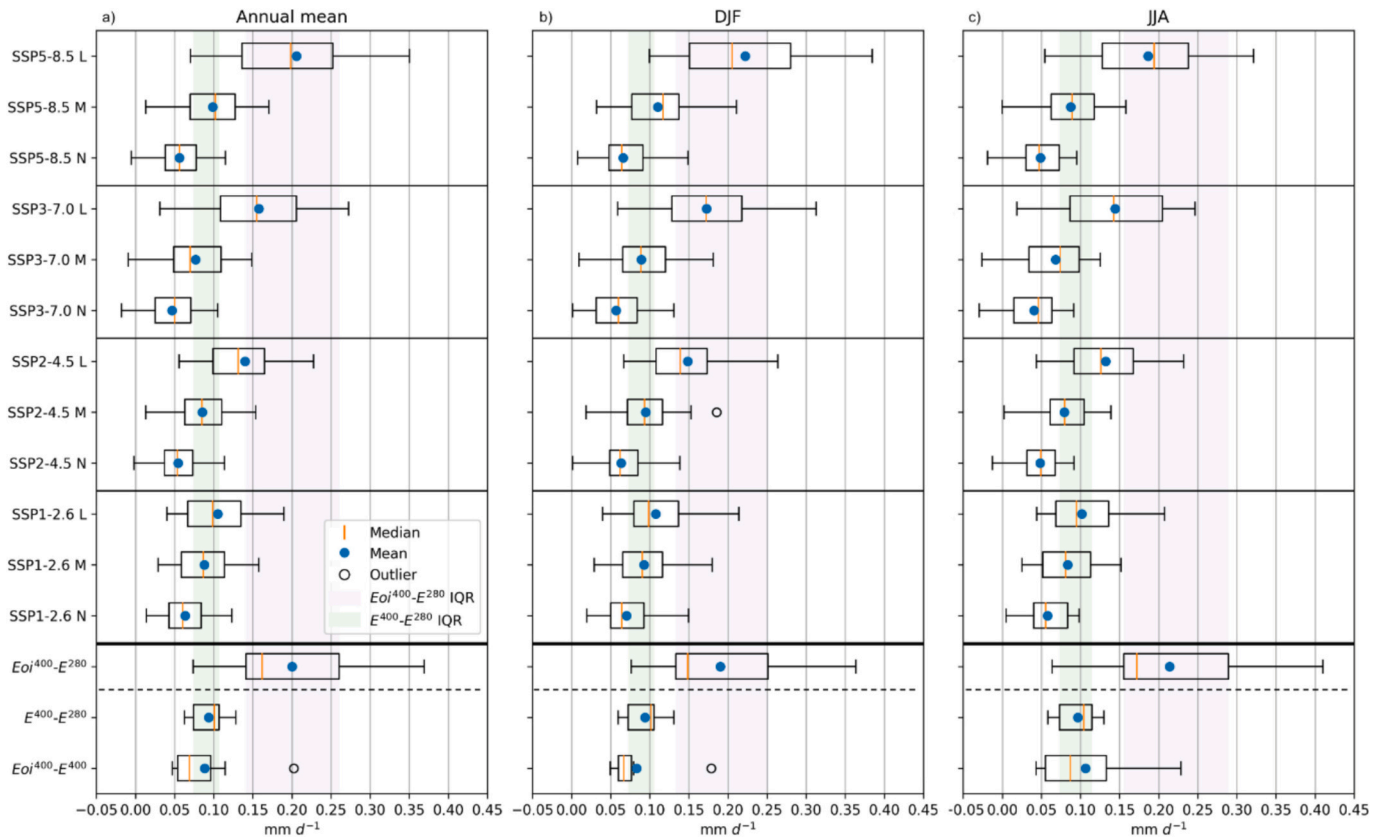


Fig. 10. Comparison of annual mean (a), DJF (b), and JJA (c) Pliocene precipitation $Eoi^{400} - E^{280}$ anomaly to near-term ('N'), medium-term ('M'), and long-term ('L') SSP scenarios. The $E^{400} - E^{280}$ and $Eoi^{400} - E^{400}$ anomalies are also included, which show the relative contribution of CO_2 forcing ($E^{400} - E^{280}$) and non- CO_2 forcing ($Eoi^{400} - E^{400}$) to the overall Pliocene anomaly ($Eoi^{400} - E^{280}$). In each case, the box represents the interquartile range (IQR) of each dataset. The tails represent the outermost data points within $1.5 \times$ the IQR; data points outside this (outliers) are represented by open black circles. The median of each dataset is represented by a vertical orange line in each box, and the mean is represented by a blue circle. The purple shading extends the $Eoi^{400} - E^{280}$ IQR for ease of comparison between the various future scenarios, and the green shading similarly extends the $E^{400} - E^{280}$ IQR. The outlier in the annual DJF for $Eoi^{400} - E^{400}$ is CESM2, and the outlier for the DJF medium-term SSP2-4.5 simulation is KACE-1-0-G. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

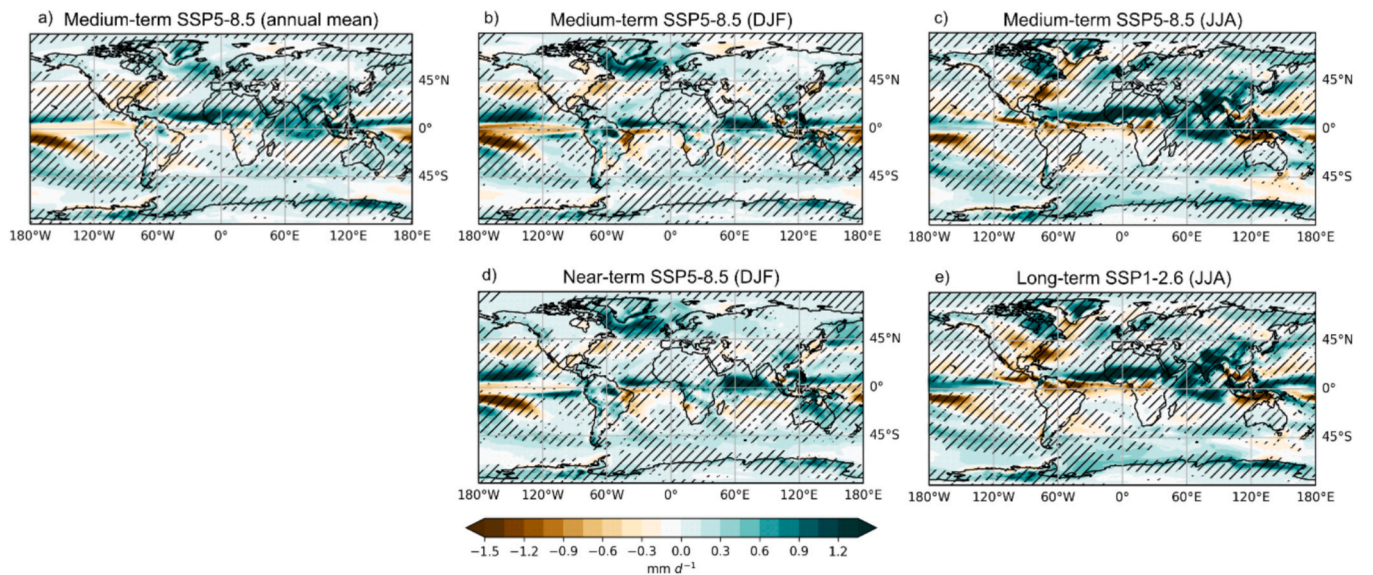


Fig. 11. Δ in annual mean, DJF, and JJA Pliocene and projected future precipitation change per eq. 1. The projected futures shown are those with the lowest RMSE values for the annual mean (a), DJF (b, d) and JJA (c, e) respectively (i.e. Fig. 6k (a), Fig. 7k (b), Fig. 7j (c), Fig. 8k (d), Fig. 8c (e)). Hatching denotes regions that are predominantly driven by non- CO_2 forcing per the FCO_2 method, i.e., where $FCO_2 < 0.5$ (see Burton et al., 2023). Note that the FCO_2 ensemble size is 7 for the annual mean, and 6 for DJF and JJA (see Section 2.1).

4. Discussion

4.1. The Pliocene as an analogue for future climate change

The results here clearly demonstrate that the level of analogy between the Pliocene and the future is highly dependent on a range of factors: the variable of interest; the region(s) of interest; the future scenario of interest; how far into the future one considers; the model(s) used; and whether one looks seasonally or annually. Given the vast literature that cites the Pliocene as ‘an analogue for the future’, this should provide cause for reflection and new, critical takes on such broad statements. Though this is not a new message (e.g., [Crowley \(1990\)](#) underlines the need for caution and to not overemphasise the usefulness of palaeoclimates for future), it is a message that takes on greater meaning as the need to prepare for and mitigate against future warming increases, and as we have more detailed climate model simulations available.

The Pliocene is most commonly referred to as an analogue in terms of having a comparable level of global mean SAT increase compared to future projections. We have shown that this is true for some SSP scenarios in some future intervals, but the Pliocene is too warm in the near term under all SSP scenarios, and too cool in the long term for higher emission scenarios (SSP3-7.0 and SSP5-8.5; [Figs. 1, 2, 3](#)). Pliocene SAT change is found to be most analogous to the long-term SSP2-4.5 ($\Delta = 0.36^\circ\text{C}$; RMSE = 2.58; $t(16) = 1.46$, $p = 0.15$) and SSP3-7.0 ($\Delta = -0.63^\circ\text{C}$; RMSE = 2.58; $t(16) = -2.15$, $p = 0.037$) projections. For the DJF season, the long-term SSP2-4.5 projection has the smallest global mean Δ value (0.05°C) and is least statistically different to the Pliocene ($t(16) = 0.22$, $p = 0.83$), whilst the medium-term SSP5-8.5 projection has the smallest RMSE (2.44). For the JJA season, the long-term SSP3-7.0 projection is the most analogous and has the smallest global mean Δ value (-0.36°C), smallest RMSE value (2.91), and is least statistically different to the Pliocene ($t(16) = -1.16$, $p = 0.25$).

For precipitation, the RMSE methodology is deemed to be more representative of analogy given the significant spatial differences in precipitation change between the Pliocene and the future scenarios presented. In terms of RMSE values alone, the medium-term SSP5-8.5 projection is the closest analogue for the annual mean (RMSE = 0.31); the medium-term SSP5-8.5 projection and near-term SSP5-8.5 projection are the closest analogues for DJF (RMSE = 0.36); and the medium-term SSP5-8.5 projection and long-term SSP1-2.6 projection are the closest analogues for JJA (RMSE = 0.48). It is also worth noting however, that, in terms of Δ values alone, the long-term SSP5-8.5 projection appears the most analogous for the annual mean ($\Delta = -0.01\text{ mm d}^{-1}$) and JJA ($\Delta = -0.02\text{ mm d}^{-1}$), and the long-term SSP3-7.0 projection appears the most analogous for DJF ($\Delta = 0.01$). These results emphasise the influence of the method(s) used to assess analogy, and hence the importance of clearly communicating the methods used in accordance with step three of the [Oldeman et al. \(in review\)](#) palaeoclimate analogy framework.

This is further emphasised when comparing our results to those of [Burke et al. \(2018\)](#). As described in [Section 1.3](#), [Burke et al. \(2018\)](#) quantitatively compared the SAT and total monthly precipitation for DJF and JJA of six geohistorical intervals (early Eocene (~50 Ma), Pliocene (~3.3–3.0 Ma), Last Interglacial (129–116 ka), mid-Holocene (6 ka), PI (~1850) and ‘historical’ (1940–1970)) to RCP4.5 and RCP8.5 projections from 2020 to 2280. Whilst this paper and [Burke et al. \(2018\)](#) both compare Pliocene SAT and precipitation to future projections, the methods used are very different. Compared to this paper, [Burke et al. \(2018\)](#): combined the SAT and precipitation results over DJF and JJA to produce a single comparison; used the same three-model ensemble to simulate all time intervals; compared the geohistorical intervals to RCP projections rather than SSP projections; and compared geohistorical intervals to projections up to 2280 rather than 2100. Direct comparisons between our results and those of [Burke et al. \(2018\)](#) are therefore difficult. Nonetheless, two common conclusions stand out: 1)

the level of analogy seen between the Pliocene and the future is dependent upon which ‘future’ is considered, and 2) the Pliocene is, broadly, most analogous to high-emission scenarios in the near-term future and medium-emission scenarios towards the end of the 21st century. The results in this paper allow for greater nuance in conclusion 2) as results are presented separately for SAT and precipitation, and for the annual mean, DJF and JJA.

It is tempting to focus on the most analogous futures in the want to find the Pliocene as a good analogue for the future, but it is important to recognise its limitations and not overstate conclusions. Even in the scenarios found to be most analogous, the Pliocene is not necessarily a good analogue. It is critical to both assess the confidence in the conclusions drawn (step four of the [Oldeman et al. \(in review\)](#) framework and caveat the conclusions with the necessary nuances (step five of the [Oldeman et al. \(in review\)](#) framework). For example, there are significant differences in the spatial patterns of precipitation change which limits the usefulness of the Pliocene as an analogue for future precipitation change. This said, the influence of non-CO₂ forcing on precipitation ([Section 3.2.4](#)) means that Pliocene might be a better analogue further into the future when, for example, vegetation and ice sheets have responded to anthropogenic CO₂ forcing. This would be an interesting and fruitful avenue for future work to explore.

Projections of current policies put us between the SSP2-4.5 and SSP3-7.0 scenarios by the end of the 21st century (e.g., [Forster et al., 2020](#); [Climate Action Tracker, 2023](#)), which may be even more analogous to Pliocene SAT response than either individual scenario. For long-term (2081–2100) precipitation, however, the Pliocene is most analogous to the SSP1-2.6 and SSP2-4.5 projections (RMSE = 0.33 for both projections), with the SSP3-7.0 and SSP5-8.5 projections displaying higher RMSE values (RMSE = 0.35 and RMSE = 0.40 respectively); given projections of current policies, as well as the significant spatial differences, the Pliocene is therefore probably not an analogue for likely future precipitation change. It is important to remember that the SSPs are possible scenarios rather than predictions of the future and that it is impossible to simulate all possible ‘futures’, though it is of course possible that doing so would find a more analogous match to the Pliocene. The SSP scenarios capture a range of plausible futures, but ultimately, we must remember that it is our own actions that will dictate future climate change and the path we will most closely follow; policy and societal choices underpin how analogous the Pliocene will be to our future ([Burke et al., 2018](#)).

As well as the choice in future scenario, [Fig. 5](#) and [Fig. 10](#) show how the model(s) used to simulate these futures may also affect the level of analogy concluded. Outliers to the model ensembles were highlighted, and within the rest of the ensemble there was still notable variation in the SAT and precipitation change simulated. This highlights the strength of using ensembles of models when assessing analogy, but also that different models may appear more/less analogous and more/less able to inform us about different elements of different futures.

Pliocene analogy is also founded in there being a similar-to-modern atmospheric CO₂ concentration (~400 ppm). The FCO₂ method of [Burton et al. \(2023\)](#) provides a means to assess the relative contribution of this forcing compared to other boundary condition changes, many of which are not analogous to the present day or relatively near-term future. CO₂ forcing is the predominant driver of Pliocene SAT and precipitation change ([Burton et al., 2023](#)), but the influence of this forcing varies spatially, with non-CO₂ forcing having a particularly important role in the spatial pattern of precipitation change (see also [Section 3.2.4](#)). If we are to truly consider the Pliocene as an analogue for the future we should also be assessing the level of analogy in the dominant climate forcing(s) (including projected future vegetation and ice sheet changes), else we risk misunderstanding and overemphasising the usefulness of the analogy (per the warning of [Crowley, 1990](#); [Oldeman et al., in review](#)).

Furthermore, an often-cited limitation of the Pliocene as an analogue for the future is its (semi-)equilibrated state to this atmospheric CO₂

concentration, compared to the transient state of the modern climate system (e.g., Crowley, 1991; Jansen et al., 2007; Dowsett et al., 2009; de Nooijer et al., 2020; Haywood et al., 2020; Tierney et al., 2020). This limitation is not restricted to the Pliocene and extends to most palaeoclimate analogies, except for some periods of rapid and abrupt global changes (see Oldeman et al., *in review*). It is unsurprising that this has been a constant criticism of the Pliocene as a palaeoclimate analogue given the policy-driven focus on future climate change to 2100, and the difficulty in considering such finely resolved time periods in deep time. However, calls to investigate climate change further into the future (e.g., Lyon et al., 2021) and the formation of a LongRunMIP (<https://www.longrunmip.org/>) may see more analogous futures to the Pliocene than the end-of-century projections shown here.

Our understanding of the Pliocene as an analogue will continue to change as additional (model and/or proxy) data become available and as models become increasingly complex. In this sense, we could consider the Pliocene in terms of what it can definitely provide insight to now, with current data, but also what it might be able to provide insight to in the future. The full extent of the Pliocene as an analogue is not currently known, and arguably might not be known until severe impacts have been felt if we most closely follow higher emission scenarios. There are also likely elements of the climate system for which the Pliocene will never be able to provide useful insight, either because of data limitations and/or because of it being a fundamentally different climate state.

4.2. Reflections on palaeoclimate analogy

As emissions continue to grow and our world continues to warm (e.g., Forster et al., 2024), it is becoming ever more important to utilise all lines of evidence and understanding we have to mitigate and prepare for future climate change. Palaeoclimate research is a key component of this in providing insight into warm periods in Earth's history, the closest thing we have to being able to 'travel' to our warmer future.

Though the concept has been around for decades, explicit palaeoclimate analogy research appears to have gone in and out of fashion. Some authors discuss the concept without using the terms 'analogue' or 'analogy', while others state that 'the Pliocene is an analogue for the future' without further expansion or consideration. The use of the term 'analogue' for the past-for-future concept is potentially problematic considering its implicit assumptions. Since its use in palaeoclimatology, 'analogue' has most often been considered as something that a time period either is or isn't: the Pliocene must be an exact replica, or using the word 'analogue' is incorrect (e.g., Crowley, 1990). However, in the English language the word 'analogue' has been used since the early 1800s in zoology and botany to describe a species which has the same general form as a species in a different time or space (OED, 2023a) and, more generally, 'analogue' is frequently used to describe something that is similar or equivalent (OED, 2023b). In both of these uses an analogue is not an exact replica, but rather something comparable or parallel.

To gain the most benefit from palaeoclimate analogies, it is important to move beyond this 'exact replica or no analogue' rhetoric that underlies much research today (see also Oldeman et al., *in review*). Some original criticisms of the analogy concept have now been overcome, or at least their effects minimised, with advances in data, modelling, and methods. Doing so will allow the concept to be more useful for both the palaeoclimate and future climate communities.

4.2.1. Lessons for the palaeoclimate modelling community

It is crucial for the discussion of palaeoclimate analogy to not be siloed in palaeoclimate research alone – it must be effectively communicated, and collaborated upon, with the future climate community. The past-for-future concept can underlie all palaeoclimate research so long as critical consideration is given to which response(s), process(es), and forcing(s) may be analogous to the future. This said, it is vital to not overemphasise the level and/or usefulness of a given analogy, and to not extrapolate conclusions beyond the component(s) researched, as well as

to be clear in the spatial, temporal and other limitations of the conclusions. Furthermore, investigations should not end after an initial assessment of analogy based on a single climate variable such as SAT; understanding the forcings and processes associated with large-scale responses is critical to advancing future projections.

Practically, modelling groups are encouraged to complete future-relevant simulations. In the case of PlioMIP, experiments that suit that past-for-future agenda are emphasised in the experimental design of PlioMIP2 (Haywood et al., 2016) and PlioMIP3 (Haywood et al., 2024), and have been shown to add value when considering palaeoclimate analogy (e.g., Burton et al., 2023). Furthermore, working towards transient palaeoclimate simulations of past abrupt changes will be beneficial to provide more directly comparable simulations to the relatively near-term future (rather than those in (semi-)equilibrium). This could extend to include the simulation of climate extremes, which are highly relevant for the future due to their disproportionately large impacts on society.

4.2.2. Lessons for the future climate community

A lesson echoed for both the palaeoclimate and future climate communities, effectively communicating will be paramount to ensuring assessments of analogy are relevant and useful. For the future climate community, this could include suggesting and defining research questions that palaeoclimate research is well placed to address. For example, would it be preferential to understand worst-case highest-warming-type scenarios, or to understand the best analogy to current most-likely projections of change? Would understanding processes (including tipping dynamics) be preferential to understanding large-scale responses? Which potential process analogies would be most useful to explore?

Defining and aiming to answer such questions would ensure that the palaeoclimate community focus on those time periods, as well as those response(s), process(es), and forcing(s), that are most relevant and useful in understanding future climate change and its impacts, and reducing uncertainties in future projections.

As highlighted in this paper, and Burton et al. (2023), non-CO₂ forcing including vegetation and ice sheet changes have an influential role in driving Pliocene precipitation change. Running long-term future climate simulations that include changes to these forcings will therefore likely improve the comparability between Pliocene simulations and future simulations, and increase the likelihood of finding specific analogies that may inform future policy decisions.

4.3. Reflections on the Oldeman et al. palaeoclimate analogy framework

Calls to use palaeoclimates to inform the future have been made since the 1980s (e.g., Budyko, 1982), but the lack of consistency between studies and the lack of a formal definition of 'analogy' mean that these calls are not reaching their full potential. It is common for the literature to refer to the Pliocene as an 'analogue' without explicitly defining the full context or meaning; some literature references that 'the Pliocene is an analogue for the future' in the abstract or introduction as justification for research, without returning to the concept in the remainder of the paper (see Oldeman et al., *in review*). This overlooks the nuance within drawing palaeoclimate analogy/analogies and may misguide readers if the conclusions of the paper are not aligned with what the authors (implicitly or explicitly) presented as an analogous time period (e.g., the Pliocene may be presented as an analogue based on comparable increases in SAT at the beginning of a paper, when the paper itself does not focus on SAT change).

Additionally, though there is a wealth of literature which suggests and supports the concept of using the Pliocene as a palaeoclimate analogue, there is little literature which critically considers or assesses what 'analogy' means and/or implies. What threshold(s) must be met for the Pliocene to be deemed an analogue? Is it accurate to call the Pliocene an 'analogue' based on similar atmospheric CO₂ concentrations and SAT

projections alone? What is not analogous between the Pliocene and the future?

The Oldeman et al. (in review) palaeoclimate analogy framework aims to address and provide a path through which it is possible to overcome these previous shortcomings. Applying elements of the framework has allowed a more detailed exploration of the spatial and temporal limitations of using the Pliocene as an analogue for future SAT and precipitation change, as well as explicitly comparing the level of analogy between the underlying forcing behind these responses for the first time.

Specifically addressing each step of the framework allows more critical conclusions of analogy to be drawn:

- 1) The aim of the analogy assessment is clearly stated in Section 1.3;
- 2) The feasibility of the assessment is considered in Section 2.3;
- 3) Data and methods, and their implications, are clearly described in Section 2;
- 4) Confidence assessments are made throughout Section 3;
- 5) Strengths and limitations of the assessment are discussed throughout Section 3 and Section 4.

The critical approach to palaeoclimate analogy encouraged through the framework proposed by Oldeman et al. (in review) is a long awaited and much needed improvement in the field and should invite a new generation of palaeoclimate analogy research which can uniquely address questions of our warmer future. In turn, this research will become more useful to the future climate community and to decision-makers, ensuring maximum impact.

Despite its benefits, the framework does not need to be strictly followed in all future research. Strictly following every step of the framework may introduce a significant amount of additional work which, depending on the aim of the research, may not be necessary. For example, the framework would not have to be strictly followed for a simple comparison between past and future climate states, but statements of analogy should then be avoided to prevent misleading or misinforming the reader. Similarly, the framework would not have to be followed if the aim of a palaeoclimate study is merely to better understand the past time interval in question, making no reference to its similarity (or lack thereof) to future projections.

This said, there are also instances where completing an analogy assessment may help to identify the time intervals of most interest and use when considering a specific aim. For example, a study with a specific aim like using past intervals to improve model parameterisations would not necessarily have to conduct an analogy assessment or follow the framework, but doing so would allow the most relevant interval(s) to be selected and focused on.

As discussed in Section 4.2.2, we encourage communication between the palaeoclimate and future climate communities to better prioritise future assessments of analogy. The framework alone cannot decide the most useful avenues for future research; interdisciplinary collaboration is a necessity. Not all palaeoclimate research will have applications to our warmer future, but it is advised that all research with the potential to reduce uncertainties in or better constrain future projections embraces this possibility and utilises (at least elements of) the Oldeman et al. (in review) framework.

5. Future work and conclusions

The Pliocene has previously been concluded the “best” analogue for near-term future climate (Burke et al., 2018). This headline finding has since been foundational to much Pliocene research, but caveats are often overlooked. Using the palaeoclimate analogy framework of Oldeman et al. (in review) and the near-term (2021–2040), medium-term (2041–2060) and long-term (2081–2100) intervals from IPCC AR6, we have been able to make a robust assessment of where, when and why Pliocene SAT and precipitation can be considered analogous to future

climate, but also where, when and why they cannot depending on region (s) and timescale(s) of interest. Multiple methods of considering analogy are presented to encourage future researchers to follow this critical practice, and conclusions are detailed and specific such that they are transferable to future research.

The results in this paper show how important including such details in conclusions of analogy are: we have shown that the strength and usefulness of the Pliocene as an analogue is wholly dependent upon the variable of interest; the region(s) of interest; the future scenario of interest; how far into the future one considers; the model(s) used; and whether one looks seasonally or annually. As emphasised by the palaeoclimate analogy framework of Oldeman et al. (in review), all audiences must understand the spatial, temporal and other limitations of conclusions of analogy; sweeping statements that ‘the Pliocene is an analogue for the future’ should be replaced with more critical and more relevant statements for the specific research questions being posed.

The results presented in this paper also emphasise the need to move beyond drawing conclusions of analogy based on simple comparisons of global mean SAT values, as this overlooks both spatial and seasonal differences in terms of the level of analogy as well as the potential difference(s) in the level of analogy between different climate variables. Pliocene SAT change is seen to be more analogous to the future than precipitation change in terms of both the magnitude and spatial patterns of change, at both annual and seasonal scales.

The future scenario most analogous to Pliocene SAT change is dependent upon the timescale of interest and the method(s) considered. In terms of annual mean SAT change, the long-term SSP2-4.5 scenario is the least statistically different from the Pliocene ($t(16) = 1.46, p = 0.15$) and has the lowest Δ value ($\Delta = 0.36^\circ\text{C}$); the lowest RMSE value (RMSE = 2.58) is seen for both the long-term SSP2-4.5 projection and long-term SSP3-7.0 projection. For DJF, the RMSE value is lowest for the medium-term SSP5-8.5 projection (RMSE = 2.44), but the long-term SSP2-4.5 projection has the lowest Δ value ($\Delta = 0.05^\circ\text{C}$) and is the least statistically different from the Pliocene ($t(16) = 0.22, p = 0.83$). For JJA, the long-term SSP3-7.0 projection is the most analogous according to all three methods; it is not statistically different from the Pliocene ($t(16) = -1.16, p = 0.25$), has the lowest Δ value ($\Delta = -0.36$), and the lowest RMSE value (RMSE = 2.91). Even in these most analogous scenarios there is a Δ of more than 10°C over Greenland and eastern and western Antarctica (with some parts exceeding 20°C Δ). In terms of global annual mean precipitation, the RMSE value is lowest for the medium-term SSP5-8.5 projection (RMSE = 0.31) but significant differences in the spatial patterns of precipitation change (exceeding 3 mm d^{-1} in some regions) mean that the Pliocene is likely not an analogue in terms of future global-scale hydrological cycle change. Assessing the underlying forcings helps to explain some of these differences; the work of Burton et al. (2023) and the results here emphasise the role of non- CO_2 forcing in driving spatial patterns of Pliocene precipitation change, many equivalent changes of which are not comparable to the near-term future. Spatial differences in warming and precipitation change reduce the accuracy and usefulness of the Pliocene as an analogue in these regions.

As modelling capability continues to improve, future palaeoclimate research should aim to incorporate climate extremes, given their disproportionately large impact compared to annual or seasonal mean values. In palaeoclimatology we are experienced in understanding the dynamics of the climate system in past warmer worlds, but future work should also translate this in a way that allows us to better understand our warmer future and possible impacts of climate change.

Ultimately, the future we experience, and how analogous it is to the Pliocene, is up to our collective actions and future emissions.

Author contribution

LEB, AMO, AMH, JCT, AMD and DJH conceptualised the study. LEB led the study, analysed all data and wrote the manuscript. JCT provided

technical support. All authors were involved in the interpretation of the results and the editing of the manuscript.

CRedit authorship contribution statement

Lauren E. Burton: Writing – review & editing, Writing – original draft, Visualization, Resources, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Arthur M. Oldeman:** Writing – review & editing, Validation, Methodology, Investigation, Conceptualization. **Alan M. Haywood:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Julia C. Tindall:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Aisling M. Dolan:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Daniel J. Hill:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Anna von der Heydt:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Michiel L.J. Baatsen:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Editor-in-Chief of Global and Planetary Change - AMH. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

For the purpose of open access, the author has applied a Creative Commons Attribution (CC BY) licence to any Author Accepted Manuscript version arising. Lauren E. Burton acknowledges that this work was supported by the Leeds-York-Hull Natural Environment Research Council (NERC) Doctoral Training Partnership (DTP) Panorama under grant NE/S007458/1. Arthur M. Oldeman, Anna von der Heydt and Michiel L. J. Baatsen acknowledge the Netherlands Earth System Science Centre (NESSC), financially supported by the Ministry of Education, Culture and Science (OCW grant no. 024.002.001). Julia C. Tindall was supported through the Centre for Environmental Modelling and Computation (CEMAC), University of Leeds. The authors gratefully acknowledge Chris Wells in aiding the provision of individual model data associated with the IPCC AR6 Interactive Atlas.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.gloplacha.2025.104860>.

Data availability

The data required to produce the results in this paper are available in the Supplement. Full data from PlioMIP2 are available on request from AMH (A.M.Haywood@leeds.ac.uk). CMIP6 SSP and PI data (ensemble mean) are available from the IPCC AR6 Interactive Atlas (Gutiérrez et al., 2021a); individual model data used in this paper are available in the Supplement.

References

- Abell, J.T., Winckler, G., 2023. Long-term variability in Pliocene North Pacific Ocean export production and its implications for ocean circulation in a warmer world. *AGU Adv.* 4 (4), e2022AV000853. <https://doi.org/10.1029/2022AV000853>.
- Arias, P.A., Bellouin, N., Coppola, E., Jones, R.G., Krinner, G., Marotzke, J., Naik, V., Palmer, M.D., Plattner, G.-K., Rogelj, J., Rojas, M., Sillmann, J., Storelvmo, T., Thorne, P.W., Trewin, B., Achuta Rao, K., Adhikary, B., Allan, R.P., Armour, K., Bala, G., Barimalala, R., Berger, S., Canadell, J.G., Cassou, C., Cherchi, A., Collins, W., Collins, W.D., Connors, S.L., Corti, S., Cruz, F., Dentener, F.J., Dereczynski, C., Di Luca, A., Diongue Niang, A., Doblas-Reyes, F.J., Dosio, A., Douville, H., Engelbrecht, F., Eyring, V., Fischer, E., Forster, P., Fox-Kemper, B., Fuglestad, J.S., Fyfe, J.C., Gillett, N.P., Goldfarb, L., Gorodetskaya, I., Gutierrez, J. M., Hamdi, R., Hawkins, E., Hewitt, H.T., Hope, P., Islam, A.S., Jones, C., Kaufman, D.S., Kopp, R.E., Kosaka, Y., Kossin, J., Krakovska, S., Lee, J.-Y., Li, J., Mauritsen, T., Maycock, T.K., Meinshausen, M., Min, S.-K., Monteiro, P.M.S., Ngo-Duc, T., Otto, F., Pinto, I., Pirani, A., Raghavan, K., Ranasinghe, R., Ruane, A.C., Ruiz, L., Sallée, J.-B., Samset, B.H., Sathyendranath, S., Seneviratne, S.I., Sörensson, A.A., Szopa, S., Takayabu, I., Tréguier, A.-M., van den Hurk, B., Vautard, R., von Schuckmann, K., Zaehele, S., Zhang, X., Zickfeld, K., 2021. Technical Summary. In: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J.B.R., Maycock, T.K., Waterfield, T., Yelekçi, O., Yu, R., Zhou, B. (Eds.), *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 33–144. <https://doi.org/10.1017/9781009157896.005>.
- Behera, P., Tiwari, M., Knies, J., 2021. Enhanced Arctic stratification in a warming scenario: evidence from the Mid Pliocene warm period. *Paleoceanogr. Paleoclimatol.* 36 (6), e2020PA004182. <https://doi.org/10.1029/2020PA004182>.
- Berntell, E., Zhang, Q., Li, Q., Haywood, A.M., Tindall, J.C., Hunter, S.J., Zhang, Z., Li, X., Guo, C., Nasancioglu, K.H., Stepanek, C., Lohmann, G., Sohl, L.E., Chandler, M. A., Tan, N., Contoux, C., Ramstein, G., Baatsen, M.L.J., von der Heydt, A.S., Chandan, D., Peltier, W.R., Abe-Ouchi, A., Chan, W.-L., Kamae, Y., Williams, C.J.R., Lunt, D.J., Feng, R., Otto-Bliesner, B.L., Brady, E.C., 2021. Mid-Pliocene West African Monsoon rainfall as simulated in the PlioMIP2 ensemble. *Clim. Past* 17 (4), 1777–1794. <https://doi.org/10.5194/cp-17-1777-2021>.
- Budyko, M.I., 1982. *The Earth's climate: past and future*. In: Donn, W.L. (Ed.), *International Geophysics Series*, 29. Academic Press. ISBN: 0-12-139460-3.
- Burke, K.D., Williams, J.W., Chandler, M.A., Haywood, A.M., Lunt, D.J., Otto-Bliesner, 2018. Pliocene and Eocene provide best analogs for near-future climates. *PNAS* 115 (52), 13,288–13,293. <https://doi.org/10.1073/pnas.1809600115>.
- Burls, N.J., Fedorov, A.V., 2017. Wetter subtropics in a warmer world: Contrasting past and future hydrological cycles. *Proc. Natl. Acad. Sci. USA* 114 (49), 12,888–12,893. <https://doi.org/10.1073/pnas.1703421114>.
- Burton, L.E., Haywood, A.M., Tindall, J.C., Dolan, A.M., Hill, D.J., Abe-Ouchi, A., Chan, W.-L., Chandan, D., Feng, R., Hunter, S.J., Li, X., Peltier, W.R., Tan, N., Stepanek, C., Zhang, Z., 2023. On the climatic influence of CO₂ forcing in the Pliocene. *Clim. Past* 19 (3), 747–764. <https://doi.org/10.5194/cp-19-747-2023>.
- Chandler, M., Rind, D., Thompson, R., 1994. Joint investigations of the middle Pliocene climate II: GISS GCM Northern Hemisphere results. *Glob. Planet. Chang.* 9 (3–4), 197–219. [https://doi.org/10.1016/0921-8181\(94\)90016-7](https://doi.org/10.1016/0921-8181(94)90016-7).
- Climate Action Tracker, 2023. 2100 Warming Projections: Emissions and expected warming based on pledges and current policies. December 2023. Available from: <https://climateactiontracker.org/global/temperatures/> [Access date 03/07/2024]. Copyright ©2023 by Climate Analytics and NewClimate Institute. All rights reserved.
- Corvec, S., Fletcher, C.G., 2017. Changes to the tropical circulation in the mid-Pliocene and their implications for future climate. *Clim. Past* 13 (2), 135–147. <https://doi.org/10.5194/cp-13-135-2017>.
- Crowley, T.J., 1990. Are there any satisfactory geologic analogs for a future greenhouse warming? *J. Clim.* 3 (11), 1282–1292. [https://doi.org/10.1175/1520-0442\(1990\)003%3C1282:ATASGA%3E2.0.CO;2](https://doi.org/10.1175/1520-0442(1990)003%3C1282:ATASGA%3E2.0.CO;2).
- Crowley, T.J., 1991. Modeling Pliocene warmth. *Quat. Sci. Rev.* 10 (2–3), 275–282. [https://doi.org/10.1016/0277-3791\(91\)90025-P](https://doi.org/10.1016/0277-3791(91)90025-P).
- de Noijer, W., Zhang, Q., Li, Q., Zhang, Q., Li, X., Zhang, Z., Guo, C., Nasancioglu, K.H., Haywood, A.M., Tindall, J.C., Hunter, S.J., Dowsett, H.J., Stepanek, C., Lohmann, G., Otto-Bliesner, B.L., Feng, R., Sohl, L.E., Chandler, M.A., Tan, N., Contoux, C., Ramstein, G., Baatsen, M.L.J., von der Heydt, A.S., Chandan, D., Peltier, W.R., Abe-Ouchi, A., Chan, W.-L., Kamae, Y., Brierley, C.M., 2020. Evaluation of Arctic warming in mid-Pliocene climate simulations. *Clim. Past* 16 (6), 2325–2341. <https://doi.org/10.5194/cp-16-2325-2020>.
- Douville, H., Raghavan, K., Renwick, J., Allan, R.P., Arias, P.A., Barlow, M., Cerezo-Mota, R., Cherchi, A., Gan, T.Y., Gergis, J., Jiang, D., Khan, A., Pokam Mba, W., Rosenfeld, D., Tierney, J., Zolina, O., 2021. Water cycle changes. In: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J. B.R., Maycock, T.K., Waterfield, T., Yelekçi, O., Yu, R., Zhou, B. (Eds.), *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1055–1210. <https://doi.org/10.1017/9781009157896.010>.
- Dowsett, H.J., Chandler, M.A., Robinson, M.M., 2009. Surface temperatures of the Mid-Pliocene North Atlantic Ocean: implications for future climate. *Phil. Trans. R. Soc. A* 367 (1886), 69–84. <https://doi.org/10.1098/rsta.2008.0213>.
- Dowsett, H., Dolan, A., Rowley, D., Moucha, R., Forte, A.M., Mitrovica, J.X., Pound, M., Salzmann, U., Robinson, M., Chandler, M., Foley, K., Haywood, A., 2016. The PRISM4 (mid-Piacenzian) paleoenvironmental reconstruction. *Clim. Past* 12, 1519–1538. <https://doi.org/10.5194/cp-12-1519-2016>.
- Eyring, V., Gillett, N.P., Achuta Rao, K.M., Barimalala, R., Barreiro Parrillo, M., Bellouin, N., Cassou, C., Durack, P.J., Kosaka, Y., McGregor, S., Min, S., Morgenstern, O., Sun, Y., 2021. Human Influence on the Climate System. In: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J. B.R., Maycock, T.K., Waterfield, T., Yelekçi, O., Yu, R., Zhou, B. (Eds.), *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the*

- Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 423–552. <https://doi.org/10.1017/9781009157896.005>.
- Feng, R., Bhattacharya, T., Otto-Bliesner, B.L., Brady, E.C., Haywood, A.M., Tindall, J.C., Hunter, S.J., Abe-Ouchi, A., Chan, W.L., Kageyama, M., Contoux, C., Guo, C., Li, X., Lohmann, G., Stepanek, C., Tan, N., Zhang, Q., Zhang, Z., Han, X., Williams, C.J.R., Lunt, D.J., Dowsett, H.J., Chandan, D., Peltier, W.R., 2022. Past terrestrial hydroclimate sensitivity controlled by Earth System feedbacks. *Nat. Commun.* 13, 1–11. <https://doi.org/10.1038/s41467-022-28814-7>.
- Forster, P.M., Forster, H.I., Evans, M.J., Gidden, M.J., Jones, C.D., Keller, C.A., Lamboll, R.D., Le Quéré, C., Rogelj, J., Rosen, D., Schleussner, C.F., Richardson, T.B., Smith, C.J., Turnock, S.T., 2020. Current and future global climate impacts resulting from COVID-19. *Nature Clim. Change* 10, 913–919. <https://doi.org/10.1038/s41558-020-0883-0>.
- Forster, P.M., Smith, C., Walsh, T., Lamb, W., Lamboll, R., Hall, B., Hauser, M., Ribes, A., Rosen, D., Gillett, N., Palmer, M.D., Rogelj, J., von Schuckmann, K., Trewin, B., Allen, M., Andrew, R., Betts, R., Boyer, T., Buontempo, C., Burgess, S., Cagnazzo, C., Cheng, L., Friedlingstein, P., Gettelman, A., Gütschow, J., Ishii, M., Jenkins, S., Lan, X., Morice, C., Mühle, J., Kadow, C., Kennedy, J., Killick, R., Krummel, P.B., Minx, J.C., Myhre, G., Naik, V., Peters, G.P., Pirani, A., Pongratz, J., Schleussner, C.-F., Seneviratne, S.I., Szopa, S., Thorne, P., Kovilakam, M.V.M., Majamäki, E., Jalkanen, J.-P., van Marle, M., Hoesly, R.M., Rohde, R., Schumacher, D., van der Werf, G., Vose, R., Zickfeld, K., Zhang, X., Masson-Delmotte, V., Zhai, P., 2024. Indicators of Global climate Change 2023: annual update of key indicators of the state of the climate system and human influence. *Earth Syst. Sci. Data* 16 (6), 2625–2658. <https://doi.org/10.5194/essd-16-2625-2024>.
- Grant, G.R., Williams, J.H.T., Naeher, S., Seki, O., McClymont, E.L., Patterson, M.O., Haywood, A.M., Behrens, E., Yamamoto, M., Johnson, K., 2023. Amplified surface warming in the south-West Pacific during the mid-Pliocene (3.3–3.0 Ma) and future implications. *Clim. Past* 19 (7), 1359–1381. <https://doi.org/10.5194/cp-19-1359-2023>.
- Gutiérrez, J.M., Jones, R.G., Narisma, G.T., Alves, L.M., Amjad, M., Gorodetskaya, I.V., Grose, M., Klutse, N.A.B., Karkovska, S., Li, J., Martínez-Castro, D., Mearns, L.O., Mernild, S.H., Ngo-Duc, T., van den Hurk, B., Yoon, J.-H., 2021a. Interactive Atlas. In: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J.B.R., Maycock, T.K., Waterfield, T., Yelekçi, O., Yu, R., Zhou, B. (Eds.), *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press. Available from: <http://interactive-atlas.ipcc.ch/> [Access date 12/04/2024].
- Gutiérrez, J.M., Jones, R.G., Narisma, G.T., Alves, L.M., Amjad, M., Gorodetskaya, I.V., Grose, M., Klutse, N.A.B., Karkovska, S., Li, J., Martínez-Castro, D., Mearns, L.O., Mernild, S.H., Ngo-Duc, T., van den Hurk, B., Yoon, J.-H., 2021b. Atlas. *Climate Change 2021: The Physical Science Basis*. In: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J.B.R., Maycock, T.K., Waterfield, T., Yelekçi, O., Yu, R., Zhou, B. (Eds.), *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1927–2058. <https://doi.org/10.1017/9781009157896.021>.
- Gutiérrez, J.M., Jones, R.G., Narisma, G.T., Alves, L.M., Amjad, M., Gorodetskaya, I.V., Grose, M., Klutse, N.A.B., Karkovska, S., Li, J., Martínez-Castro, D., Mearns, L.O., Mernild, S.H., Ngo-Duc, T., van den Hurk, B., Yoon, J.-H., Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., 2021c. Atlas Supplementary Material. In: Chen, Y., Goldfarb, L., Gomis, M.I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J.B.R., Maycock, T.K., Waterfield, T., Yelekçi, O., Yu, R., Zhou, B. (Eds.), *Climate Change 2021: the Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on climate Change*. Available from: <https://www.ipcc.ch/> [Access date 17/07/2024].
- Han, Z., Zhang, Q., Li, Q., Feng, R., Haywood, A.M., Tindall, J.C., Hunter, S.J., Otto-Bliesner, B.L., Brady, E.C., Rosenbloom, N., Zhang, Z., Li, X., Guo, C., Nisancioglu, K. H., Stepanek, C., Lohmann, G., Sohl, L.E., Chandler, M.A., Tan, N., Ramstein, G., Baatsen, M.J., von der Heydt, A.S., Chandan, D., Peltier, W.R., Williams, C.J.R., Lunt, D.J., Cheng, J., Wen, Q., Burls, N.J., 2021. Evaluating the large-scale hydrological cycle response within the Pliocene Model Intercomparison Project phase 2 (PlioMIP2) ensemble. *Clim. Past* 17 (6), 2537–2558. <https://doi.org/10.5194/cp-17-2537-2021>.
- Han, Z., Li, G., Zhang, Q., 2023. Changes in Sahel summer rainfall in a global warming climate: contrasting the mid-Pliocene and future regional hydrological cycles. *Clim. Dyn.* 61, 1353–1370. <https://doi.org/10.1007/s00382-022-06630-5>.
- Harrison, G.W.M., Santodomingo, N., Johnson, K.G., Renema, W., 2023. Is the Coral Triangle's future shown in a Pliocene reef gap? *Coral Reefs* 42, 1219–1225. <https://doi.org/10.1007/s00338-023-02412-5>.
- Haywood, A.M., Valdes, P.J., Sellwood, B.J., 2000. Global scale paleoclimate reconstruction of the middle Pliocene climate using the UKMO GCM: initial results. *Glob. Planet. Chang.* 25 (3–4), 239–256. [https://doi.org/10.1016/S0921-8181\(00\)00028-X](https://doi.org/10.1016/S0921-8181(00)00028-X).
- Haywood, A.M., Dowsett, H.J., Valdes, P.J., Lunt, D.J., Francis, J.E., Sellwood, B.W., 2009. Introduction. *Pliocene climate, processes and problems*. *Phil. Trans. R. Soc. A* 367 (1886), 3–17. <https://doi.org/10.1098/rsta.2008.0205>.
- Haywood, A.M., Ridgwell, A., Lunt, D.J., Hill, D.J., Pound, M.J., Dowsett, H.J., Dolan, A.M., Francis, J.E., Williams, M., 2011. Are there pre-Quaternary geological analogues for a future greenhouse warming? *Phil. Trans. R. Soc. A* 369 (1938), 933–956. <https://doi.org/10.1098/rsta.2010.0317>.
- Haywood, A.M., Dolan, A.M., Pickering, S.J., Dowsett, H.J., McClymont, E.L., Prescott, C. L., Salzmann, U., Hill, D.J., Hunter, S.J., Lunt, D.J., Pope, J.O., Valdes, P.J., 2013. On the identification of a Pliocene time slice for data-model comparison. *Philos. T. Roy. Soc. A* 371, 20120515. <https://doi.org/10.1098/rsta.2012.0515>.
- Haywood, A.M., Dowsett, H.J., Dolan, A.M., Rowley, D., Abe-Ouchi, A., Otto-Bliesner, B., Chandler, M.A., Hunter, S.J., Lunt, D.J., Pound, M., Salzmann, U., 2016. The Pliocene Model Intercomparison Project (PlioMIP) phase 2: scientific objectives and experimental design. *Clim. Past* 12 (3), 663–675. <https://doi.org/10.5194/cp-12-663-2016>.
- Haywood, A.M., Tindall, J.C., Dowsett, H.J., Dolan, A.M., Foley, K.M., Hunter, S.J., Hill, D.J., Chan, W.-L., Abe-Ouchi, A., Stepanek, C., Lohmann, G., Chandan, D., Peltier, W.R., Tan, N., Contoux, C., Ramstein, G., Li, X., Zhang, Z., Guo, C., Nisancioglu, K.H., Zhang, Q., Li, Q., Kamae, Y., Chandler, M.A., Sohl, L.E., Otto-Bliesner, B.L., Feng, R., Brady, E.C., von der Heydt, A.S., Baatsen, M.L.J., Lunt, D.J., 2020. The Pliocene Model Intercomparison Project phase 2: large-scale climate features and climate sensitivity. *Clim. Past* 16, 2095–2123. <https://doi.org/10.5194/cp-16-2095-2020>.
- Haywood, A.M., Tindall, J.C., Burton, L.E., Chandler, M.A., Dolan, A.M., Dowsett, H.J., Feng, R., Fletcher, T.L., Foley, K.M., Hill, D.J., Hunter, S.J., Otto-Bliesner, B., Lunt, D.J., Robinson, M.M., Salzmann, U., 2024. Pliocene Model Intercomparison Project phase 3 (PlioMIP3) – Science Plan and Experimental Design. *Glob. Planet. Chang.* 232, 104316. <https://doi.org/10.1016/j.gloplacha.2023.104316>.
- Hill, D.J., 2015. The non-analogue nature of Pliocene temperature gradients. *Earth Planet. Sc. Lett.* 425 (1), 232–241. <https://doi.org/10.1016/j.epsl.2015.05.044>.
- Hutton, J., 1795. *Theory of the Earth: with proofs and illustrations*. In: Four Parts. By James Hutton, M. D. & F.R.S.E. Edinburgh: printed for Messrs Cadell, Junior, and Davies, London; and William Creech, Edinburgh.
- Ibarra, D.E., Oster, J.L., Winnick, M.J., Caves Rugenstein, J.K., Byrne, M.P., Chamberlain, C.P., 2018. Warm and cold wet states in the western United States during the Pliocene-Pleistocene. *Geology* 46 (4), 355–358. <https://doi.org/10.1130/G39962.1>.
- Iturbide, M., Fernández, J., Gutiérrez, J.M., Pirani, A., Huard, D., Al Khourdajie, A., Baño-Medina, J., Bedia, J., Casanueva, A., Cimadevilla, E., Cofino, A.S., De Felice, M., Díez-Sierra, J., García-Díez, M., Goldie, J., Herrera, D.A., Herrera, S., Manzanar, R., Milovac, J., Radhakrishnan, A., San-Martín, D., Spinuso, A., Thyng, K. M., Trenham, C., Yelekçi, Ö., 2021a. Implementation of FAIR principles in the IPCC: the WGI AR6 Atlas repository. *Sci. Data* 9, 629. <https://doi.org/10.1038/s41597-022-01739-y>.
- Iturbide, M., Fernández, J., Gutiérrez, J.M., Bedia, J., Cimadevilla, E., Díez-Sierra, J., Manzanar, R., Casanueva, A., Baño-Medina, J., Milovac, J., Herrera, S., Cofino, A.S., San Martín, D., García-Díez, M., Hauser, M., Huard, D., Yelekçi, Ö., 2021b. Repository supporting the implementation of FAIR principles in the IPCC-WGI Atlas. Zenodo. <https://doi.org/10.5281/zenodo.3691645>. Available from: <https://github.com/IPCC-WGI/Atlas> [Access date: 12/04/2024].
- Jansen, E., Overpeck, J., Briffa, K.R., Duplessy, J.-C., Joos, F., Masson-Delmotte, V., Olago, D., Otto-Bliesner, B., Peltier, W.R., Rahmstorf, S., Ramesh, R., Raynaud, D., Rind, D., Solomina, O., Villalba, R., Zhang, D., 2007. Palaeoclimate. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (Eds.), *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- Jiang, D., Wang, H., Ding, Z., Lang, X., Drange, H., 2005. Modeling the middle Pliocene climate with a global atmospheric general circulation model. *J. Geophys. Res.* 110 (D14), D14107. <https://doi.org/10.1029/2004JD005639>.
- Lunt, D.J., Haywood, A.M., Foster, G.L., Stone, E.J., 2009. The Arctic cryosphere in the mid-Pliocene and the future. *Phil. Trans. Soc. A* 367 (1886), 49–67. <https://doi.org/10.1098/rsta.2008.0218>.
- Lyell, C., 1830. *Principles of Geology; Being an Attempt to Explain the Former Changes of the Earth's Surface, by Reference to Causes Now in Operation*. John Murray, Albemarle-Street, London.
- Lyon, C., Saupé, E.E., Smith, C.J., Hill, D.J., Beckerman, A.P., Stringer, L.C., Marchant, R., McKay, J., Burke, A., O'Higgins, P., Dunhill, A.M., Allen, B.J., Riel-Salvatore, J., Aze, T., 2021. Climate change research and action must look beyond 2100. *Glob. Chang. Biol.* 28 (2), 349–361. <https://doi.org/10.1111/gcb.15871>.
- Menemenlis, S., Lora, J.M., Lofverstrom, M., Chandan, D., 2021. Influence of stationary waves on mid-Pliocene atmospheric rivers and hydroclimate. *Glob. Planet. Chang.* 204, 203557. <https://doi.org/10.1016/j.gloplacha.2021.103557>.
- Myers-Smith, I.H., Kerby, J.T., Phoenix, G.K., Bjerke, J.W., Epstein, H.E., Assmann, J.J., John, C., Andreu-Hayles, L., Angers-Blondin, S., Beck, P.S.A., Berner, L.T., Bhatt, U. S., Bjorkman, A.D., Blok, D., Bryn, A., Christiansen, C.T., Cornelissen, J.H.C., Cunliffe, A.M., Elmendorf, S.C., Forbes, B.C., Goetz, S.J., Hollister, R.D., de Jong, R., Loran, M.M., Macias-Fauria, M., Maseyk, K., Normand, S., Olofsson, J., Parker, T. C., Parmentier, F.-J.W., Post, E., Schaeppman-Strub, G., Stordal, F., Sullivan, P.F., Thomas, H.J.D., Tømmervik, H., Treharne, R., Tweedie, C.E., Walker, D.A., Wilmking, M., Wipf, S., 2020. Complexity revealed in the greening of the Arctic. *Nat. Clim. Chang.* 10, 106–117. <https://doi.org/10.1038/s41558-019-0688-1>.
- NOAA Global Monitoring Laboratory, 2024. NOAA Global Monitoring Laboratory - Trends in Atmospheric Carbon Dioxide (2024); EPA based on various sources (2022) – with major processing by Our World in Data. “Carbon dioxide concentrations in the atmosphere” [dataset]. NOAA Global Monitoring Laboratory, “Trends in Atmospheric Carbon Dioxide”; United States Environmental Protection Agency, “Climate Change Indicators: Atmospheric Concentrations of Greenhouse Gases” [original data]. Available from: <https://ourworldindata.org/grapher/co2-long-term-concentration> [Access date 16/05/2024].

- OED, 2023a. Analogue (n.), sense I.1.a. Oxford English Dictionary, Oxford University Press. <https://doi.org/10.1093/OED/1219179620>.
- OED, 2023b. Analogue (n.), sense II.6. Oxford English Dictionary, Oxford University Press. <https://doi.org/10.1093/OED/7134045647>.
- Oldeman, A.M., Burton, L.E., Baatsen, M.L.J., Dijkstra, H.A., von der Heydt, A.S., Dolan, A.M., Haywood, A.M., Hill, D.J., Tindall, J.C., 2025a. in review A framework for assessing analogy between past and future climates.
- Oldeman, A.M., Baatsen, M.L.J., von der Heydt, A.S., Selten, F.M., Dijkstra, H.A., 2025b. accepted Similar North Pacific variability despite suppressed El Niño variability in the warm mid-Pliocene climate, EGU sphere [preprint]. <https://doi.org/10.5194/egusphere-2024-766>.
- Pontes, G.M., Taschetto, A.S., Sen Gupta, A., Santoso, A., Wainer, I., Haywood, A.M., Chan, W.-L., Abe-Ouchi, A., Stepanek, C., Lohmann, G., Hunter, S.J., Tindall, J.C., Chandler, M.A., Sohl, L.E., Peltier, W.R., Chandan, D., Kamae, Y., Nisancioglu, K.H., Zhang, Z., Contoux, C., Tan, N., Zhang, Q., Otto-Bliesner, B.L., Brady, E.C., Feng, R., von der Heydt, A.S., Baatsen, M.L.J., Oldeman, A.M., 2022. Mid-Pliocene El Niño/Southern Oscillation suppressed by Pacific intertropical convergence zone shift. *Nat. Geosci.* 15, 726–734. <https://doi.org/10.1038/s41561-022-00999-y>.
- Robinson, M.M., Dowsett, H.J., Chandler, M.A., 2008. Pliocene role in assessing future climate impacts. *EOS Trans. Am. Geophys. Union* 89 (49), 501–502. <https://doi.org/10.1029/2008EO490001>.
- Salzmann, U., Haywood, A.M., Lunt, D.J., Valdes, P.J., Hill, D.J., 2008. A new global biome reconstruction and data-model comparison for the Middle Pliocene. *Glob. Ecol. Biogeogr.* 8, 432–447. <https://doi.org/10.1111/j.1466-8238.2008.00381.x>.
- Salzmann, U., Haywood, A.M., Lunt, D.J., 2009. The past is a guide to the future? Comparing Middle Pliocene vegetation with predicted biome distributions for the twenty-first century. *Phil. Trans. R. Soc. A* 367 (1886), 189–204. <https://doi.org/10.1098/rsta.2008.0200>.
- Sun, Y., Ramstein, G., Li, L.Z.X., Contoux, C., Tan, N., Zhou, T., 2018. Quantifying East Asian summer monsoon dynamics in the ECP4.5 scenario with reference to the mid-Piacenzian warm period. *Geophys. Res. Lett.* 45 (22), 12,523–12,533. <https://doi.org/10.1029/2018GL080061>.
- Tierney, J.E., Poulsen, C.J., Montañez, I.P., Bhattacharya, T., Feng, R., Ford, H.L., Hönisch, B., Inglis, G.N., Petersen, S.V., Sagoo, N., Tabor, C.R., Thirumalai, K., Zhu, J., Burls, N.J., Foster, G.L., Goddérís, Y., Huber, B.T., Ivany, L.C., Turner, S.K., Lunt, D.J., McElwain, J.C., Mills, B.J.W., Otto-Bliesner, B.L., Ridgwell, A., Zhang, Y. G., 2020. Past climates inform our future. *Science* 370, eaay3701. <https://doi.org/10.1126/science.aay3701>.
- Weiffenbach, J.E., Baatsen, M.L.J., Dijkstra, H.A., von der Heydt, A.S., Abe-Ouchi, A., Brady, E.C., Chan, W.-L., Chandan, D., Chandler, M.A., Contoux, C., Feng, R., Guo, C., Han, Z., Haywood, A.M., Li, Q., Li, X., Lohmann, G., Lunt, D.J., Nisancioglu, K.H., Otto-Bliesner, B.L., Peltier, W.R., Ramstein, G., Sohl, L.E., Stepanek, C., Tan, N., Tindall, J.C., Williams, C.J.R., Zhang, Q., Zhang, Z., 2023. Unravelling the mechanisms and implications of a stronger mid-Pliocene Atlantic Meridional Overturning Circulation (AMOC) in PlioMIP2. *Clim. Past* 19 (1), 61–85. <https://doi.org/10.5194/cp-19-61-2023>.
- Weiffenbach, J.E., Dijkstra, H.A., von der Heydt, A.S., Abe-Ouchi, A., Chan, W.-L., Chandan, D., Feng, R., Haywood, A.M., Hunter, S.J., Li, X., Otto-Bliesner, B.L., Peltier, W.R., Stepanek, C., Tan, N., Tindall, J.C., Zhang, Z., 2024. Highly stratified mid-Pliocene Southern Ocean in PlioMIP2. *Clim. Past* 20 (4), 1067–1086. <https://doi.org/10.5194/cp-20-1067-2024>.
- Williams, C.J.R., Sellar, A.A., Ren, X., Haywood, A.M., Hopcroft, P., Hunter, S.J., Roberts, W.H.G., Smith, R.S., Stone, E.J., Tindall, J.C., Lunt, D.J., 2021. Simulation of the mid-Pliocene warm period using HadGEM3: experimental design and results from model-model and model-data comparison. *Clim. Past* 17 (5), 2139–2163. <https://doi.org/10.5194/cp-17-2139-2021>.
- Zubakov, V.A., Borzenkova, I.I., 1988. Pliocene palaeoclimates: past climates as possible analogues of mid-twenty-first century climate. *Palaeogeogr. Palaeoclimatol.* 65 (1–2), 35–49. [https://doi.org/10.1016/0031-0182\(88\)90110-1](https://doi.org/10.1016/0031-0182(88)90110-1).