The Pliocene Model Intercomparison Project (PlioMIP) Phase 2: Scientific Objectives and Experimental Design

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Abstract

The Pliocene Model Intercomparison Project (PlioMIP) is a co-ordinated international climate modelling initiative to study and understand climate and environments of the Late Pliocene, and their potential relevance in the context of future climate change. PlioMIP

examines the consistency of model predictions in simulating Pliocene climate, and their ability to reproduce climate signals preserved by geological climate archives. Here we provide a description of the aim and objectives of the next phase of the model intercomparison project (PlioMIP Phase 2), and we present the experimental design and boundary conditions that will be utilised for climate model experiments in Phase 2.

Following on from PlioMIP Phase 1, Phase 2 will continue to be a mechanism for sampling structural uncertainty within climate models. However, Phase 1 demonstrated the requirement to better understand boundary condition uncertainties as well as uncertainty in the methodologies used for data-model comparison. Therefore, our strategy for Phase 2 is to utilise state-of-the-art boundary conditions that have emerged over the last 5 years. These include a new palaeogeographic reconstruction, detailing ocean bathymetry and land/ice surface topography. The ice surface topography is built upon the lessons learned from offline ice sheet modelling studies. Land surface cover has been enhanced by recent additions of Pliocene soils and lakes. Atmospheric reconstructions of palaeo-CO_2 are emerging on orbital timescales and these are also incorporated into PlioMIP Phase 2. New records of surface and sea surface temperature change are being produced that will be more temporally consistent with the boundary conditions and forcings used within models.

Finally we have designed a suite of prioritized experiments that tackle issues surrounding the basic understanding of the Pliocene and its relevance in the context of future climate change in a discrete way.

1. Introduction to PlioMIP

1.1 PlioMIP Phase 1 Design and Objectives

The PlioMIP project was initiated in 2008 and is closely aligned with the U.S. Geological Survey Project known as PRISM (Pliocene Research Interpretation and Synoptic Mapping). The PRISM project has spent more than 25 years focusing on the reconstruction and understanding of the mid-Pliocene climate (~3.3 to 3 million years ago), as well as the production of boundary condition data sets suitable for use with numerical climate models.

Phase 1 of the PlioMIP project commenced in 2008 and was concluded in 2014. In Phase 1 two mid-Pliocene experiments were performed. Experiment 1 used atmosphere-only General Circulation Models (GCMs) with prescribed surface boundary conditions (sea-surface temperatures, sea-ice, and vegetation) derived from the PRISM3D data set (Dowsett et al., 2010). Land/sea distribution and topography were also prescribed from PRISM3D. Experiment 2 used coupled ocean-atmosphere GCMs where sea-surface temperatures and sea-ice were predicted dynamically by the models; vegetation, land/sea distribution, and topography remained fixed to PRISM3D estimates.

The scientific objectives in Phase 1 were to:

- Examine large-scale features of mid-Pliocene climate that are consistent across models.
- Determine the dominant components of mid-Pliocene warming derived from the imposed boundary conditions.
- Examine first order changes in ocean circulation between the mid-Pliocene and present-day.
- Examine the behaviour of the monsoons (e.g. their intensity).
- Compare model results with proxy data to determine the performance of models simulating a warm climate state.
- Use the mid-Pliocene as a tool to evaluate the long term sensitivity of the climate system to near modern concentrations of atmospheric CO_2.

1.2 PlioMIP Phase 1 Accomplishments

In the context of co-ordinated international model intercomparison projects, PlioMIP achieved a number of firsts. For example, it was the first palaeoclimate modelling intercomparison project to require altered vegetation distributions to be modified in climate models, facilitating vegetation-climate feedbacks to be incorporated into the model intercomparison. It was also the first intercomparison project that required individual groups to fully document the implementation of palaeo-boundary conditions within their models, along with the basic climatological responses. This was designed to facilitate the intercomparison itself by enabling artefacts of individual methodologies of boundary condition implementation to be separated from robust model responses to imposed Pliocene boundary conditions. Through PlioMIP, a spin off project known as PLISMIP (Pliocene Ice Sheet Model Intercomparison Project; Dolan et al. 2011) was initiated and has focused on 1) assessing ice sheet model dependency of Greenland Ice Sheet reconstructions during the Pliocene using shallow ice approximation ice sheet models (Dolan et al., 2011; Koenig et al., 2014), 2) examining the effect of different GCM climatological forcing on predicted ice sheet configurations (Dolan et al. 2014) and 3) using shallow shelf ice sheet models for Antarctica to test both ice sheet model and climate model dependency on predicted ice sheet reconstructions (de Boer et al. 2015).

Outputs from PlioMIP Phase 1 include:

- Identified consistency in surface temperature change across models in the tropics and a lack of consistency in the simulated temperature response at high latitudes (Haywood et al., 2013a).
- Model predictions are inconsistent in terms of total precipitation rate in the tropics (Haywood et al., 2013a).
- Global annual mean surface temperatures increased by 1.8°C to 3.6°C and show a greater range for Experiment 2 using coupled ocean-atmosphere models than Experiment 1 using fixed sea-surface temperatures (Haywood et al., 2013a).
- There was no clear indication in the model ensemble to support either enhanced or weaker Atlantic Meridional Overturning Circulation and Ocean Heat Transport to the high latitudes (Z. Zhang et al., 2013).
- Model predictions of enhanced Atlantic Meridional Overturning Circulation and Ocean Heat Transport to high latitudes are inconsistent, in sign as well as strength (Z. Zhang et al., 2013).
- Clear sky albedo and greenhouse gas emissivity dominate polar amplification of surface temperature warming during the Pliocene. This demonstrated the importance of specified ice sheet and high latitude vegetation boundary conditions and simulated sea ice and snow

albedo feedbacks. Furthermore, the dominance of greenhouse gas emissivity in driving surface temperature changes in the tropics was identified (Hill et al., 2014).

- The simulated weakened mid-Pliocene East Asian winter winds in north monsoon China and intensified East Asian summer winds in monsoon China agreed well with geological reconstructions (R. Zhang et al., 2013).
- Data-model comparison using both sea surface and surface temperature proxies indicate that climate models potentially underestimate the magnitude of polar amplification. However, current limitations in age control and correlation make interpreting data-model discrepancies challenging (Dowsett et al., 2012, Dowsett et al., 2013a, Salzmann et al., 2013).
- Model results indicate that longer term climate sensitivity (Earth System Sensitivity) is greater than Charney Sensitivity (best estimate ESS/CS ratio of 1.5: Haywood et al., 2013a).

1.3 PlioMIP - Emerging Challenges/Opportunities

One of the key findings in PlioMIP Phase 1 was the potential underestimation of model-predicted surface temperature warming in the high latitudes. Understanding data-model discord is non-trivial and can rarely be attributed to a single factor. The complexity of understanding data-model discord is highlighted by the PMIP Triangle (Figure 1), which illustrates three possible contributions to data-model discrepancy, and has at its vertices model physics (structural and parameter uncertainty), model boundary conditions and proxy data uncertainty.

Following on from PlioMIP Phase 1, Phase 2 will continue to be a mechanism for sampling structural uncertainty within climate models as a suite of different models will take part in PlioMIP. However, Phase 1 demonstrated the requirement to better understand boundary condition uncertainties as well as weaknesses in the methodologies used for data-model comparison which largely stemmed from the time averaged nature of proxy data used in previous data-model comparisons (Dowsett et al., 2013a; Salzmann et al., 2013). Therefore, our strategy for Phase 2 is to utilise state-of-the-art boundary conditions that have emerged over the last 5 years. These include a new palaeogeography reconstruction detailing ocean bathymetry and land/ice surface topography, and new data sets describing the distribution of Pliocene soils and lakes. The ice surface topography is built upon the lessons learned during the PLISMIP project (Dolan et al., 2014). Land surface cover will be enhanced by recent additions of Pliocene soils and lakes (Pound et al., 2014). Atmospheric reconstructions of palaeo-CO_2 are emerging on orbital timescales (e.g. Bartoli et al., 2011; Badger et al., 2013) and these will also be incorporated into PlioMIP Phase 2.

It was recognised during Phase 1, that a key influence on data-model discord stems from uncertainties associated with the derivation of the proxy data sets used to assess the climate models. Although certainty surrounding any proxy data set is limited by analytical, spatial and temporal uncertainty, Phase 1 highlighted temporal uncertainty as an important constraint on more robust methodologies for data-model comparison (DMC: Dowsett et al., 2013a; Haywood et al., 2013b; Salzmann et al., 2013). The concept of climate stability during the Pliocene is overly simplistic both in geological climate archives and climate modelling approaches.

Due to the increasing recognition of climate variability in the Pliocene, time averaged approaches to palaeoenvironmental reconstruction have reached their ultimate potential to evaluate climate models. Therefore, enhancing the temporal resolution of data collection in order to more adequately understand climate variation in the Pliocene is required, along with developing a more strategic approach to the choice of relevant Pliocene event(s) to reconstruct and model. One of PlioMIP's guiding principles is to utilise palaeoenvironments to better inform us of likely scenarios for future global change. To this end, the event chosen for PlioMIP Phase 2 focuses on the identification of a 'time slice' centred on an interglacial peak (MIS KM5c; 3.205 Ma) that has near-modern orbital forcing, and yet retains many of the characteristics of Pliocene warmth on which we have focussed in the past (Dowsett et al., 2013b; Haywood et al., 2013b; Salzmann et al., 2013; Prescott et al., 2014). Discussions surrounding potential modification of the LR04 benthic isotope stack (Lisiecki and Raymo, 2005) are currently ongoing, which may lead to a modification of the Marine Isotope Stage assigned to the astrochronological age of 3.205.

PRISM and the wider Pliocene data community are rising to the challenge to obtain higher resolution proxy data that will inform the models about the chosen time slice (e.g. Dowsett et al., 2013b; see also Haywood et al., 2013b). The key differences between the PRISM data that underpinned PlioMIP Phase 1 and the new direction for data collection include:

- Expanding to a community-wide effort, new data generation will focus on key locations and specific regions that have been identified by PlioMIP Phase 1 as important for understanding Pliocene climate variability and model performance.
- In order to increase our understanding of temporal changes in Pliocene climate, time series data are being produced as standard, which will in essence increase previous temporal resolution by two orders of magnitude and lead to enhanced methods of data-model comparison (Dowsett et al. 2013b).
- We will encourage the use of multi-proxy methods of data generation. This will enable us to derive more robust and holistic palaeoenvironmental reconstructions.

1.4 Pliocene for Future and Pliocene for Pliocene

The utilization of the mid-Pliocene as a means to understand future global change ("Pliocene for Future") remains a priority in Phase 2. It is our intention to forge even stronger links between PlioMIP, PMIP, CMIP and the next IPCC assessment. However, we recognise that many researchers are primarily interested in the Pliocene because it represents a considerable challenge to our understanding of the operation of the Earth System ("Pliocene for Pliocene"). Furthermore, a number of scientific requirements and priorities do not fit exclusively within a Pliocene for Future mandate. For example, palaeographic reconstructions are indicating more substantial regional variations in palaeogeography than were appreciated in the past (Hill, 2014). Due to the differing requirements identified, in PlioMIP Phase 2 we have designed a portfolio of model experiments that effectively address both the "Pliocene for Future" and "Pliocene for Pliocene" agendas. This is illustrated in the following CMIP-style diagram (e.g. Taylor et al., 2012) where priorities for both agendas are highlighted, with both agendas sharing a common core experiment, which will be promoted as the PlioMIP Phase 2 experiment within CMIP.

2. Strategy and Methodology

2.1 Naming Convention and Summary of the Experimental Design for PlioMIP Phase 2

The experiments in PlioMIP Phase 2 have been grouped into halves "**Pliocene4Pliocene**" and "**Pliocene4Future**" and would ideally be completed by all participating groups. However, only the core experiments **must be completed** by all groups. Each half of the project is divided into two 'tiers' (Fig. 2). After the core experiments, tier 1 experiments are identified as a higher priority for completion than tier 2.

We describe several model simulations, which essentially consist of various combinations of boundary conditions associated with prescribed CO_2, orography, soils, lakes, and ice sheets. To simplify the experimental descriptions, we use the following nomenclature: Ex^c, where c is the concentration of CO_2 in ppmv, and x are any boundary conditions which are Pliocene as opposed to pre-industrial, where x can be any or none of o,i, where o is orography and i is ice sheets. For example, a pre-industrial simulation with 280 ppmv CO_2 we denote E^{280}. A Pliocene simulation with 400 ppmv is Eoi^{400}, and a simulation with Pliocene ice sheets, but preindustrial orography, and at 560 ppmv, is Ei^{560}. Note that in all our simulations, orography and lakes and soils are modified in unison, and so 'o' denotes changes to orography, bathymetry, land-sea mask, lakes and soils combined.

Within the **Pliocene4Future** agenda, given the uncertainty in total greenhouse gas forcing for the KM5c time slice, we have proposed simulations using 350 and 450 ppmv CO_2 (Eoi^{350}, Eoi^{450}). Both these experiments will facilitate model evaluation using proxy data. Eoi^{450} enables the experimental design to accommodate other Earth System processes that may have an effect on radiative forcing, besides greenhouse gas concentrations. For example, Unger and Yue (2014) have demonstrated that chemistry–climate feedbacks, in terms of their radiative forcing, may play as important, or even more important, role as CO_2 during the Pliocene. With a 450 ppmv experiment we also aim to address how uncertainty in radiative forcing can account for high latitude data-model mismatches that were revealed in PlioMIP Phase 1 (Haywood et al. 2013a; Dowsett et al., 2012 and 2013a; Salzmann et al., 2013). We have also specified a pre-industrial experiment with 560 ppmv CO_2 as a tier 1 experiment (E^{560}) to facilitate an investigation into Climate (Charney) and Earth System Sensitivity.

Within tier 2 we have proposed two experiments that are designed to assess the dependence of climate sensitivity on the background climate and boundary condition states. Here we wish to compare the response of the system to CO_2 forcing, between the Pliocene and the modern, by specifying a Pliocene experiment with 280 ppmv CO_2 (Eoi^{280}), as well as a pre-industrial experiment using 400 ppmv CO_2 (E^{400}).

For our **Pliocene4Pliocene** agenda we have within tier 1 focused on the atmospheric CO_2 uncertainty by specifying a higher and lower CO_2 experiment at 450 and 350 ppmv (Eoi^{450} and Eoi^{350}), which provides a 100 ppmv uncertainty bracket around our KM5c core experiment (using 400 ppmv CO_2). Within tier 2 we have specified a series of experiments designed to identify the individual contribution of boundary condition changes to the overall modelled Pliocene climate response (E^{400}, E^{280}, Eo^{400}, Eoi^{400}). To assess non-linearity in the factorization of the forcings, we have specified an enhanced factorization methodology (E^{400}, E^{280}, Eo^{400}, Eo^{280}, Ei^{400}, Ei^{280}, Eoi^{400}, Eoi^{280}: see section 3.2).

2.2 Standard and enhanced boundary conditions

All required boundary conditions can be accessed from the United States Geological Survey PlioMIP2 website (see: http://geology.er.usgs.gov/egpsc/prism/7_pliomip2.html). For the Pliocene experiment two versions of the palaeogeography (including land/sea mask (LSM), topography, bathymetry and ice distribution) are provided. The **standard** boundary condition data package does not require a modelling group to have the ability to alter the LSM or bathymetry (apart for selected regions of the Bering Strait, Canadian Archipelago and Hudson Bay). The **enhanced** boundary condition requires the ability to change the model's LSM and ocean bathymetry more generally. The standard boundary conditions data set is provided in order to maximise the potential number of participating modelling groups. If groups are unable to make any changes to their models LSM then they may use their own LSM from their pre-industrial simulation. A PRISM4/PlioMIP Phase 2 modern land/sea mask is provided to help guide the implementation of Pliocene topography into different climate models. Groups are asked to make every effort to implement as many of the boundary conditions in the enhanced data packages as possible; however, we recognise that this will not be possible for all groups.

2.3 Core Experimental Design and Boundary Conditions

2.3.1 Integration, atmospheric gases/aerosols, solar constant/orbital configuration

The experimental design for the core Pliocene KM5c time slice experiment is summarised in Table 1 (standard and enhanced boundary conditions). **Integration length is to be set to at least 500 years** in accordance with CMIP guidelines (Coupled Model Intercomparison Project Phase) for equilibrated coupled model experiments (Taylor et al., 2012). **The concentration of CO_2 in the atmosphere is to be set to 400 ppmv.** In the absence of proxy data, **all other trace gases and aerosols are specified to be identical to the individual group's pre-industrial control experiment.**

While Pliocene CO_2 reconstruction is difficult, it is an important ongoing area of research with new records and syntheses due to emerge over the next few years. Current evidence for Pliocene CO_2 comes from a number of sources: (1) the stomatal density of fossil leaves (Kürschner et al., 1996), (2) carbon isotope analyses (e.g. Raymo et al., 1996), (3) alkenone-based estimates (Pagani et al., 2010; Seki et al., 2010; Badger et al., 2014) and (4) boron isotope analyses (e.g. Seki et al., 2010). For the warm intervals of the Pliocene values of CO_2 from each of these proxies vary, but within error they may overlap (Bartoli et al., 2011). The stomatal density records support a CO_2 concentration of 350 to 380 ppmv. The average of the Raymo et al. (1996) carbon isotope analyses is similar to the stomatal-based estimates, but peaks above that value (beyond 425 ppmv) occur. The Pagani et al. (2010) study reconstructed CO_2 from a number of different marine records, and in three of the six marine records a CO_2 value of 400 is reasonable and within the range of 365 to 415 ppmv. In the Seki et al. (2010) study the alkenone-based CO_2 record is consistent with a value around 400 ppmv. Badger et al. (2014), have demonstrated that while absolute alkenone-based CO_2 reconstructions are influenced by a number of factors including productivity, cell size, SST, other local palaeoceanographic conditions as well as secondary effects of alkenone $\delta^{13}C$, assessments of the degree of variability in CO_2 (rather than absolute concentration) are likely to be more robust, and indicate less than 55 ppmv of variation between 3.3 and 2.8 million years ago. **Atmospheric CO_2 is an obvious choice for sensitivity tests as part of PlioMIP Phase 2 and is addressed within the experimental design for PlioMIP Phase 2**. Information on the concentration of other greenhouse gasses such as **Methane and Nitrogen Dioxide is absent for the Pliocene and must therefore be prescribed at a pre-industrial level.** The CO_2 concentrations specified within PlioMIP Phase 2 are therefore designed to **account for the total greenhouse gas forcing derived from all sources.**

The solar constant is to be specified as the same as in each participating group's pre-industrial control run. In previous versions, the PRISM boundary conditions (Dowsett et al. 2010) represented an average of the warm intervals during the time slab (~3.3 to 3 million yr), rather than conditions occurring during a discrete time slice. This made it impossible to prescribe an orbital configuration that would be representative of the entire 300,000 year interval. However, due to the new focus within PRISM4 and PlioMIP Phase 2 to increase the temporal resolution of proxy records, and to concentrate on a smaller interval of time approaching a time slice reconstruction for MIS KM5c, it is now possible to provide climate models with more certain values for astronomical and orbital forcing. The KM5c time slice was selected partly on the basis of a strong similarity in orbital forcing to present-day. Therefore, in the interests of simplicity of the experimental design, **astronomical/orbital forcing in Pliocene experiments (eccentricity, obliquity, and precession) is to remain unchanged from each models pre-industrial control simulation**.

2.3.2 Palaeogeography (land/sea mask, topography, bathymetry, ocean gateways, land ice)

The PRISM4 palaeogeography provides a consistent reconstruction of topography, bathymetry, ice sheets and the land-sea mask that can be implemented in PlioMIP Phase 2 models. The PRISM4 Pliocene palaeogeography data set is provided in NetCDF format at a 1° × 1° resolution. The PRISM4 palaeogeography includes components, such as the contribution of dynamic topography caused by changes in the mantle flow (e.g. Rowley et al., 2013) and the glacial isostatic response of loading specific Pliocene ice sheets (e.g. Raymo et al., 2010), that were not previously considered in the PRISM3D reconstruction of Sohl et al. (2009). **In the standard boundary condition data set all ocean gateways remain the same as the modern except for the Bering Strait, which should be closed, and the Canadian Arctic Archipelago which should also be closed** (isolating Baffin Bay and the Labrador Sea from the Arctic Ocean). **In the enhanced boundary condition data set the Bering Strait and Canadian Arctic Archipelago are closed, but there are other required changes in the Torres Strait, Java Sea, South China Sea, Kara Strait as well as a West Antarctic Seaway.**

The approach taken to derive PRISM4 ice sheets in the palaeogeography reconstruction is different to PRISM3D (Dowsett et al., 2010). The results of PLISMIP have shown that ice sheet model dependency over Greenland is low. However, the initial climatological forcing has a large impact on the predicted Greenland ice sheet configuration (Dolan et al., 2014; Koenig et al., 2014). Using a compilation of the results presented in Koenig et al. (2014), we have implemented an ice sheet configuration over Greenland in PRISM4 where we have the highest-confidence in the possibility of ice sheet location during the warmest parts of the Late Pliocene (see Fig. 6b in Koenig et al. 2014). The reconstruction of Keonig et al. (2014) was modified by removing ice from Southern Greenland. The presence of ice in that region is inconsistent with palynological studies that suggest that Southern Greenland was vegetated during warm intervals of the Pliocene (e.g. de Vernal and Mudie, 1989). **The PRISM4 Greenland Ice Sheet configuration is smaller than in PRISM3D and ice is limited to high elevations in the Eastern Greenland Mountains** (Fig. 4).

Over Antarctica, work in PLISMIP is still ongoing (de Boer et al. 2015); therefore we have decided to use an ice sheet that best agrees with the available proxy data. Based on evidence from the ANDRILL core data and ice sheet modelling (Naish et al., 2009; Pollard and DeConto, 2009) that suggests that, in specific warm periods of the Late Pliocene, there was no ice present in West Antarctica, this region remains ice free in the PRISM4 palaeogeography reconstruction (Fig. 4). Over East Antarctica, Cook et al. (2013) show that the Wilkes subglacial basin may have been highly dynamic during the warmest parts of the Late Pliocene and they infer significant potential for ice sheet retreat in this region. Additionally, Young et al. (2011) highlight the Aurora subglacial basin as an area which may have been subject to marine ice sheet instabilities in the past (potentially in the Pliocene). Therefore, **over East Antarctica PlioMIP Phase 2 uses the PRISM3D ice sheet reconstruction** (Hill et al., 2007; Hill, 2009; Dowsett et al., 2010), as this remains consistent with more recently available data. In this reconstruction (Fig. 4) large portions of the East Antarctic ice sheet show little change or a small increase in surface altitude with respect to modern, and significant ice sheet retreat is limited to the low-lying Wilkes and Aurora subglacial basins.

For the Pliocene experiments, two versions of the palaeogeography will be provided to climate modelling groups:

- **Standard**: For the models where altering the LSM and bathymetry is problematic, we provide a palaeogeography with a modern land-sea configuration and bathymetry (apart from in the Hudson Bay, Bering Strait and Canadian Archipelago). In this instance the Late Pliocene topographic elevations were extended to the modern coastline, and the bathymetry remained at modern values. Groups that are unable to change their land-sea mask or bathymetry at all are asked to use their local modern boundary conditions; however guidance on the implementation of Pliocene topography in this case should be taken from the standard palaeogeography data set.
- **Enhanced**: This presents the full palaeogeographic reconstruction including all changes to topography, bathymetry, ice sheets and the LSM.

To ensure that the climate anomalies (Pliocene minus present day) from all PlioMIP Phase 2 climate models are directly comparable, i.e. that they reflect differences in the models themselves rather than the differences of modern boundary conditions, **it has been decided to implement Pliocene topography (and bathymetry) as an anomaly to whatever modern topographic data set is used by each modelling group in their own model**. To create the Pliocene topography (and bathymetry) the difference between the PRISM4 Pliocene and PRISM4 Modern topography (bathymetry) should be calculated and added to the modern topographic (bathymetric) data sets each participating modelling group employs within their own pre-industrial control simulations.

Such that:

$$\text{Plio}^{\text{TOPO}} = (\text{PRISM4}^{\text{PlioTOPO}} - \text{PRISM4}^{\text{ModernTOPO}}) + \text{Modern}^{\text{TOPO}}\ \text{Local}$$

and

$$\text{Plio}^{\text{BATH}} = (\text{PRISM4}^{\text{PlioBATH}} - \text{PRISM4}^{\text{ModernBATH}}) + \text{Modern}^{\text{BATH}}\ \text{Local}$$

With this formulation it is possible that on occasion grid cells may become land where the intention is for an ocean cell to be specified and vice-versa. In this case the specified Pliocene LSM takes precedence, in other words ensure that the integrity of Pliocene LSM boundary condition data is always preserved. Data sets to be provided at a 1° × 1° resolution for the core experiments can be found in Table 1.

2.3.3 Vegetation, Lakes, Soils and Rivers

A global data set of vegetation for the KM5c time slice is not available. A number of climate models now have the ability to simulate the type and distribution of vegetation using dynamic vegetation models. **In PlioMIP Phase 2 vegetation models should be initialised with pre-industrial vegetation cover and spun up until an equilibrium condition is reached**. **If Pliocene vegetation cannot be predicted dynamically, modelling groups can prescribe vegetation using the Salzmann et al. (2008) PRISM3 vegetation reconstruction used within PlioMIP Phase 1** (Haywood et al. 2010 and Haywood et al. 2011), and provided as a mega biome reconstruction in the PlioMIP Phase 2 boundary condition files. An equivalent potential natural vegetation data set is also provided to guide how groups implement prescribed Pliocene vegetation. **Further details on correctly approaching the implementation of prescribed Pliocene vegetation for PlioMIP Phase 2 can be found in Haywood et al. (2010: Section 3.5).**

Due to lack of information covering the distribution of lakes and soils during PlioMIP Phase 1, lakes were absent from the land cover boundary conditions. Since PlioMIP Phase 1, the global distribution of Late Pliocene soils and lakes have been reconstructed through a synthesis of geological data (Pound et al. 2014). Initial experiments using the Hadley Centre Coupled Climate Model Version 3 (HadCM3) indicate regionally confined changes of local climate and vegetation in response to the new lakes and soils boundary condition (Pound et al. 2014). When combined (lakes plus soils), the feedbacks on climate from Late Pliocene lakes and soils improve the proxy data-model fit in western North America as well as the southern part of northern Africa (Pound et al. 2014).

In PlioMIP Phase 2 all modelling groups should implement the Pound et al. (2014) data sets for global lake (Fig. 5) **and soils distribution** (Fig. 6). **If lake distribution is a dynamically predicted variable within a model (i.e. lake distributions can change as a result of predicted changes in climate), prescribing the Pound et al. (2014) lake data set is not necessary**. The lake data set provides information on both lake size as well as the fractional coverage of lakes within model grid boxes. Figure 5 also shows how the lake distribution and sizes differ from modern, most notably the absence of post-glacial lakes in North America and the presence of large lakes in Central Africa (Pound et al., 2014).

The colour (for albedo) and texture translations for the nine soil orders used in the modelling of Late Pliocene soils and lakes are provided to guide the implementation of soil type and distribution in models. This translation is based upon the definition of soils with the HadCM3 (Table 2).

Groups should **implement Pliocene lakes using the anomaly method** (the anomaly between the provided Pliocene and modern lake data sets added to each groups local modern lake distribution data set), and ensure that minimum lake fractions do not fall below 0 and the maximum do not exceed 1 (100%). **Groups may implement the Pliocene soils using whatever method they deem most appropriate for their model**. This may be by applying the provided Pliocene soil properties directly in their Pliocene simulation (i.e. as an absolute), or by calculating an anomaly from the provided modern soils data, and adding this to the local modern control soil properties. Alternatively, groups may choose to develop a regression of the provided modern soil properties with their local modern control soil properties, and then apply the resulting regression formulae to the provided Pliocene soil properties.

With regard to **river routing** the required solution is to follow modern river routes except where this would be inappropriate due to the appearance of new land grid cells in the Pliocene land/sea mask, in which case rivers should be routed to the nearest ocean grid box or most appropriate river outflow point.

3. Sensitivity experiments and forcing factorization

3.1 Sensitivity Experiments

3.1.1 Pliocene for Future Tier 1 and 2

Within the Pliocene for Future agenda a pre-industrial experiment with 560 ppmv CO_2 has been selected as a tier 1 experiment (E^{560}). This is to facilitate an investigation into Climate (Charney) and Earth System Sensitivity. Also given the uncertainty in total greenhouse gas forcing for the KM5c time slice, we have proposed a simulation using 450 and 350 ppmv CO_2 (Eoi^{450}, Eoi^{350}). Within tier 2 we have proposed two experiments that are designed to assess the similarity of Pliocene and future climate feedbacks to higher CO_2 levels by specifying a

Pliocene experiment using 280 ppmv CO_2 (Eoi^{280}) as well as pre-industrial experiment using 400 ppmv (E^{400}).

3.1.2 Pliocene for Pliocene Tier 1

For the Pliocene for Pliocene agenda we have within tier 1 focused on the atmospheric CO_2 uncertainty by specifying a high and low CO_2 experiment at 450 and 350 ppmv (Eoi^{450} and Eoi^{350} respectively), which provides a 100 ppmv uncertainty bracket around our KM5c core experiment (using 400 ppmv CO_2).

3.2 Pliocene for Pliocene Tier 2 Forcing Factorization Experiments

The primary aim of the Pliocene for Pliocene Tier 2 forcing factorisation experiments is to assess the relative importance of various boundary condition changes which contribute to Pliocene warmth. Following a similar methodology adopted in Lunt et al. (2012) we intend to partition the total Pliocene warming (or temperature change; ΔT) into three components, each due to the change in one of the following boundary conditions: CO_2, topography and ice sheets. Our factorisation, which is that proposed by Lunt et al. (2012), can be written:

$$\Delta T = dT_{CO2} + dT_{topo} + dT_{ice}$$

$$dT_{CO2} = ¼ [(E^{400} – E^{280}) + (Eo^{400} – Eo^{280}) + (Ei^{400} – Ei^{280}) + (Eoi^{400} – Eoi^{280})$$

$$dT_{orog} = ¼ [(Eo^{280} – E^{280}) + (Eo^{400} – E^{400}) + (Eoi^{280} – Ei^{280}) + (Eoi^{400} – Ei^{400})$$

$$dT_{ice} = ¼ [(Ei^{280} – E^{280}) + (Ei^{400} – E^{400}) + (Eoi^{280} – Eo^{280}) + (Eoi^{400} – Eo^{400})$$

This gives a total of 8 simulations required (2^N, where N is the number of processes factorised, = 3 in this case), although only 5 of them (Eo^{400}, Eo^{280}, Ei^{400}, Ei^{280}, Eoi^{280}) are in addition to simulations already in Tier 1 or the Core. This method, although more computationally demanding than the linear approach (e.g. Broccoli and Manabe, 1987; von Deimling et al., 2006), has the advantage that it takes into account non-linear interactions, is symmetric, and is unique (Table 3).

If groups do not have the computational resource to carry out the full factorisation, they may carry out a linear factorisation, as follows:

$dT_{CO2} = E^{400} – E^{280}$

$dT_{orog} = Eo^{400} – E^{400}$

$dT_{ice} = Eoi^{400} – Eo^{400}$

This is a total of 4 simulations, but only 1 of them (Eo^{400}) in addition to simulations already in Tier 1 or the Core. Further guidance on boundary condition implementation for the forcing factorization experiment can be found in Figure 1 of the Supplementary Information.

4. Proxy data for the evaluation of model outputs

Short, high-resolution time series extending from MIS M2 through KM3 will be necessary to meet the evaluation requirements of PlioMIP Phase 2. Marine sequences will depend upon chronology from the Lisiecki and Raymo 2005 (LR04) time scale and should have multiple palaeoenvironmental proxies (Dowsett et al. 2013a). Previous work from the palaeoclimate data community suggests a number of sites potentially suitable for evaluation of PlioMIP Phase 2 model outputs (e.g. Dowsett et al., 2013a, 2013b; Fedorov et al., 2013; Salzmann et al., 2013, Brigham-Grette et al., 2013). Well-dated, high resolution records from the continental interior are scarce, and terrestrial reconstructions will be mostly based on marine and marginal marine sequences. The primary areas of discord between simulated and estimated Pliocene palaeoclimate conditions identified in PlioMIP Phase 1 include the mid-to-high latitude North Atlantic, tropics and upwelling regions (Dowsett et al., 2012). The PRISM4 marine and terrestrial contribution to the PlioMIP Phase 2 community evaluation data set has been initially concentrated in the North Atlantic region (Fig. 7).

5. Variables, output format, data processing and storage

If the PlioMIP Phase 2 core experiment is adopted as a CMIP6 simulation, model data for this experiment must use the Climate Model Output Rewriter (CMOR) format and stored on an ESGF node (The Earth System Grid Federation). The CMOR library has been specially developed to help meet the requirements of the Model Intercomparison. Further details of CMIP6 experiments and required outputs/CMOR file formats will be made available on the CMIP6 website (http://www.wcrp-climate.org/index.php/wgcm-cmip/wgcm-cmip6).

If the PlioMIP Phase 2 core experiment is specified as a PMIP core experiment the same guidelines for output format and storage of data detailed for CMIP6 applies. For PlioMIP Phase 2 experiments listed within Tiers 1 and 2 more flexibility in terms of data storage and file formats is available. PlioMIP Phase 2 has modified the established variables list outlined by the 3rd Phase of the PMIP project. The list of required variables can be found on the PlioMIP Phase 2 website (http://geology.er.usgs.gov/egpsc/prism/7_pliomip2.html). All model outputs will be submitted initially to a data repository at the University of Leeds (including the PlioMIP Phase 2 core experiment, which may have data replicated in CMOR format on an ESGF node). Requests for access should be sent to A Haywood. In general (CMIP6 guidelines aside) PlioMIP project requires participants to prepare their data files so that they meet the following constraints (regardless of the way their models produce and store their results).

- The data files have to be in the (now widely used) NetCDF binary file format and conform to the CF (Climate and Forecast) metadata convention (outlined on the website http://cf-pcmdi.llnl.gov/).
- There must be only one output variable per file.
- For the data that are a function of longitude and latitude, only regular grids (grids representable as a Cartesian product of longitude and latitude axes) are allowed.
- The file names have to follow the PMIP2 file name convention and be unique (see the PMIP2 website).

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Table 2: The colour (for albedo) and texture translations for the soil orders used in the modelling of Late Pliocene soils, based upon HadCM3 classification.

Table 3: Details of all experiments proposed in PlioMIP Phase 2. *By ice sheet regions we mean the land masses of Greenland and Antarctica (not the areas of ice specified within the ice-masks). ** Where ice retreat (i.e. the change from pre-industrial ice to Pliocene ice) leaves information gaps in soils, please extrapolate modern soil values from nearest grid square. [1]For experiment Eoi^{400}, Eoi^{350} and Eoi^{450} this may be using the standard or enhanced Pliocene LSM. [2]For simplicity of approach we assume that all forcing factorisation experiments will only use the standard rather than enhanced data sets. [3]Prescribed static vegetation is also an option. Red = Core experiment (compulsory), Blue = Tier 1 and 2 sensitivity experiments (optional). [4]P4F = Pliocene for Future; P4P = Pliocene for Pliocene. See also Appendix 1 in Supplementary Information.

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Figure 2: Experimental design strategy adopted for PlioMIP Phase 2. Core experiments will be completed by all model groups. Tier 1 and Tier 2 in either “Pliocene4Future” or “Pliocene4Pliocene” describe a series of sensitivity tests (Tier 1 being a higher priority for completion than Tier 2). Please note that Pliocene4Future Tier 1 experiment Pre-Industrial CO_2 400 also appears as a Tier 2 Pliocene4Pliocene experiment (Pre-Ind+PlioCO_2). See Table 3 for the naming convention and further details of all PlioMIP Phase 2 experiments, as well as Appendix 1 in Supplementary Information.

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Figure 7: Initial PRISM4 sites being investigated to generate time slice proxy data for model evaluation in PlioMIP Phase 2.

Tables

Data set Name		Description
Plio_std.zip	Plio_std_topo_v1.0.nc Plio_std_LSM_v1.0.nc Plio_std_soil_v1.0.nc Plio_std_lake_v1.0.nc Plio_std_mbiome_v1.0.nc *(only for models that cannot predict vegetation)* Plio_std_icemask_v1.0.nc	PRISM4 Pliocene palaeogeography reconstruction including new topography and ice sheets; however a modern land-sea mask has been applied. No information on bathymetry is provided. Fractional coverage of lakes as well as the global distribution of soil characteristics is also provided. Salzmann et al. (2008) Pliocene biome reconstruction is also available and has been adapted to fit the new ice mask.
Plio_enh.zip	Plio_enh_topo_v1.0.nc Plio_enh_LSM_v1.0.nc Plio_enh_soil_v1.0.nc Plio_enh_lake_v1.0.nc Plio_enh_mbiome_v1.0.nc *(only for models that cannot predict vegetation)* Plio_enh_icemask_v1.0.nc	Full PRISM4 Pliocene palaeogeography reconstruction including new topography, bathymetry, ice sheets and land-sea mask. Fractional coverage of lakes as well as the global distribution of soil characteristics also provided (soil distributions altered to match enhanced land-sea mask). Salzmann et al. (2008) Pliocene biome reconstruction is also available and has been modified to fit the new palaeogeographic and ice reconstruction.
Modern_std.zip	Modern_std_topo_v1.0.nc Modern_std_LSM_v1.0.nc Modern_std_soil_v1.0.nc Modern_std_mbiome_v1.0.nc	Modern files for reference purposes only. Full modern palaeogeography reconstruction including present-day topography, bathymetry, ice sheets and land-sea mask derived from ETOPO1. Global distribution of soil and vegetation characteristics using the same descriptors as the Pliocene reconstruction provided to aid the implementation of Pliocene soil and vegetation characteristics. Soil file also contains the lake distribution and ice-mask information.

Table 1: Details of NetCDF data packages provided to facilitate PlioMIP Phase 2 experiments.

Soil Group	Soil Colour	Texture	Albedo
Gelisol (31)	Intermediate	Medium	0.17
Histosol (32)	Dark	Fine	0.11
Spodosol (33)	Intermediate	Medium/Coarse	0.17
Oxisol (34)	Intermediate	Fine/Medium	0.17
Vertisol (35)	Dark	Fine	0.11
Aridisol (36)	Light	Coarse	0.35
Ultisol (37)	Intermediate	Fine/Medium	0.17
Mollisol (38)	Dark	Medium	0.35
Alfisol (39)	Intermediate	Medium	0.17

Table 2: The colour (for albedo) and texture translations for the soil orders used in the modelling of Late Pliocene soils, based upon HadCM3 classification.

ID	Description	LSM[1,2]	TOPO.	SOILS	LAKES	ICE	VEGETATION[3]	CO_2	STATUS: Tier 1 or 2 (T) & P4F/P4P[4]
E^{280}	**Pre-industrial experiment as per control simulation in PlioMIP2 experiment.**	**Modern**	**Modern**	**Modern**	**Modern**	**Modern**	**Dynamic**	**280**	**CORE**
E^{400}	Pre-industrial experiment as per control simulation in core PlioMIP2 experiment - CO_2 400 ppmv.	Modern	Modern	Modern	Modern	Modern	Dynamic	400	T2: P4F - T2: P4P
E^{560}	Pre-industrial experiment as per control simulation in core PlioMIP2 experiment - CO_2 560 ppmv.	Modern	Modern	Modern	Modern	Modern	Dynamic	560	T1: P4F
Eo^{280}	Pre-industrial experiment as per control simulation in core PlioMIP2 experiment, however topography (including soils and lakes) is set to Pliocene values outside of ice sheet regions. The land masses of Greenland and Antarctica should have pre-industrial boundary conditions (see Fig. S1a).	Modern	Pliocene	Pliocene	Pliocene	Modern	Dynamic	280	T2: P4P
Ei^{280}	Pre-industrial experiment as per control simulation in core PlioMIP2 experiment, however the ice configurations on Greenland and Antarctica are set to be Pliocene.**	Modern	Modern	Modern	Modern	Pliocene	Dynamic	280	T2: P4P
Eo^{400}	Pliocene experiment as per control simulation in core PlioMIP2 experiment, however ice sheets on Greenland and Antarctica set to modern.	Modern	Pliocene	Pliocene	Pliocene	Modern	Dynamic	400	T2: P4P
Ei^{400}	Pliocene experiment as per control simulation in Core PlioMIP2 experiment. Topography outside of the ice sheet regions set to modern. Soils and lakes are also modern in this experiment.	Modern	Modern	Modern	Modern	Pliocene	Dynamic	400	T2: P4P
Eoi^{280}	Pliocene experiment as per control simulation in Core PlioMIP2 experiment - CO_2 280 ppmv	Modern	Pliocene	Pliocene	Pliocene	Pliocene	Dynamic	280	T2: P4P – T2: P4F
Eoi^{400}	**Pliocene experiment as per control simulation in Core PlioMIP2 experiment.**	**Pliocene/Modern**	**Pliocene**	**Pliocene**	**Pliocene**	**Pliocene**	**Dynamic**	**400**	**CORE**
Eoi^{450}	Pliocene experiment as per control simulation in Core PlioMIP2 experiment - CO_2 @ 450 ppmv)	Pliocene/Modern	Pliocene	Pliocene	Pliocene	Pliocene	Dynamic	450	T1: P4F - T1: P4P
Eoi^{350}	Pliocene experiment as per control simulation in Core PlioMIP2 experiment , but with CO_2 set to 350 ppmv)	Pliocene/Modern	Pliocene	Pliocene	Pliocene	Pliocene	Dynamic	350	T1: P4F - T1: P4P

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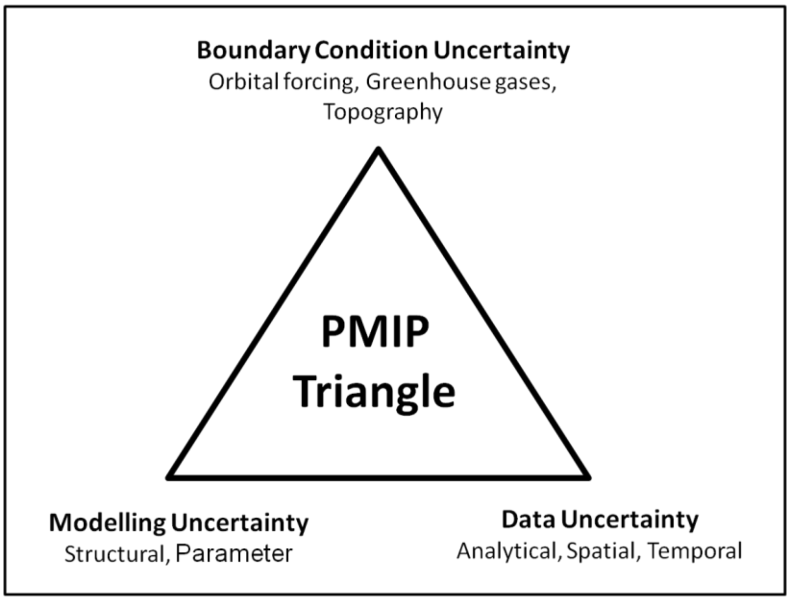
Core experiments (compulsory), Blue = Tier 1 and 2 sensitivity experiments (optional). [4]P4F = Pliocene for Future; P4P = Pliocene for Pliocene. See also Appendix 1 in Supplementary Information.

Figures



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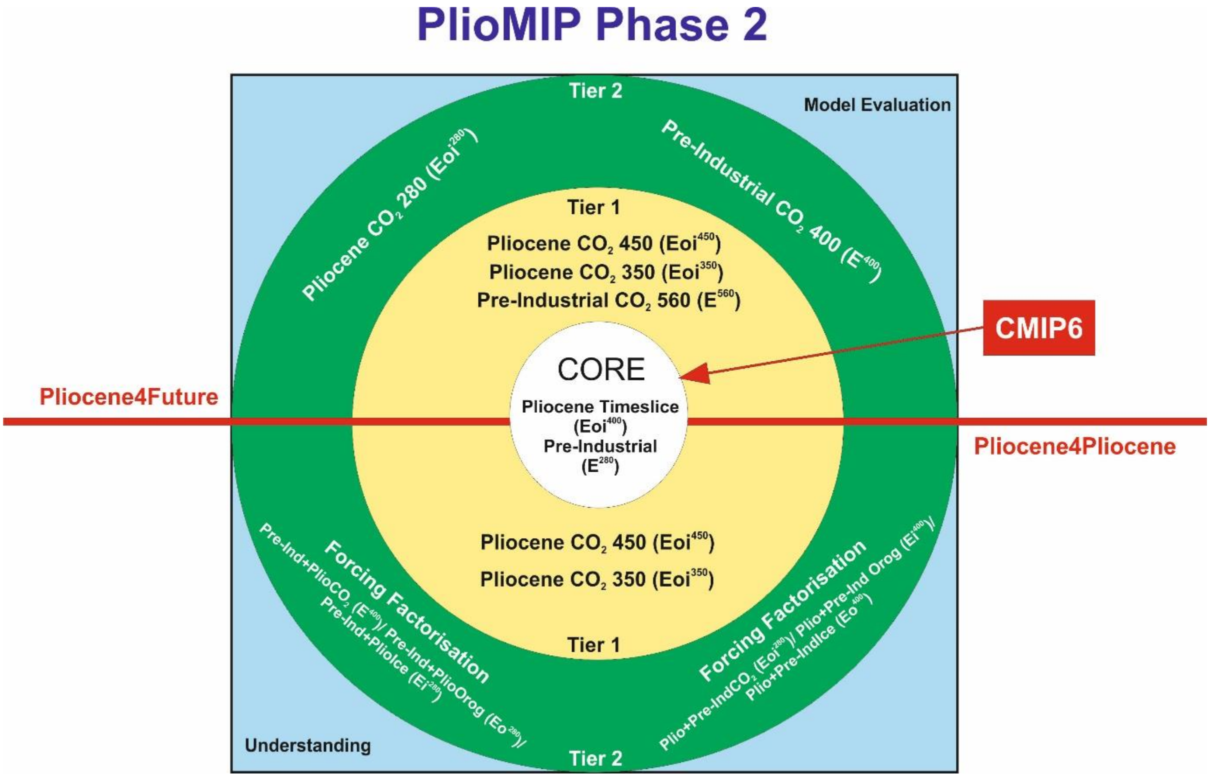

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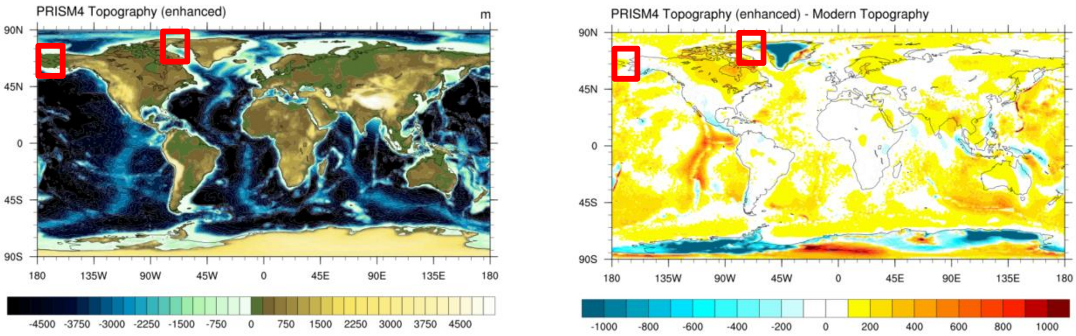

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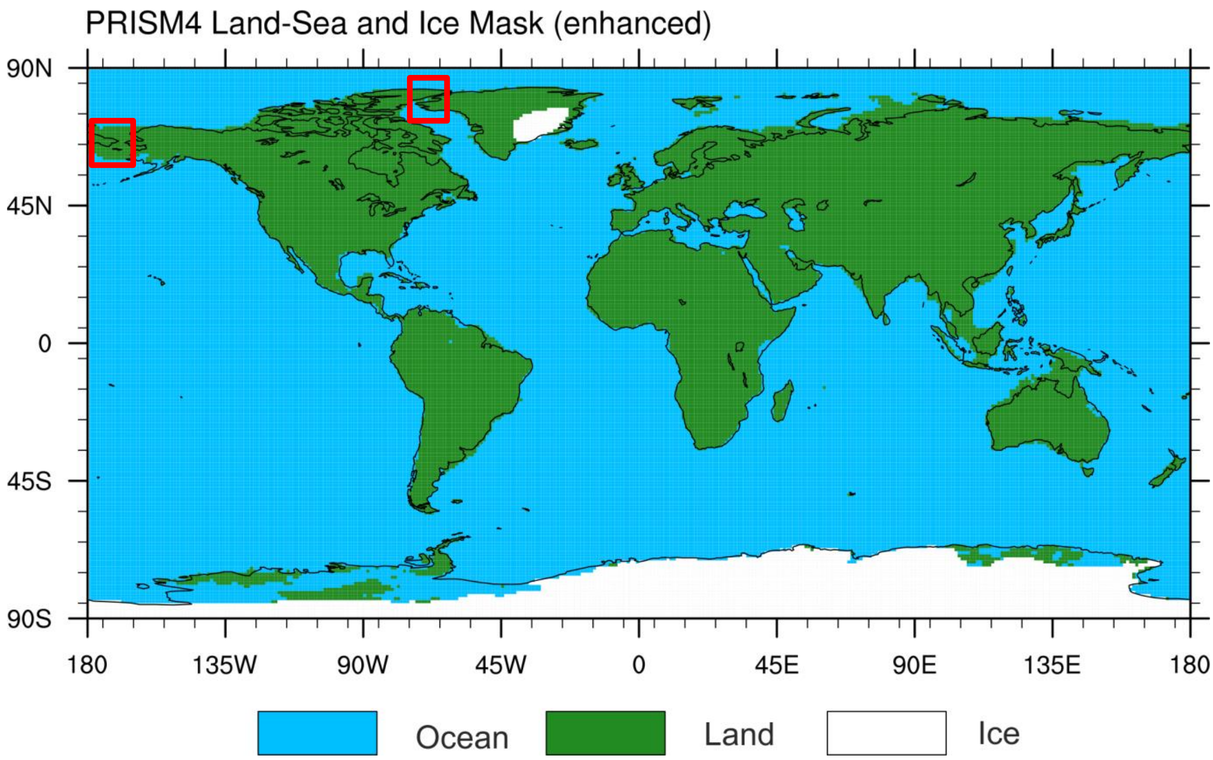

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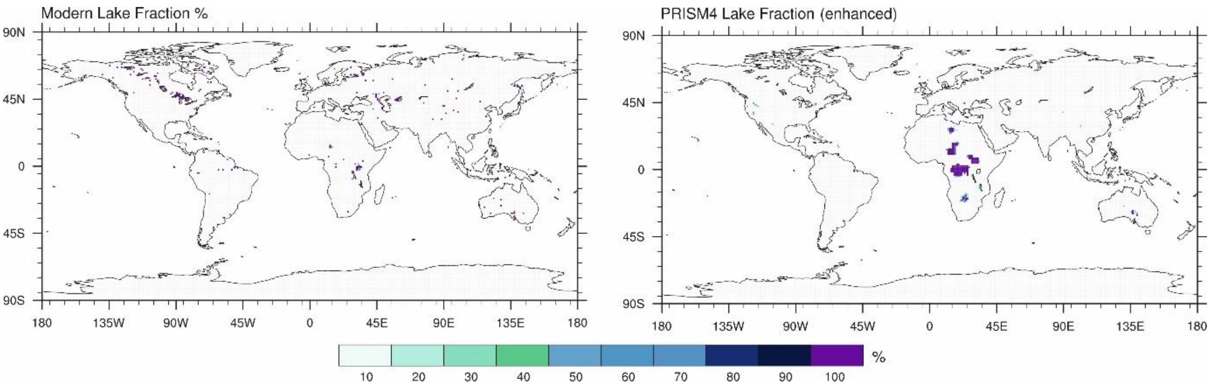

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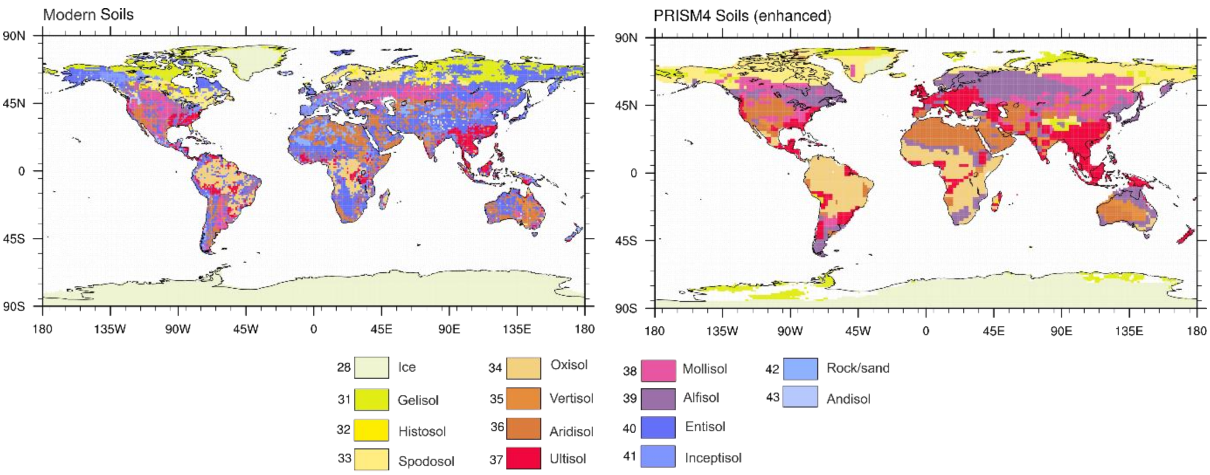

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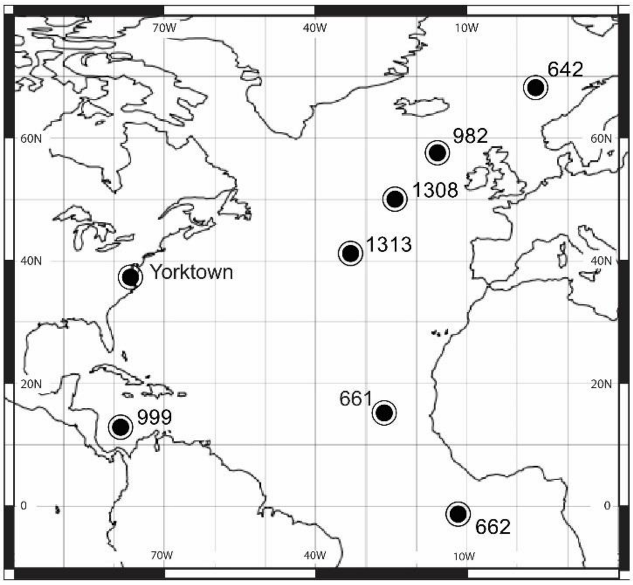

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