



## RESEARCH LETTER

10.1029/2020GL091873

# Observationally Constrained Cloud Phase Unmasks Orbitally Driven Climate Feedbacks

Navjit Sagoo<sup>1,2</sup> , Trude Storelvmo<sup>1,3</sup> , Lily Hahn<sup>1,4</sup> , Ivy Tan<sup>1,5</sup> , James Danco<sup>6,7</sup>, Bryan Raney<sup>6</sup> , and Anthony J. Broccoli<sup>6</sup> 

<sup>1</sup>Geology & Geophysics Department, Yale University, New Haven, CT, USA, <sup>2</sup>Department of Meteorology, University of Stockholm, Stockholm, Sweden, <sup>3</sup>Department of Geosciences, University of Oslo, Oslo, Norway, <sup>4</sup>Department of Atmospheric Sciences, University of Washington, Seattle, WA, USA, <sup>5</sup>Department of Atmospheric and Oceanic Sciences, McGill University, QC, Canada, <sup>6</sup>Department of Environmental Sciences, Rutgers, The State University of New Jersey, New Brunswick, NJ, USA, <sup>7</sup>National Oceanic and Atmospheric Administration, National Weather Service, Raleigh, NC, USA

### Key Points:

- Low cloud phase feedback is less negative in response to orbital forcing when cloud phase is observationally constrained by satellite data
- Shortwave cloud and net water vapor feedbacks are identified as mechanisms which amplify orbitally driven changes in insolation
- Improving cloud phase representation in models is important for understanding the climate system response to forcing in past climates

### Supporting Information:

Supporting Information may be found in the online version of this article.

### Correspondence to:

N. Sagoo,  
[navjit.sagoo@misu.su.se](mailto:navjit.sagoo@misu.su.se)

### Citation:

Sagoo, N., Storelvmo, T., Hahn, L., Tan, I., Danco, J., Raney, B., & Broccoli, A. J. (2021). Observationally constrained cloud phase unmasks orbitally driven climate feedbacks. *Geophysical Research Letters*, 48, e2020GL091873. <https://doi.org/10.1029/2020GL091873>

Received 17 JUN 2020

Accepted 23 JAN 2021

### Author Contributions:

**Conceptualization:** Anthony J. Broccoli  
**Formal analysis:** Navjit Sagoo, Lily Hahn  
**Funding acquisition:** Trude Storelvmo, Anthony J. Broccoli  
**Investigation:** Navjit Sagoo, Lily Hahn  
**Methodology:** Navjit Sagoo, Trude Storelvmo, Anthony J. Broccoli  
**Software:** Ivy Tan, James Danco, Bryan Raney  
**Visualization:** Navjit Sagoo, Lily Hahn  
**Writing – original draft:** Navjit Sagoo, Trude Storelvmo, Lily Hahn  
**Writing – review & editing:** Navjit Sagoo, Trude Storelvmo, Lily Hahn, Ivy Tan, James Danco, Bryan Raney, Anthony J. Broccoli

© 2021. The Authors.

This is an open access article under the terms of the [Creative Commons Attribution-NonCommercial License](https://creativecommons.org/licenses/by/4.0/), which permits use, distribution and reproduction in any medium, provided the original work is properly cited and is not used for commercial purposes.

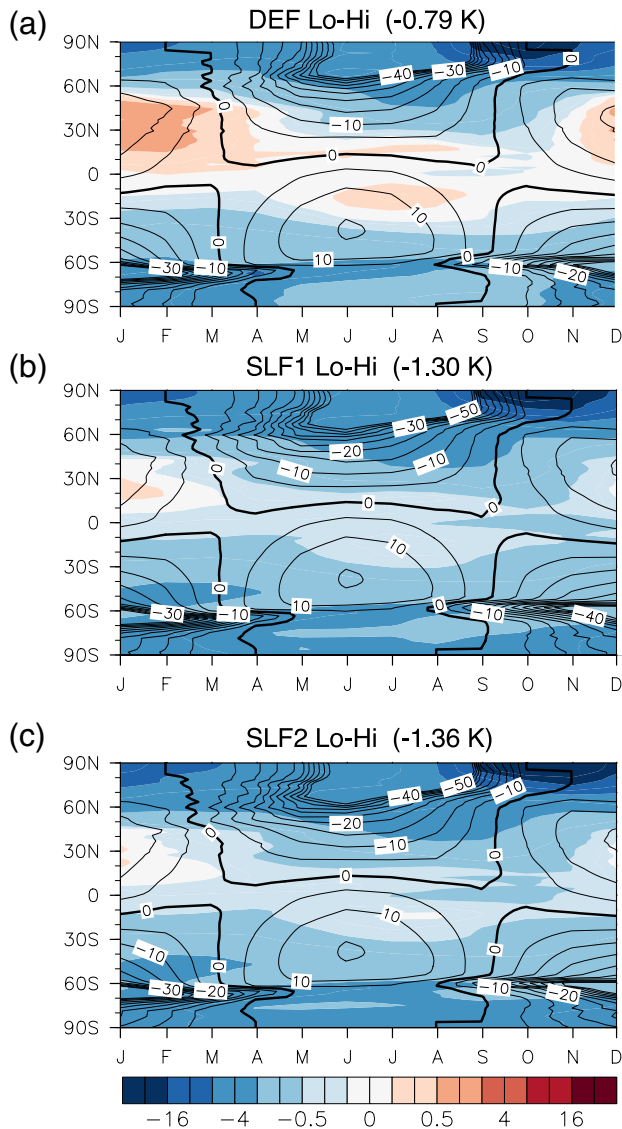
**Abstract** The mechanisms which amplify orbitally driven changes in insolation and drive the glacial cycles of the past 2.6 million years, the Pleistocene, are poorly understood. Previous studies indicate that cloud phase feedbacks oppose ice sheet initiation when orbital configuration supports ice sheet growth. Cloud phase was observationally constrained in a recent study and provides evidence for a weaker negative cloud feedback in response to carbon dioxide doubling. We observationally constrain cloud phase in the Community Earth System Model and explore how changes in orbital configuration impact the climate response. Constraining cloud phase weakens the negative high latitude cloud phase feedback and unmasks positive water vapor and cloud feedbacks (amount and optical depth) that extend cooling to lower latitudes. Snowfall accumulation and ablation metrics also support ice sheet expansion as seen in proxy records. This indicates that well-known cloud and water vapor feedbacks are the mechanisms amplifying orbital climate forcing.

**Plain Language Summary** The recent ice ages represent large transitions in climate that are forced by small changes in solar radiation, driven by variations in the Earth's orbit. This study aims to identify plausible mechanisms that can amplify this small solar signal and lead to the development of large ice sheets, thereby improving our understanding of the climate system. Cloud phase (the proportion of liquid to ice) is poorly represented in climate models and previous work has shown that this can lead to an underestimation of the climate response to carbon dioxide forcing. This study explores the climate response to orbital forcing when cloud phase is observationally constrained by satellite. Previous modeling studies have found that when high latitude solar radiation is reduced due to orbital variations, clouds thin, allowing more absorption of solar radiation which effectively opposes the orbital cooling that encourages ice sheet growth. We find that when cloud phase is constrained, this opposing cloud thinning is reduced and cooling extends to lower latitudes via cloud and water vapor feedbacks. Our work indicates that well-understood climate processes are the mechanisms that amplify orbital climate forcing, and reiterate the importance in properly simulating cloud phase in climate models.

## 1. Introduction

The Earth has experienced dramatic shifts in climate from glacial to interglacial states during the Pleistocene (the past 2.6 million years). These changes are paced by changes in orbital configuration (Hays et al., 1976) but there is no satisfactory theory to fully explain how changes in orbit (eccentricity, obliquity and precession) drive ice sheet growth and decay. Obliquity refers to the angle of the Earth's axis with respect to the orbital plane with a periodicity of 41 kyr, eccentricity is the shape of the Earth's orbit from nearly circular to elliptical with a periodicity of 100 kyr, while precession, with a periodicity of 26 kyr is the “wobble” of the Earth on its axis analogous to the wobble of a spinning top. Milutin Milanković, whose orbital theory is the leading theory, postulated that changes in Earth's orbit affecting summertime insolation were important in determining global ice volume, and that changes in orbit that led to cooler summers would increase snow and ice preservation (Milanković, 1941).

Sedimentary archives from deep sea, bottom dwelling foraminifera, record strong obliquity, and precession forcing over the Cenozoic era (past 65 My) with the obliquity signal dominating these records (Lisiecki & Raymo, 2005; Raymo et al., 2006; Westerhold et al., 2020; Zachos et al., 2001). These proxies show that Pleistocene glacial climates initially varied with a periodicity of around 40 kyr switching to 100 kyr around 1 million years ago.



**Figure 1.** Seasonal changes in zonally averaged surface air temperature (SAT) and insolation shown as Lo-Hi obliquity anomalies. (a) DEF, (b) SLF1, and (c) SLF2. SAT is shown in color shading with the global annual mean SAT anomaly value shown at the top of each figure in parenthesis. Overlaid black contours and labels denote the Lo-Hi surface insolation anomaly with the thick black line indicating the zero-insolation contour. DEF, Default; SLF, supercooled liquid fraction.

The precession signal is modulated by eccentricity, and is weaker in the early Pleistocene and stronger in late Pleistocene records (Huybers, 2011; Liautaud et al., 2020). Numerous hypotheses have been proposed to explain the weak precession signal in the early Pleistocene proxies, e.g. interhemispheric cancellation of ice-volume changes (Raymo et al., 2006), summer duration and intensity being antiphased (Huybers, 2006), and meridional insolation gradients (Raymo & Nisancioglu, 2003). A recent study using statistical methods argues that precession has a stronger contribution than previously recognized in the early Pleistocene and increases through this epoch (Liautaud et al., 2020).

While precession controls the intensity of summer insolation (Huybers, 2006) glaciers are sensitive to insolation integrated over the duration of the summer of which obliquity is a primary control. Our study focuses on the role of obliquity in driving the glacial climates because this is the dominant signal recorded in proxies, particularly in the early Pleistocene (Zachos et al., 2001). When Earth's obliquity is low, summers are cooler and winters are warmer, with the cool summers thought to favor the preservation of ice and glacial conditions. Changes in obliquity affect the annual mean meridional gradient in insolation with larger changes in the high latitudes than in the low latitudes. For the range of high and low obliquity values used in this work (see methods) and previous studies (Erb et al., 2013; Mantsis et al., 2011) a reduction in the obliquity from  $24.480^\circ$  to  $22.079^\circ$  leads to a reduction in high latitude insolation of up to  $50 \text{ Wm}^{-2}$  over the summer (see Figure 1). While these changes in insolation are large, they are not sufficient to completely drive the glacial cycles of the Pleistocene (Erb et al., 2013; Huybers, 2011; Lisiecki, 2010; Mantsis et al., 2011; Rind et al., 1989; Saltzman et al., 1984).

The relationship among the different orbital frequencies, as well as  $\text{CO}_2$  and dust which covary with the Pleistocene glacial cycles is complex (Martínez-García et al., 2011; Petit et al., 1990; Sigman & Boyle, 2000). General Circulation Models (GCMs) which have incorporated orbital changes and additional climate forcings such as  $\text{CO}_2$  (Barnola et al., 1987), dust (Lambert et al., 2008), vegetation (Tabor et al., 2015), topography or coupled ice sheet models (Abe-Ouchi et al., 2013), and including regolith, as previously hypothesized and tested (Clark & Pollard, 1998; Tabor & Poulsen, 2016), have had modest success in both simulating glacial inception and/or glacial melt as well as the sawtooth shape and periodicity of the glacial cycles.

Transient simulations run over several glacial cycles using Earth system Models of Intermediate Complexity (EMICs) have had considerably more success in simulating glacial-interglacial climates. Ganopolski and Brovkin (2017) were able to simulate the temporal dynamics of  $\text{CO}_2$  and global ice volume over the past four glacial cycles using orbital variability as the only external forcing. The timing of glacial terminations was well simulated, but changes in  $\text{CO}_2$  concentration lagged, and the amplitude of simulated changes were smaller than that indicated in the proxy record. In a later study using the same model Willeit et al. (2019) found that including regolith removal allowed them to better simulate Pleistocene climate variability, and increase the amplitude of the simulated variations. While the results of these studies are impressive, EMICs have coarse resolution and many simplifications—particularly in the atmosphere compared to GCMs and Earth System Models (ESMs). The physical mechanisms, and climate feedbacks that can contribute to orbitally driven ice sheet growth and decay are still poorly understood and simulated in GCMs.

Our study is inspired by the findings of Erb et al. (2013) who quantified the role of radiative feedbacks to changes in obliquity. They found that a negative low cloud feedback, due to a reduction in low cloud amount and cloud

water content, impeded ice sheet initiation by opposing glaciation at times when orbital forcing would otherwise support it. A negative low cloud feedback has also been identified in other studies (Birch et al., 2017; Jochum et al., 2012) and highlights additional complications to understanding the orbit-climate relationship. Jochum et al. (2012) ran simulations using insolation from the last glacial inception (115 kya) and also found a reduction in low cloud amount, resulting in a negative shortwave (SW) cloud feedback. They calculated that the initial (orbital) forcing of  $1.9 \text{ Wm}^2$  above  $60^\circ\text{N}$  was amplified by the snow-ice-albedo feedback by  $6.7 \text{ Wm}^{-2}$  and was damped by a negative SW cloud feedback of  $3.1 \text{ Wm}^{-2}$ , due to a reduction in low cloud. Birch et al. (2017) used a high-resolution cloud resolving model to examine the role of clouds in glacial inception and their results confirmed those of Jochum et al. (2012).

Clouds are one of the most challenging and uncertain aspects of the climate system (Boucher et al., 2013) and new research suggests that the negative feedback associated with cloud phase changes in existing models may be too strong (Tan et al., 2016). Cloud phase is poorly represented in global climate models, which have tended to underestimate the supercooled liquid fraction (SLF) in mixed phase clouds (MPCs; Cesana et al., 2015; Komurcu et al., 2014). MPCs are common in the mid and high latitudes (Morrison et al., 2012; Shupe, 2011; Zhang et al., 2010) but are difficult to model for several reasons: there is a paucity of observational data (Illingworth et al., 2007; Morrison et al., 2012) and general difficulties in representing MPC microphysics (Komurcu et al., 2014; Lohmann & Hoose, 2009), in particular the conversion from liquid to ice known as the Wegner-Bergeron-Findeisen (WBF) process (Storelvmo et al., 2008; Tan & Storelvmo, 2016).

The cloud phase feedback can be explained as so: in response to warming the liquid-ice phase transition isotherm moves to higher altitudes such that, for a given altitude, the SLF is enhanced relative to the initial state. For a given amount of cloud water, supercooled liquid droplets are more reflective to SW radiation than cloud ice due to their smaller size and larger population (Murray et al., 2012; Pruppacher & Klett, 1978). The transition from ice to liquid therefore produces a negative feedback as supported by both models (Mitchell et al., 1989) and satellite observations (Tan et al., 2019). When SLFs are initially underestimated, this negative feedback is too strong and masks other cloud processes that generally yield positive feedbacks (Tan et al., 2016).

Using observationally constrained cloud phase, Tan et al. (2016) found that the liquid-to-ice transition isotherm moved upward, where there are fewer and thinner clouds, and poleward where incoming solar radiation is reduced. Subsequently the phase transition response to radiative perturbation is weakened and equilibrium climate sensitivity (ECS) increased. Climate sensitivity in the latest generation of climate models, the Coupled Modeling Intercomparison Project (CMIP6), has increased in the 27 models currently available (1.8–5.6 K) compared to previous estimates (1.5–4.5 K; Bindoff et al., 2013). This is attributed to stronger positive cloud feedbacks (amount and scatter), and linked to reductions in low cloud cover and water content in the mid-latitudes in response to changes in sea-surface temperatures (SSTs; Zelinka et al., 2020). The small negative feedback from low cloud scattering in CMIP5 is on average positive in CMIP6. This weaker liquid water path (LWP) increase with warming is qualitatively consistent with Tan et al. (2016) and several other studies (Bodas-Salcedo et al., 2019; Gettelman et al., 2019; McCoy et al., 2015; Zelinka et al., 2020).

This study examines the response of observationally constrained clouds to orbital forcing in pairs of simulations in which obliquity is prescribed at the extremes of its Pleistocene range (Lo and Hi simulations). We use the same model set up and observationally constrained SLF values (SLF1 and SLF2) as used in Tan et al. (2016). However, in this work, we explore the impact of observationally constrained SLFs on the response to obliquity forcing rather than  $\text{CO}_2$  forcing. Changes in obliquity are not spatially uniform, with a larger impact in the higher latitudes than in the tropics. Obliquity values are taken from the Erb et al. (2013) study which first evaluated radiative feedbacks in response to orbital forcing and identified a negative high latitude cloud feedback.

## 2. Materials and Methods

### 2.1. Climate Model Setup

The Community Earth System Model (CESM) version 1.0.6 (Hurrell et al., 2013) is comprised of the atmospheric component CAM5.1 (X. Liu et al., 2012; Neale et al., 2010) which has 30 vertical levels and uses the three-mode

version of the Modal Aerosol Module (MAM3; X. Liu et al., 2012); the Community Land Model (CLM4.0; Lawrence et al., 2011; Oleson et al., 2010); the ocean model (Parallel Ocean Program Ocean model, POP2; Smith et al., 2010) and the Ice Model (Community Ice CodE, CICE4.0; Holland et al., 2012; Hunke et al., 2010). In these simulations, CAM5.1 and CLM4.0 are run with a resolution of  $1.9^\circ \times 2.5^\circ$  while POP2 and CICE4.0 have a nominal  $1^\circ$  resolution. The Default (DEF) simulation is run with the default cloud microphysics scheme (Morrison & Gettelman, 2008) and the standard ice-nucleation parameterization scheme (Meyers et al., 1992) in which ice nucleating particle number concentration is calculated based on temperature and supersaturation. For the SLF1 and SLF2 simulations, the ice-nucleation parameterization scheme is updated (DeMott et al., 2015) to a more realistic scheme which enables ice nucleating particle number concentration to be diagnosed as a function of the concentration of large dust particles in addition to temperature. This allows for the spatial and temporal variability of dust ice nucleating particles (INP) to be taken into account. As in Tan et al. (2016) SLFs in SLF1 and SLF2 were determined from the results of a 256 member quasi Monte Carlo sampling approach in which six cloud microphysical parameters were modified, and the resulting cloud phase was compared with satellite data from NASA's Cloud-Aerosol-Lidar with Orthogonal Polarization (CALIOP; Winker et al., 2009). The parameter combinations selected for SLF1 and SLF2 were very different (Table S1) but both produced SLFs in excellent agreement with CALIOP.

## 2.2. Climate Simulations

We use a preindustrial model configuration (i.e., land mask, ice sheets, greenhouse gases, vegetation, and aerosols) whereas Tan et al. (2016) used a present-day configuration. This leads to a large top-of-atmosphere (TOA) radiative imbalance which would require very long simulations to reduce. We re-tune the model slightly (Table S2) and the findings from our untuned simulations (not included) and tuned simulations are consistent.

Following Erb et al. (2013), we perform idealized simulations in which only obliquity is modified to a low (Lo) value of  $22.079^\circ$  and a high (Hi) value of  $24.480^\circ$  representative of the past 600 kyr. DEF, SLF1, and SLF2 are run with Lo and Hi obliquity (six simulations) until the TOA energy budget is  $< 0.3 \text{ Wm}^{-2}$  which takes between 350 and 850 years for the different simulations (Table S3). These simulation lengths are long enough to capture broad changes in the atmosphere and surface ocean but are not long enough for the oceans to fully respond to the obliquity forcing. The final 50 years of the simulation are used as the input for cloud radiative kernel computations, for calculations of climate means and for the International Satellite Cloud Climatology Project (ISCCP) satellite simulator analysis (Klein & Hartmann, 1993; Webb et al., 2001). The majority of results are presented as Lo-Hi anomalies as this convention reduces northern hemisphere (NH) summer insolation, which is conducive to a cooling climate and NH glaciation.

## 2.3. Downscaling Model

Because climate model resolutions are too coarse to capture the detail required for realistic ice sheet dynamics, i.e. underlying bedrock topography, (Birch et al., 2017; Pollard & Thompson, 1997), a downscaling approach was also used to determine the extent to which the differences in cloud parameterization would affect the persistence of snow cover in the low obliquity simulation. As in Notaro et al. (2014), the downscaling method we used employed the SNOW-17 snow accumulation and ablation model (Anderson, 2006), which is used by the United States National Weather Service for real-time hydrologic modeling. SNOW-17 is driven by daily temperature and precipitation. Modern snow cover was simulated on a  $1^\circ$  by  $1^\circ$  latitude-longitude grid by using 30 years of observed daily temperature and precipitation from the data set compiled by Kluver et al., (2016). To simulate snow cover in the low obliquity experiments, the so-called "delta-change" approach is used (Lettenmaier et al., 1999). For each month, climatological differences in surface air temperature were computed between each low obliquity simulation and a corresponding historical simulation (using historical forcing from 1850 to 2000) with the same cloud parameterization. These differences were interpolated to the  $1^\circ$  by  $1^\circ$  grid and added to the 30-year observed daily temperature time series at each point. A similar approach was used for precipitation except that the ratio of low obliquity and historical precipitation was determined, and the observed precipitation time series was multiplied by this ratio.

### 3. Results

#### 3.1. Temperature and Insolation Seasonal Cycle

Obliquity affects the annual latitudinal distribution of insolation and modulates seasonality especially in the high latitudes. These changes have a negligible impact on global annual mean insolation, with lower (Lo) obliquity reducing polar insolation in summer and increasing it in winter. Figure 1 shows the annual mean Lo-Hi surface air temperature (SAT) anomaly (colored contours) with the insolation anomaly overlaid (black contours). The negative insolation anomaly (in all simulations) extends across almost all the northern hemisphere (NH) from March to September. In the DEF experiment, negative SAT anomalies lag the insolation anomaly by  $\sim 6$  weeks and have a smaller spatial and temporal extent than the negative anomalies in SLF1 and SLF2. In SLF1 and SLF2, negative SAT anomalies extend equator-wards in March and over the entire NH (and globe) until January where a very small 0.25 K tropical warming occurs.

Negative SAT anomalies in SLF1 and SLF2 extend into areas with a positive insolation anomaly and indicate the importance of climate feedbacks over direct insolation forcing. The Lo-Hi global annual mean SAT anomalies for our experiments are  $-0.79$  K,  $-1.30$  K and  $-1.36$  K for DEF, SLF1, and SLF2, respectively. This cooling signal and its extension to lower latitudes with constrained SLF applies to both hemispheres, unlike other studies which simulate very little cooling in the Southern Hemisphere (Jochum et al., 2012). These SAT anomalies indicate that the climate response to obliquity forcing is considerably larger when cloud phase is observationally constrained.

#### 3.2. Radiative Feedbacks

We calculate the radiative feedbacks of surface albedo, atmospheric water vapor, vertical temperature lapse rate and cloud optical properties using the radiative kernel method of climate feedback analysis (Shell et al., 2008; Soden et al., 2008). Note that results are presented as the effect of feedbacks on net TOA radiation  $\Delta R_{\text{net}}$  ( $\text{Wm}^{-2}$ ) and not as feedbacks ( $\text{Wm}^{-2} \text{K}^{-1}$ ) as this avoids dividing by small values of global mean  $\Delta T$  (Erb et al., 2013). In the context of how our results are presented: For Lo-Hi anomalies, a positive value of  $\Delta R_{\text{net}}$  indicates a feedback effect that opposes orbitally driven cooling. A negative value of  $\Delta R_{\text{net}}$  indicates a feedback effect that strengthens the orbital signal. Globally, the  $\Delta R_{\text{net}}$  from all radiative feedbacks is  $\sim 1.6$ – $1.7$  times stronger in SLF1 and SLF2 compared to DEF. Global mean  $\Delta R_{\text{net}}$  from SW cloud and water vapor feedbacks are much larger in SLF1 and SLF2 compared to DEF, while the  $\Delta R_{\text{net}}$  from lapse rate feedback is similar in all simulations and the  $\Delta R_{\text{net}}$  from surface albedo feedback is only marginally larger in SLF1 and SLF2. When broken down into hemispheres and regions (Figure 2), the mid-latitude cloud feedback and tropical water vapor feedback effects stand out as being much larger in SLF1 and SLF2 compared to DEF.

During late summer in the high latitude insolation is reduced due to low obliquity, which should lead to local cooling. Over this period in DEF, column-integrated liquid (i.e., LWP) reduces and acts to oppose and reduce cooling from this obliquity driven reduction in insolation (Figure S1). In the SLF1 and SLF2 simulations this high-latitude LWP reduction in summer is not evident, but a large increase in total (ice + liquid) water path (TWP) appears in the mid-latitudes ( $30^{\circ}\text{N}$ – $60^{\circ}\text{N}$ ) which increases cloud reflectivity and thus cooling throughout the year (Figure S2).

In response to obliquity forcing (Lo-Hi), cooling leads to cloud liquid being converted to cloud ice, which is optically thinner. The cloud phase bias in DEF causes an exaggerated cloud thinning as too much liquid is converted to ice with cooling. This exaggerated reduction in cloud optical depth counters the other, mainly positive, cloud feedbacks and therefore weakens the spreading of high-latitude cooling to mid- and low latitudes. In contrast, the amplifying mid-latitude cloud feedback in SLF1 and SLF2 is twice as strong as in DEF, permitting high-latitude cooling to spread across the mid-latitudes toward the tropics. The slight cooling in the tropics (as opposed to the warming seen in DEF) is accompanied by a slight decrease in atmospheric water vapor, as expected according to the Clausius-Clapeyron relation. Since water vapor is a potent greenhouse gas, this reduction in water vapor increases outgoing longwave (LW) radiation and thus constitutes a powerful amplifying feedback in the tropics. High and mid-latitude cooling in DEF is not amplified by cloud feedbacks as in SLF1 and SLF2. This results in the slightly positive summer Lo-Hi tropical insolation anomaly producing a warming in DEF and thus a positive water vapor feedback that opposes high-latitude orbitally forced cooling.

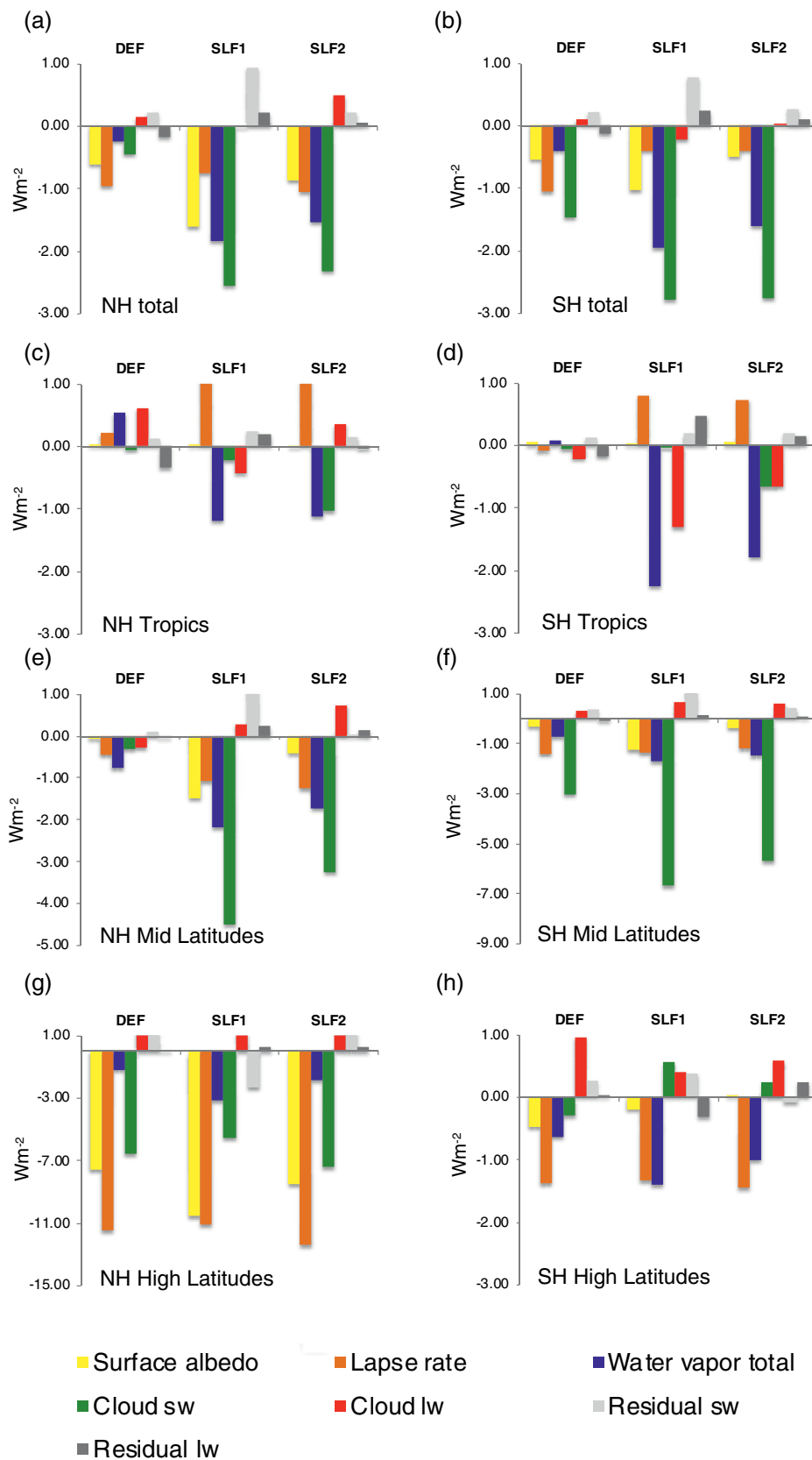
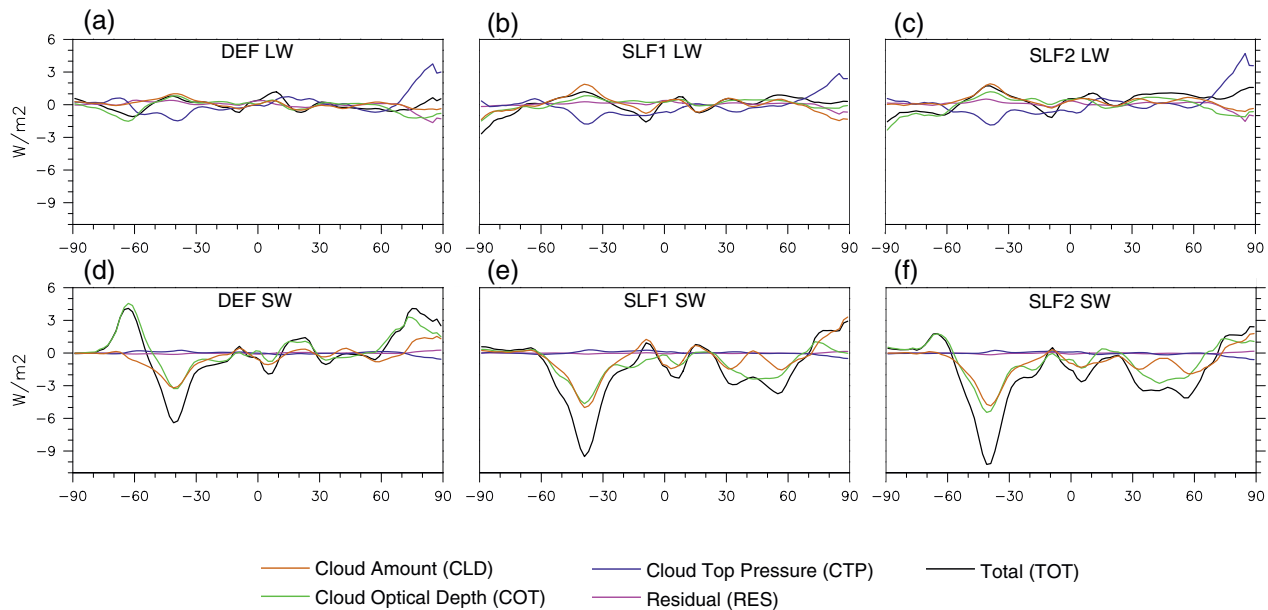


Figure 2.



**Figure 3.** Longwave (LW) and shortwave (SW) and net cloud feedback effects (expressed as  $\Delta R_{\text{net}}$  in  $\text{W m}^{-2}$ ) calculated using the International Satellite Cloud Climatology Project satellite simulator (ISCCP). LW feedbacks are shown in the top row: (a) DEF, (b) SLF1, and (c) SLF2, SW feedbacks are shown in the bottom row: (d) DEF, (e) SLF1 and (f) SLF2 with feedbacks due to changes in cloud amount (CLD) shown in orange, cloud optical depth (COT) in green, cloud top pressure (CTP) in blue, a residual component in magenta and total feedbacks are shown in black. DEF, Default; SLF, supercooled liquid fraction.

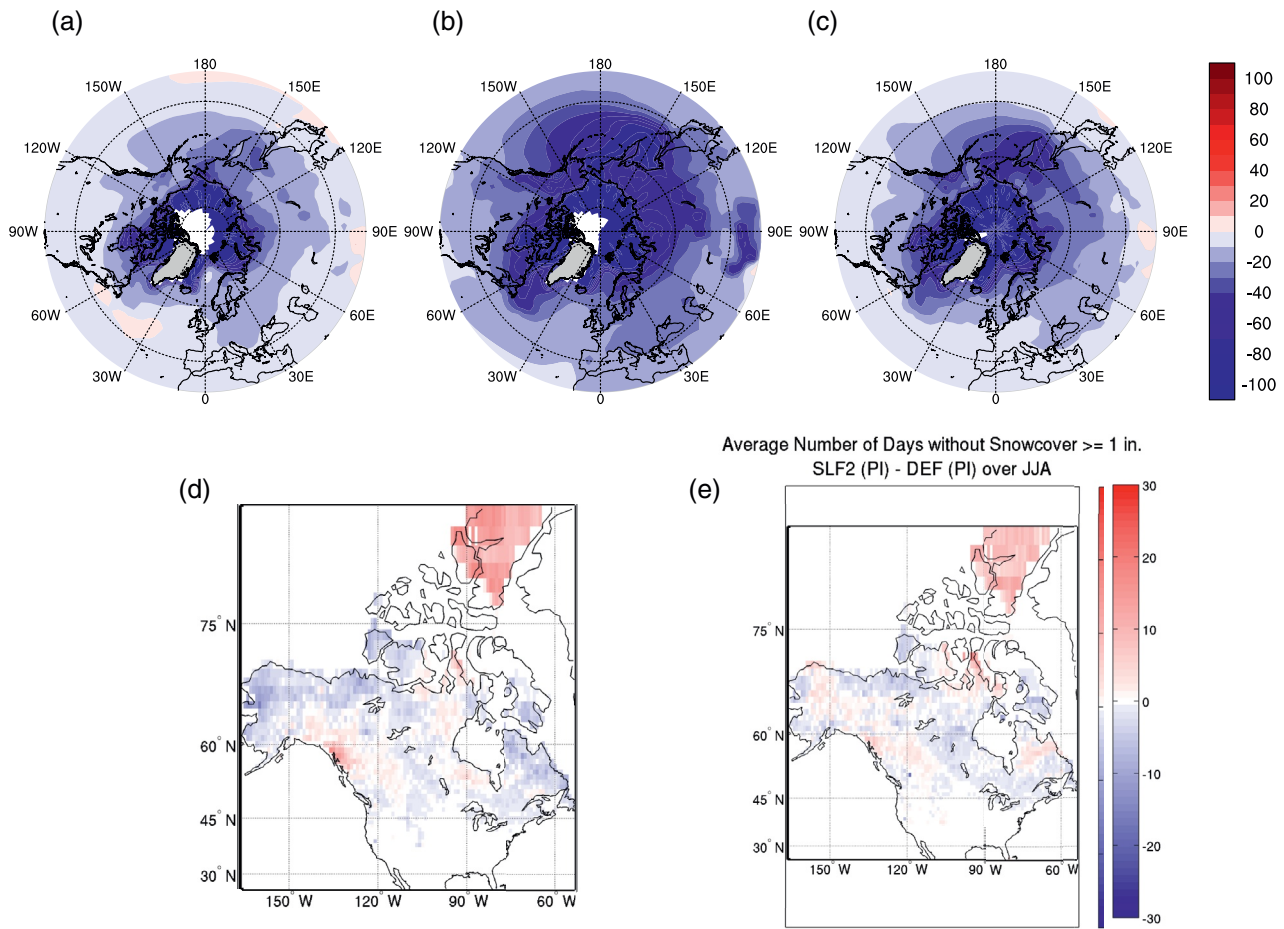
### 3.3. Decomposing the Cloud (Feedback) Response to Orbital Forcing

In order to more fully understand the changes in cloud properties that occur in response to orbital forcing we examine the output from the International Satellite Cloud Climatology Project satellite simulator (ISCCP; Klein & Jakob, 1999; Webb et al., 2001) which is implemented in the atmosphere component of CESM, the Community Atmosphere Model (CAM5.1). The ISCCP simulator allows cloud properties in models to be diagnosed in a manner consistent with the satellite view from space. The radiative impact of changes in cloud amount (CLD), optical depth (COT), and cloud top pressure (CTP) as well as a residual term are calculated following Zelinka et al. (2012) and summarized by feedback in Figure 3 with the net feedback shown in Figure S2. This decomposition of the net (SW + LW) cloud feedback into contributions from CLD, CTP and COT reveals that the latter component is responsible for the difference in mid-latitude cloud feedback between DEF on one hand, and SLF1 and SLF2 on the other. Because the orbital signal is strongest between  $60^{\circ}\text{N}$  and  $90^{\circ}\text{N}$ , it helps to consider this region first. Between  $60^{\circ}\text{N}$  and  $90^{\circ}\text{N}$  SW COT is positive in DEF, while in SLF1 and SLF2, it is shifted to less positive values. Between  $30^{\circ}\text{N}$  and  $60^{\circ}\text{N}$ , SW COT has decreased from near zero in DEF, to  $-3 \text{ W m}^{-2}$  in SLF1 and SLF2 across this latitude band. In the Southern Hemisphere, the SW COT feedback becomes significantly less positive ( $60^{\circ}\text{S}$ – $90^{\circ}\text{S}$ ) and more negative ( $30^{\circ}\text{S}$ – $60^{\circ}\text{S}$ ) in SLF1 and SLF2 compared to DEF.

### 3.4. Glacial Inception

The central tenet of Milanković's orbital theory is that cooler summers allow high latitude snow to survive the summer melt season. Perennial snow cover subsequently leads to snow-albedo feedbacks, which amplify ice cap expansion and initiate the growth of large-scale ice-sheets. Sediment cores indicate that in the NH the last glacial inception occurred  $\sim 115,000$  years ago in the region of Hudson Bay and Baffin Island over a period of around 20,000 years (Clark et al., 1993). Furthermore, SLF2, which generally has a higher supercooled liquid water content than SLF1 (Tan et al., 2016) exhibits more snow-free days than SLF1, in line with Tan and Storelvmo (2019), suggesting the importance of ice cloud microphysics on Arctic amplification. We gauge the summer melt

**Figure 2.** The effect of radiative feedbacks partitioned into individual components (surface albedo, lapse rate, water vapor, cloud shortwave (SW), cloud longwave (LW) and residuals (SW and LW)) and split by region and hemisphere: (a) & (b) Northern and Southern hemisphere mean (NH & SH); (c) & (d) tropics ( $0$ – $20^{\circ}\text{N}$  and  $0$ – $20^{\circ}\text{S}$ ); (e) & (f) mid-latitudes ( $30^{\circ}\text{N}$ – $60^{\circ}\text{N}$  and  $30$ – $60^{\circ}\text{S}$ ) and (g) & (h) high latitudes ( $60^{\circ}\text{N}$ – $90^{\circ}\text{N}$  and  $60^{\circ}\text{S}$ – $90^{\circ}\text{S}$ ). Note that results are presented as the effect of feedbacks on net TOA radiation ( $\text{W m}^{-2}$ ) and not as surface temperature-mediated feedbacks ( $\text{W m}^{-2} \text{ K}^{-1}$ ). SLF, supercooled liquid fraction; TOA, Top-of-atmosphere.



**Figure 4.** Indicators of change in summer (June, July, August) snow preservation. Percentage change in positive-degree days (PDD) polewards of 30°N for northern hemisphere for Lo-Hi anomaly shown for (a) DEF, (b) SLF1, and (c) SLF2 Lo-Hi experiments with blue indicating fewer PDD and increased likelihood of snow preservation. A downscaling model was used to calculate the average number of days without snow  $\geq 1$ " in the Canadian Arctic for the Lo-Pre-industrial anomaly for DEF, SLF1 and SLF2. The anomaly of (d) SLF1-DEF and (e) SLF2-DEF are shown in the bottom row where blue indicates an increase in snow covered days. DEF, Default; SLF, supercooled liquid fraction.

response to the cooling signal in these experiments by calculating the percentage change in positive degree-days (PDD) for Lo-Hi over the June-July-August (JJA) period (Figures 4a–4c). PDD are calculated as the sum total of daily average temperatures above 0°C in a given time period. We focus on JJA as although Milanković theory considers caloric summer half year, the majority of glacial melt takes place over the short summer season. All three experiments show a substantial reduction in PDD (up to 50%) in the high Arctic, Hudson Bay area and over Baffin Island, which are likely locations of the last initiation of the Laurentide ice sheet. In SLF1 and SLF2 the reduction in PDD extends further into the mid-latitudes than DEF, in agreement with the increased extent of negative SATs.

As climate models are too coarse to capture the detail required for realistic ice sheet dynamics. We use a downscaling method to provide an additional metric for evaluating glacial inception. Figures 4d and 4e shows the average number of days without snow cover  $> 1$ " for the Lo - historical anomaly over the Canadian Arctic. SLF1 and SLF2 have fewer snow free days over the summer than DEF, with this increase in snow preservation occurring over the southern part of Baffin Island, eastwards of the Hudson Bay and over much of northern and middle Canada, which is in line with the proxy evidence (Clark et al., 1993). Because modern simulations were not available for this study, and the modern climate is warmer than the historical climate, our use of historical anomalies likely underestimates the duration of snow cover in the low obliquity experiments.



#### 4. Discussion and Conclusions

We have repeated the experiments in Erb et al. (2013) to examine the obliquity driven climate response in a model with observationally constrained supercooled liquid fraction (SLF) in mixed phase clouds (MPCs). SLFs are increased in two experiments (SLF1 and SLF2) using a more realistic ice-nucleation scheme (DeMott et al., 2015) but using different methods in order to account for the uncertainties associated with MPC microphysics. These are compared with a default model (DEF) in which SLFs are known to be underestimated (Cesana et al., 2015; Komurcu et al., 2014). Other studies have found that orbitally induced climate changes are opposed by negative high latitude low cloud feedbacks (Birch et al., 2017; Erb et al., 2013; Jochum et al., 2012). However, when realistic present-day SLFs are used, the strength of this negative cloud feedback is reduced which allows obliquity-driven cooling to spread to lower latitudes. This cooling leads to an increased liquid water path (LWP) and ice water path (IWP) in mid-latitude clouds and this positive cloud feedback further extends the cooling signal both throughout the year and leads to a strong tropical water vapor feedback.

We compare our three simulations with the CM2.1 the model used in the Erb et al. (2013) study. Overall the SAT response in CESM is larger than that in CM2.1: the response of SLF1 and SLF2 is 1.6–1.7 times that in DEF and is 2–3 times larger than that in CM2.1. The sum of net radiative feedbacks effects ( $\Delta R_{\text{net}}$ ) are 1.9–2.4 times larger in SLF1 and SLF2 compared with DEF and 2.6–3.5 times larger than in CM2.1. Reductions in positive degree days (PDDs) of up to 50% occur in the summer melt season in the Hudson Bay and Baffin Island area which have been identified as probable locations for the expansion of the Laurentide ice sheet (Clark et al., 1993). These and further reductions in PDD which extend into the mid-latitudes in SLF1 and SLF2, and reduction in snow-free days calculated from the downscaling approach provide further support that the climate in these experiments is more conducive to ice-sheet growth.

Column-integrated liquid (i.e., LWP) reduces and acts to oppose and reduce cooling from this obliquity driven reduction in insolation (Figure S1). This process is also seen in CM2.1. The cloud feedback processes that contribute to the extension and expansion of the cooling signal apply to both hemispheres (Figures 1 and 3) unlike previous studies in which only a strong northern hemisphere cooling signal is simulated (Jochum et al., 2012). Southern hemisphere cooling is important for sea ice expansion in the Antarctic, which drives increased carbon sequestration in the ocean. Proxy records indicate that early during the last glacial cycle around, 115 kya, polar cooling and sea ice expansion in the Antarctica were associated with an initial drawdown of CO<sub>2</sub> (35 ppm) (Kohfeld & Chase, 2017). In addition to the snowfall and ablation metrics which support larger ice sheet expansion in SLF1 and SLF2 than in DEF, increased southern hemisphere cooling and ice formation would sequester more CO<sub>2</sub>.

Proxy reconstructions from the tropical oceans indicate that Pleistocene SSTs cooled prior to changes in continental ice volume (Dyez et al., 2016; Medina-Elizalde & Lea, 2005) and in regions SST changed in the opposite direction to changes in local annual insolation (Z. Liu & Herbert, 2004). As ours is an idealized study, and we have only presented Lo-Hi surface temperature anomalies (Figure 1), subsequently explicit comparisons with proxy records are not suitable. However, in our work, SLF1 and SLF2 both demonstrate tropical cooling throughout much of the year despite a positive insolation anomaly, whereas DEF and CM2.1 show a warming. This provides further support for the notion that high latitude cooling can drive tropical climate change, in qualitative agreement with proxy reconstructions.

Simulating cloud processes is a challenging area of study and it should be noted that the microphysics that contribute to high SLFs in mixed phase clouds are not completely understood: both reductions in the efficiency of the Wegner-Bergeron-Findeisen (WBF) process (Lohmann & Hoose, 2009; Storelvmo et al., 2008; Tan & Storelvmo, 2016) and the availability, size distribution and effectiveness of INPs such as mineral dust (Atkinson et al., 2013; Kok et al., 2017; Murray et al., 2012; Sagoo & Storelvmo, 2017) have a significant impact on SLFs and climate. The positive cloud and water vapor feedbacks which amplify the orbital signal in this work are unmasked because the high latitude negative low cloud feedback was not present in SLF1 and SLF2. Understanding the response of low Arctic clouds to changes in climate and sea-ice cover is challenging (Kay & Gettelman, 2009; Kay et al., 2011) and thus the magnitude and even the presence of a high latitude summer low cloud feedback are still not well constrained. Finally, in summary, we find strong support for Milanković's orbital theory in this study when SLFs are observationally constrained. Enhanced cooling in the high latitudes leads to

the unmasking of well-known positive mid-latitude cloud feedbacks and tropical water vapor feedback, which amplify the obliquity signal by additional cooling which reduces summer snow/ice melt.

### Conflict of Interest Statement

The authors declare no conflicts of interest relevant to this study.

### Data Availability Statement

CESM model output relevant for study figures is available at <https://doi.org/10.5281/zenodo.3891912>.

### Acknowledgments

Simulations were run on the Yale High Performance Computing Cluster. T. Storelvmo was supported by ERC grant 758005. N. Sagoo was supported by NSF grant 1352417 while at Yale University.

### References

- Abe-Ouchi, A., Saito, F., Kawamura, K., Raymo, M. E., Okuno, J., Takahashi, K., & Blatter, H. (2013). Insolation-driven 100,000-year glacial cycles and hysteresis of ice-sheet volume. *Nature*, *500*(7461), 190–193. <https://doi.org/10.1038/nature12374>
- Anderson, E. A. (2006). *Snow accumulation and ablation model—SNOW-17*, (Vol. 61). Silver Spring, MD: US National Weather Service.
- Atkinson, J. D., Murray, B. J., Woodhouse, M. T., Whale, T. F., Baustian, K. J., Carslaw, K. S., et al. (2013). The importance of feldspar for ice nucleation by mineral dust in mixed-phase clouds. *Nature*, *498*(7454), 355–358. <https://doi.org/10.1038/nature12278>
- Barnola, J.-M., Raynaud, D., Korotkevich, Y. S., & Lorius, C. (1987). Vostok ice core provides 160,000-year record of atmospheric CO<sub>2</sub>. *Nature*, *329*(6138), 408–414. <https://doi.org/10.1038/329408a0>
- Bindoff, N. L., Stott, P. A., AchutaRao, K. M., Allen, M. R., Gillett, N., Gutzler, D., et al. (2013). *Detection and attribution of climate change: From global to regional*. IPCC.
- Birch, L., Cronin, T., & Tziperman, E. (2017). Glacial inception on Baffin Island: The role of insolation, meteorology, and topography. *Journal of Climate*, *30*(11), 4047–4064. <https://doi.org/10.1175/JCLI-D-16-0576.1>
- Bodas-Salcedo, A., Mulcahy, J. P., Andrews, T., Williams, K. D., Ringer, M. A., Field, P. R., & Elsaesser, G. S. (2019). Strong dependence of atmospheric feedbacks on mixed-phase microphysics and aerosol-cloud interactions in HadGEM3. *Journal of Advances in Modeling Earth Systems*, *11*(6), 1735–1758. <https://doi.org/10.1029/2019MS001688>
- Boucher, O., Randall, D., Artaxo, P., Bretherton, C., Feingold, G., Forster, P., et al. (2013). Clouds and aerosols. In K. M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, & P. M. Midgley (Eds.), *Climate change 2013: The physical science basis contribution of working group I to the fifth assessment report of the Intergovernmental Panel on Climate Change*. IPCC.
- Cesana, G., Waliser, D. E., Jiang, X., & Li, J.-L. (2015). Multimodel evaluation of cloud phase transition using satellite and reanalysis data. *Journal of Geophysical Research: Atmospheres*, *120*(15), 7871–7892. <https://doi.org/10.1002/2014JD022932>
- Clark, P. U., Clague, J. J., Curry, B. B., Dreimanis, A., Hicock, S. R., Miller, G. H., et al. (1993). Initiation and development of the Laurentide and Cordilleran ice sheets following the last interglaciation. *Quaternary Science Reviews*, *12*(2), 79–114. [https://doi.org/10.1016/0277-3791\(93\)90011-A](https://doi.org/10.1016/0277-3791(93)90011-A)
- Clark, P. U., & Pollard, D. (1998). Origin of the middle Pleistocene transition by ice sheet erosion of regolith. *Paleoceanography*, *13*(1), 1–9.
- DeMott, P. J., Prenni, A. J., McMeeking, G. R., Sullivan, R. C., Petters, M. D., Tobo, Y., et al. (2015). Integrating laboratory and field data to quantify the immersion freezing ice nucleation activity of mineral dust particles. *Atmospheric Chemistry and Physics*, *15*(1), 393–409. <https://doi.org/10.5194/acp-15-393-2015>
- Dyez, K. A., Ravelo, A. C., & Mix, A. C. (2016). Evaluating drivers of Pleistocene eastern tropical Pacific sea surface temperature. *Paleoceanography*, *31*(8), 2015PA002873. <https://doi.org/10.1002/2015PA002873>
- Erb, M. P., Broccoli, A. J., & Clement, A. C. (2013). The contribution of radiative feedbacks to orbitally driven climate change. *Journal of Climate*, *26*(16), 5897–5914. <https://doi.org/10.1175/JCLI-D-12-00419.1>
- Ganopolski, A., & Brovkin, V. (2017). Simulation of climate, ice sheets and CO<sub>2</sub> evolution during the last four glacial cycles with an Earth system model of intermediate complexity. *Climate of the Past*, *13*, 1695–1716. <https://doi.org/10.5194/cp-13-1695-2017>
- Gottelman, A., Hannay, C., Bacmeister, J. T., Neale, R. B., Pendergrass, A. G., Danabasoglu, G., et al. (2019). High climate sensitivity in the Community Earth System Model version 2 (CESM2). *Geophysical Research Letters*, *46*(14), 8329–8337. <https://doi.org/10.1029/2019GL083978>
- Hays, J. D., Imbrie, J., Shackleton, N. J., et al. (1976). Variations in the Earth's orbit: pacemaker of the ice ages. *American Association for the Advancement of Science*, *194*, 1121–1132. Retrieved from [https://www.researchgate.net/profile/J\\_Hays/publication/301325552\\_Variations\\_in\\_the\\_Earth\\_pacemaker\\_of\\_the\\_ice\\_ages/links/573cca0c08ae9ace840fe240.pdf](https://www.researchgate.net/profile/J_Hays/publication/301325552_Variations_in_the_Earth_pacemaker_of_the_ice_ages/links/573cca0c08ae9ace840fe240.pdf)
- Holland, M. M., Bailey, D. A., Briegleb, B. P., Light, B., & Hunke, E. (2012). Improved sea ice shortwave radiation physics in CCSM4: The impact of melt ponds and aerosols on Arctic Sea ice\*. *Journal of Climate*, *25*(5), 1413–1430. <https://doi.org/10.1175/JCLI-D-11-00078.1>
- Hunke, E. C., Lipscomb, W. H., Turner, A. K., Jeffery, N., & Elliott, S. (2010). *CICE: The Los Alamos Sea ice model documentation and software user's manual version 4.1 LA-CC-06-012. T-3 fluid dynamics group* (Vol. 675, p. 500). Los Alamos National Laboratory. Retrieved from <http://oceans11.lanl.gov/svn/CICE/tags/release-5.1/doc/cicedoc.pdf>
- Hurrell, J. W., Holland, M. M., Gent, P. R., Ghan, S., Kay, J. E., Kushner, P. J., et al. (2013). The community earth system model: A framework for collaborative research. *Bulletin of the American Meteorological Society*, *94*(9), 1339–1360. <https://doi.org/10.1175/BAMS-D-12-00121.1>
- Huybers, P. (2006). Early Pleistocene glacial cycles and the integrated summer insolation forcing. *Science*, *313*(5786), 508–511. <https://doi.org/10.1126/science.1125249>
- Huybers, P. (2011). Combined obliquity and precession pacing of late Pleistocene deglaciations. *Nature*, *480*(7376), 229–232. <https://doi.org/10.1038/nature10626>
- Illingworth, A. J., Hogan, R. J., O'Connor, E. J., Bouniol, D., Delanoë, J., Pelon, J., et al. (2007). Cloudnet: Continuous evaluation of cloud profiles in seven operational models using ground-based observations. *Bulletin of the American Meteorological Society*, *88*(6), 883–898. <https://doi.org/10.1175/BAMS-88-6-883>
- Jochum, M., Jahn, A., Peacock, S., Bailey, D. A., Fasullo, J. T., Kay, J., et al. (2012). True to Milankovitch: Glacial inception in the new community climate system model. *Journal of Climate*, *25*(7), 2226–2239. <https://doi.org/10.1175/JCLI-D-11-00044.1>
- Kay, J. E., & Gettelman, A. (2009). Cloud influence on and response to seasonal Arctic sea ice loss. *Journal of Geophysical Research*, *114*(D18), D18204. <https://doi.org/10.1029/2009JD011773>

- Kay, J. E., Holland, M. M., & Jahn, A. (2011). Inter-annual to multi-decadal Arctic sea ice extent trends in a warming world. *Geophysical Research Letters*, 38(5), L15708. <https://doi.org/10.1029/2011GL048008>
- Klein, S. A., & Hartmann, D. L. (1993). The seasonal cycle of low stratiform clouds. *Journal of Climate*, 68, 1587–1606. [https://doi.org/10.1175/1520-0442\(1993\)006<1587:TSCOLS>2.0.CO;2](https://doi.org/10.1175/1520-0442(1993)006<1587:TSCOLS>2.0.CO;2)
- Klein, S. A., & Jakob, C. (1999). Validation and sensitivities of frontal clouds simulated by the ECMWF model. *Monthly Weather Review*, 127(10), 2514–2531. [https://doi.org/10.1175/1520-0493\(1999\)127%3C2514:VASOFC%3E2.0.CO;2](https://doi.org/10.1175/1520-0493(1999)127%3C2514:VASOFC%3E2.0.CO;2)
- Kliver, D., Mote, T., Leathers, D., Henderson, G. R., Chan, W., & Robinson, D. A. (2016). Creation and validation of a comprehensive 1 by 1 daily gridded North American dataset for 1900–2009: Snowfall. *Journal of Atmospheric and Oceanic Technology*, 33(5), 857–871. <https://doi.org/10.1175/JTECH-D-15-0027.1>
- Kohfeld, K. E., & Chase, Z. (2017). Temporal evolution of mechanisms controlling ocean carbon uptake during the last glacial cycle. *Earth and Planetary Science Letters*, 472, 206–215. <https://doi.org/10.1016/j.epsl.2017.05.015>
- Kok, J. F., Ridley, D. A., Zhou, Q., Miller, R. L., Zhao, C., Heald, C. L., et al. (2017). Smaller desert dust cooling effect estimated from analysis of dust size and abundance. *Nature Geoscience*, 10(4), 274–278. <https://doi.org/10.1038/ngeo2912>
- Komurcu, M., Storelvmo, T., Tan, I., Lohmann, U., Yun, Y., Penner, J. E., et al. (2014). Intercomparison of the cloud water phase among global climate models. *Journal of Geophysical Research: Atmospheres*, 119(6), 2013JD021119. <https://doi.org/10.1002/2013JD021119>
- Lambert, F., Delmonte, B., Petit, J.-R., Bigler, M., Kaufmann, P. R., Hutterli, M. A., et al. (2008). Dust-climate couplings over the past 800,000 years from the EPICA Dome C ice core. *Nature*, 452(7187), 616–619. <https://doi.org/10.1038/nature06763>
- Lawrence, D. M., Oleson, K. W., Flanner, M. G., Thornton, P. E., Swenson, S. C., Lawrence, P. J., et al. (2011). Parameterization improvements and functional and structural advances in Version 4 of the Community Land Model. *Journal of Advances in Modeling Earth Systems*, 3(1), M03001. <https://doi.org/10.1029/2011MS00045>
- Lettenmaier, D. P., Wood, A. W., Palmer, R. N., Wood, E. F., & Stakhiv, E. Z. (1999). Water resources implications of global warming: A US regional perspective. *Climatic Change*, 43(3), 537–579. <https://doi.org/10.1023/A:1005448007910>
- Liautaud, P. R., Hodell, D. A., & Huybers, P. J. (2020). Detection of significant climatic precession variability in early Pleistocene glacial cycles. *Earth and Planetary Science Letters*, 536, 116137. <https://doi.org/10.1016/j.epsl.2020.116137>
- Lisiecki, L. E. (2010). Links between eccentricity forcing and the 100,000-year glacial cycle. *Nature Geoscience*, 3(5), 349–352. <https://doi.org/10.1038/ngeo828>
- Lisiecki, L. E., & Raymo, M. E. (2005). A Pliocene-Pleistocene stack of 57 globally distributed benthic  $\delta^{18}O$  records. *Paleoceanography*, 20(1), PA1003. Retrieved from <http://onlinelibrary.wiley.com/doi/10.1029/2004PA001071/full>
- Liu, X., Easter, R. C., Ghan, S. J., Zaveri, R., Rasch, P., Shi, X., et al. (2012). Toward a minimal representation of aerosols in climate models: Description and evaluation in the Community Atmosphere Model CAM5. *Geoscientific Model Development*, 5(3), 709. <https://doi.org/10.1175/JCLI-D-11-00650.1>
- Liu, Z., & Herbert, T. D. (2004). High-latitude influence on the eastern equatorial Pacific climate in the early Pleistocene epoch. *Nature*, 427(6976), 720–723. <https://doi.org/10.1038/nature02338>
- Lohmann, U., & Hoose, C. (2009). Sensitivity studies of different aerosol indirect effects in mixed-phase clouds. *Atmospheric Chemistry and Physics*, 9(22), 8917–8934. <https://doi.org/10.5194/acp-9-8917-2009>
- Mantsis, D. F., Clement, A. C., Broccoli, A. J., & Erb, M. P. (2011). Climate feedbacks in response to changes in obliquity. *Journal of Climate*, 24(11), 2830–2845. <https://doi.org/10.1175/2010JCLI3986.1>
- Martínez-García, A., Rosell-Melé, A., Jaccard, S. L., Geibert, W., Sigman, D. M., & Haug, G. H. (2011). Southern Ocean dust-climate coupling over the past four million years. *Nature*, 476(7360), 312–315. <https://doi.org/10.1038/nature10310>
- McCoy, D. T., Hartmann, D. L., Zelinka, M. D., Ceppi, P., & Grosvenor, D. P. (2015). Mixed-phase cloud physics and Southern Ocean cloud feedback in climate models. *Journal of Geophysical Research: Atmospheres*, 120(18), 9539–9554. <https://doi.org/10.1002/2015JD023603>
- Medina-Elizalde, M., & Lea, D. W. (2005). The mid-Pleistocene transition in the tropical Pacific. *Science*, 310(5750), 1009–1012. <https://doi.org/10.1126/science.1115933>
- Meyers, M. P., DeMott, P. J., & Cotton, W. R. (1992). New primary ice-nucleation parameterizations in an explicit cloud model. *Journal of Applied Meteorology*, 31(7), 708–721.
- Milanković, M. (1941). *Kanon der Erdbestrahlung und seine Anwendung auf das Eiszeitenproblem*. Belgrade: Mihaila Ćurčića.
- Mitchell, J. F., Senior, C. A., & Ingram, W. J. (1989). CO<sub>2</sub> and climate: A missing feedback? *Nature*, 341(6238), 132–134.
- Morrison, H., de Boer, G., Feingold, G., Harrington, J., Shupe, M. D., & Sulia, K. (2012). Resilience of persistent Arctic mixed-phase clouds. *Nature Geoscience*, 5(1), 11–17. <https://doi.org/10.1038/ngeo1332>
- Morrison, H., & Gettelman, A. (2008). A new two-moment bulk stratiform cloud microphysics scheme in the Community Atmosphere Model, version 3 (CAM3). Part I: Description and numerical tests. *Journal of Climate*, 21(15), 3642–3659. <https://doi.org/10.1175/2008JCLI2105.1>
- Murray, B. J., O'Sullivan, D., Atkinson, J. D., & Webb, M. E. (2012). Ice nucleation by particles immersed in supercooled cloud droplets. *Chemical Society Reviews*, 41(19), 6519–6554.
- Neale, R. B., Chen, C.-C., Gettelman, A., Lauritzen, P. H., Park, S., Williamson, D. L., et al. (2010). *Description of the NCAR community atmosphere model (CAM 5.0)*. NCAR Technical Note. NCAR/TN-486+STR. Retrieved from [https://www.cesm.ucar.edu/models/ccsm4.0/cam/docs/description/cam4\\_desc.pdf](https://www.cesm.ucar.edu/models/ccsm4.0/cam/docs/description/cam4_desc.pdf)
- Notaro, M., Lorenz, D., Hoving, C., & Schummer, M. (2014). Twenty-first-century projections of snowfall and winter severity across central-eastern North America. *Journal of Climate*, 27(17), 6526–6550. <https://doi.org/10.1175/JCLI-D-13-00520.1>
- Oleson, K. W., Lawrence, D. M., Gordon, B., Flanner, M. G., Kluzek, E., Peter, J., et al. (2010). *Technical description of version 4.0 of the Community Land Model (CLM)*. Retrieved from <http://citeserx.ist.psu.edu/viewdoc/summary?doi=10.1.1.172.7769>
- Petit, J.-R., Mournier, L., Jouzel, J., Korotkevich, Y. S., Kotlyakov, V. I., & Lorius, C. (1990). Palaeoclimatological and chronological implications of the Vostok core dust record. *Nature*, 343, 56–58. <https://doi.org/10.1038/343056a0>
- Pollard, D., & Thompson, S. L. (1997). Driving a high-resolution dynamic ice-sheet model with GCM climate: Ice-sheet initiation at 116 000 BP. *Annals of Glaciology*, 25, 296–304.
- Pruppacher, H. R., & Klett, J. D. (1978). *Microphysics of clouds and precipitation* (p. 714). Dordrecht: Reidel.
- Raymo, M. E., Lisiecki, L. E., & Nisancioglu, K. H. (2006). Plio-Pleistocene ice volume, Antarctic climate, and the global  $\delta^{18}O$  record. *Science*, 313(5786), 492–495. <https://doi.org/10.1126/science.1123296>
- Raymo, M. E., & Nisancioglu, K. H. (2003). The 41 kyr world: Milankovitch's other unsolved mystery. *Paleoceanography*, 18(1), 1011. <https://doi.org/10.1029/2002PA000791>
- Rind, D., Peteet, D., & Kukla, G. (1989). Can Milankovitch orbital variations initiate the growth of ice sheets in a general circulation model? *Journal of Geophysical Research*, 94(D10), 12851–12871.

- Sagoo, N., & Storelvmo, T. (2017). Testing the sensitivity of past climates to the indirect effects of dust. *Geophysical Research Letters*, *44*(11), 2017GL072584. <https://doi.org/10.1002/2017GL072584>
- Saltzman, B., Hansen, A. R., & Maasch, K. A. (1984). The late Quaternary glaciations as the response of a three-component feedback system to Earth-orbital forcing. *Journal of the Atmospheric Sciences*, *41*(23), 3380–3389. [https://doi.org/10.1175/1520-0469\(1984\)041%3C3380:TLQGAT%3E2.0.CO;2](https://doi.org/10.1175/1520-0469(1984)041%3C3380:TLQGAT%3E2.0.CO;2)
- Shell, K. M., Kiehl, J. T., & Shields, C. A. (2008). Using the radiative kernel technique to calculate climate feedbacks in NCAR's Community Atmospheric Model. *Journal of Climate*, *21*(10), 2269–2282. <https://doi.org/10.1175/2007JCLI2044.1>
- Shupe, M. D. (2011). Clouds at Arctic atmospheric observatories. Part II: Thermodynamic phase characteristics. *Journal of Applied Meteorology and Climatology*, *50*(3), 645–661. <https://doi.org/10.1175/2010JAMC2468.1>
- Sigman, D. M., & Boyle, E. A. (2000). Glacial/interglacial variations in atmospheric carbon dioxide. *Nature*, *407*(6806), 859–869. <https://doi.org/10.1038/35038000>
- Smith, R., Jones, P., Briegleb, B., Bryan, F., Danabasoglu, G., Dennis, J., et al. (2010). *The parallel ocean program (POP) reference manual ocean component of the community climate system model (CCSM) and community earth system model (CESM)* (Vol. 141, pp. 1–140). Rep. LAUR-01853.
- Soden, B. J., Held, I. M., Colman, R., Shell, K. M., Kiehl, J. T., & Shields, C. A. (2008). Quantifying climate feedbacks using radiative kernels. *Journal of Climate*, *21*(14), 3504–3520. <https://doi.org/10.1175/2007JCLI2110.1>
- Storelvmo, T., Kristjánsson, J. E., Lohmann, U., Iversen, T., Kirkevåg, A., & Seland, Ø. (2008). Modeling of the Wegener–Bergeron–Findeisen process—Implications for aerosol indirect effects. *Environmental Research Letters*, *3*(4), 045001. <https://doi.org/10.1088/1748-9326/3/4/045001>
- Tabor, C. R., & Poulsen, C. J. (2016). Simulating the mid-Pleistocene transition through regolith removal. *Earth and Planetary Science Letters*, *434*, 231–240. <https://doi.org/10.1016/j.epsl.2015.11.034>
- Tabor, C. R., Poulsen, C. J., & Pollard, D. (2015). How obliquity cycles powered early Pleistocene global ice-volume variability. *Geophysical Research Letters*, *42*(6), 1871–1879. <https://doi.org/10.1002/2015GL063322>
- Tan, I., Oreopoulos, L., & Cho, N. (2019). The role of thermodynamic phase shifts in cloud optical depth variations with temperature. *Geophysical Research Letters*, *46*(8), 4502–4511. <https://doi.org/10.1029/2018GL081590>
- Tan, I., & Storelvmo, T. (2016). Sensitivity study on the influence of cloud microphysical parameters on mixed-phase cloud thermodynamic phase partitioning in CAM5. *Journal of the Atmospheric Sciences*, *73*(2), 709–728. <https://doi.org/10.1175/JAS-D-15-0152.1>
- Tan, I., & Storelvmo, T. (2019). Evidence of strong contributions from mixed-phase clouds to Arctic climate change. *Geophysical Research Letters*, *46*(5), 2894–2902.
- Tan, I., Storelvmo, T., & Zelinka, M. D. (2016). Observational constraints on mixed-phase clouds imply higher climate sensitivity. *Science*, *352*(6282), 224–227. <https://doi.org/10.1126/science.aad5300>
- Webb, M., Senior, C., Bony, S., & Morcrette, J.-J. (2001). Combining ERBE and ISCCP data to assess clouds in the Hadley Centre, ECMWF and LMD atmospheric climate models. *Climate Dynamics*, *17*(12), 905–922. <https://doi.org/10.1007/s003820100157>
- Westerhold, T., Marwan, N., Drury, A. J., Liebrand, D., Agnini, C., Anagnostou, E., et al. (2020). An astronomically dated record of Earth's climate and its predictability over the last 66 million years. *Science*, *369*(6509), 1383–1387. <https://doi.org/10.1126/science.aba6853>
- Willeit, M., Ganopolski, A., Calov, R., & Brovkin, V. (2019). Mid-Pleistocene transition in glacial cycles explained by declining CO<sub>2</sub> and regolith removal. *Science Advances*, *5*(4), eaav7337. <https://doi.org/10.1126/sciadv.aav7337>
- Winker, D. M., Vaughan, M. A., Omar, A., Hu, Y., Powell, K. A., Liu, Z., et al. (2009). Overview of the CALIPSO mission and CALIOP data processing algorithms. *Journal of Atmospheric and Oceanic Technology*, *26*(11), 2310–2323. <https://doi.org/10.1175/2009JTECHA1281.1>
- Zachos, J., Pagani, M., Sloan, L., Thomas, E., & Billups, K. (2001). Trends, rhythms, and aberrations in global climate 65 Ma to present. *Science*, *292*(5517), 686–693. <https://doi.org/10.1126/science.1059412>
- Zelinka, M. D., Klein, S. A., & Hartmann, D. L. (2012). Computing and partitioning cloud feedbacks using cloud property histograms. Part I: Cloud radiative kernels. *Journal of Climate*, *25*(11), 3715–3735. <https://doi.org/10.1175/JCLI-D-11-00248.1>
- Zelinka, M. D., Myers, T. A., McCoy, D. T., Po-Chedley, S., Caldwell, P. M., Ceppi, P., et al. (2020). Causes of higher climate sensitivity in CMIP6 models. *Geophysical Research Letters*, *47*(1), e2019GL085782. <https://doi.org/10.1029/2019GL085782>
- Zhang, D., Wang, Z., & Liu, D. (2010). A global view of midlevel liquid-layer topped stratiform cloud distribution and phase partition from CALIPSO and CloudSat measurements. *Journal of Geophysical Research: Atmospheres*, *115*(D4), D00H13. <https://doi.org/10.1029/2009JD012143>