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Sea ice, high-latitude convection, and equable climates

D. S. Abbot[1] and Eli Tziperman[1,2]

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[1] It is argued that deep atmospheric convection might occur during winter in ice-free high-latitude oceans, and that the surface radiative warming effects of the clouds and water vapor associated with this winter convection could keep high-latitude oceans ice-free through polar night. In such an ice-free high-latitude ocean the annual-mean SST would be much higher and the seasonal cycle would be dramatically reduced - making potential implications for equable climates manifest. The constraints that atmospheric heat transport, ocean heat transport, and CO_2 concentration place on this mechanism are established. These ideas are investigated using the NCAR column model, which has state-of-the-art atmospheric physics parameterizations, high vertical resolution, a full seasonal cycle, a thermodynamic sea ice model, and a mixed layer ocean. **Citation:** Abbot, D. S., and E. Tziperman (2008), Sea ice, high-latitude convection, and equable climates, *Geophys. Res. Lett.*, *35*, L03702, doi:10.1029/2007GL032286.

1. Introduction

[2] Paleoclimatic data suggest that during the late Cretaceous period (~100 to ~65.5 Ma) and the early Paleogene period (~65.5 Ma to ~34 Ma) the global-mean temperature was higher than its modern value and the equator to pole temperature difference and the amplitude of the high-latitude seasonal cycle were both much smaller than they are today, particularly in continental interiors, which has led to the characterization of climates during these periods as "equable" [e.g., *Greenwood and Wing*, 1995]. Researchers have as yet been unable to reproduce equable climates in coupled ocean-atmosphere global climate models (GCMs) by simply changing boundary conditions and increasing greenhouse gas levels [*Huber and Sloan*, 2001; *Bush and Philander*, 1997]. Relative to existing data, either the polar regions are too cold or the tropical regions are too warm in these simulations.

[3] It is possible that the resolution of unknown biases in paleoclimatic data will bring them into agreement with GCM results. Proceeding under the assumption that the data faithfully represent paleoclimate, many ideas have been proposed to explain the discrepancy between models and data, including the extension of the Hadley circulation to high latitudes [*Farrell*, 1990], mixing of the ocean caused by tropical cyclones [*Emanuel*, 2002; *Korty et al.*, 2007], and polar stratospheric clouds [*Sloan et al.*, 1992; *Kirk-Davidoff et al.*, 2002]. Alternatively, *Abbot and Tziperman* [2007] used a simple zonally-averaged model forced by equinoctial shortwave (SW) radiation to argue that the advent of convection and convective clouds, which are mostly tropospheric rather than stratospheric, at high latitudes could represent a positive feedback on high-latitude surface temperature. More complex atmospheric models lend some support to the idea of increased high-latitude convection during equable climates when they are forced with a high mean surface temperature and a low meridional surface temperature gradient [*Huber and Sloan*, 1999; *Korty and Emanuel*, 2007].

[4] Observations of winter cloud radiative forcing (CRF) in the modern climate suggest that sea ice may play an important role in the high-latitude convective cloud feedback mechanism that *Abbot and Tziperman* [2007] proposed. CRF is strongly positive over subpolar oceans without sea ice and near zero over subpolar and polar oceans with sea ice (Figure S1 of the auxiliary material[1]). The clouds causing this positive CRF may be associated with large-scale dynamics, convection, or other processes, although the sharp jumps in CRF at sea ice/open ocean boundaries may represent evidence that the positive CRF is mainly due to a local process, such as convection.

[5] We will use the single-column version of the NCAR CAM GCM (J. J. Hack et al., SCAM user's guide, 2004, available at http://www.ccsm.ucar.edu/models/atm-cam/docs/scam/) which has state-of-the-art atmospheric physics parameterizations, high vertical resolution, a full seasonal cycle, a thermodynamic sea ice model, and a mixed layer ocean, to argue that winter convection may indeed be the driver of positive winter CRF over ice-free high-latitude oceans and that sea ice prevents such convection so that the removal of winter sea ice could be an essential prerequisite for the high-latitude convective cloud feedback. We will further show that the surface warming effects caused by winter convection, specifically the increase in the LW optical depth of the atmosphere due to thick convective clouds and increased water vapor concentration, can be essential for the maintenance of an ice-free state on which the winter convection itself depends. The removal of sea ice from high-latitude oceans would lead to greatly increased annual-mean temperatures, a drastically reduced seasonal cycle, and generally equable conditions.

[6] In order to provide a concrete and limiting example, we focus our study on the Arctic ocean. We model the ocean with a mixed layer with a constant depth of 50 m and force SCAM with present-day seasonally and diurnally varying 79.5°N SW radiation. It is unusual to make inferences about high-latitude climate using a single-column model, however we take into account departures from radiative-convective equilibrium by specifying convergences of ocean heat

[1]School of Engineering and Applied Sciences, Harvard University, Cambridge, Massachusetts, USA.

[2]Department of Earth and Planetary Sciences, Harvard University, Cambridge, Massachusetts, USA.

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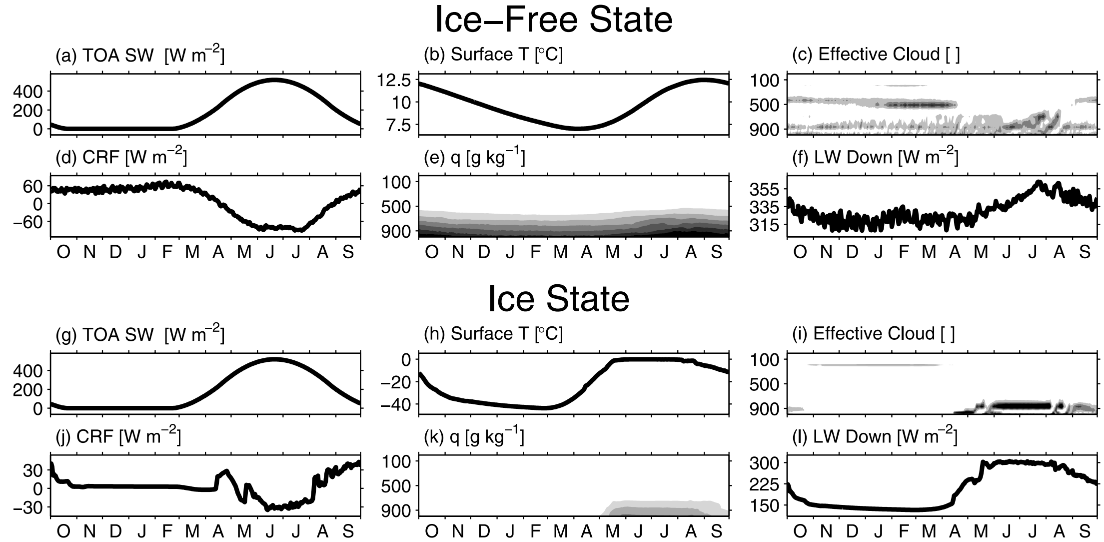

Figure 1. Seasonal cycle of important physical quantities in the (a, b, c, d, e, f) ice-free and (g, h, i, j, k, l) ice states at 79.5°. Each panel displays the average values for the last 15 years of a 50 year model run. The specified convergence of atmospheric heat transport is 100 W m^{-2}, the specified convergence of ocean heat transport is zero, and the specified CO_2 is 1000 ppm. Figures 1a and 1g, TOA SW, daily-averaged downward shortwave radiation at the top of the atmosphere; Figures 1b and 1h, Surface T, the surface temperature; Figures 1c and 1i, Effective Cloud, the product of the cloud fraction and the cloud emissivity, with shading intervals of 0.1; Figures 1d and 1j, CRF, the cloud radiative forcing at the surface; Figures 1e and 1k, q, the specific humidity, with shading intervals of 1 g kg^{-1}; and Figures 1f and 1l, LW Down, downward longwave radiation at the surface.

transport (OHT) and atmospheric heat transport (AHT). We sample a large range of OHT and AHT, as their values during equable climates are uncertain. The OHT and AHT we apply are constant in time and we show results for a dry AHT applied equally by mass to the atmosphere below 245 mb, so that the applied temperature tendency is the same for each pressure level below 245 mb. We apply no vertical velocity, nor clouds associated with large-scale dynamics. SCAM calculates surface heat fluxes using bulk aerodynamic formulae and surface winds from standard CAM input files.

2. Convective Clouds and Sea Ice

[7] We find that SCAM has two different types of equilibria at 79.5° latitude over ocean: (1) An equilibrium with perennial or seasonal sea ice, which we will call the ice state and (2) An equilibrium without sea ice, which we will call the ice-free state. At low CO_2 and low heat transport (HT) only the ice state is stable and at high CO_2 and high HT only the ice-free state is stable. There is a small parameter regime at the boundary of the ice-free and ice regimes in which both ice-free and ice state are possible at the same external forcing.

[8] Figure 1 displays the seasonal cycle of some important physical quantities for the ice-free and the ice states. For both states we specify AHT = 100 W m^{-2}, OHT = 0 (roughly equal to modern values at 80°N [*Trenberth and Stepaniak*, 2003]) and CO_2 = 1000 ppm. We display model output for boundary conditions at which the ice and ice-free states are both stable to emphasize the striking difference between the two states without confounding the difference between states with differences caused by boundary conditions. It is not clear whether using the same AHT for the ice and ice-free states is realistic because the implications of a competition between a reduction in eddy activity due to a decreased meridional temperature gradient and increased latent HT due to potentially warmer subtropical temperatures are not fully understood [*Pierrehumbert*, 2002; *Caballero and Langen*, 2005]. As SCAM is isolated from lower latitudes, we cannot address this issue here.

[9] Although we apply the same external forcing in both cases, the annual-mean temperature is much higher and the amplitude of the seasonal cycle is much lower in the ice-free state. Strikingly, the minimum temperature for the ice-free state is 7°C (Figure 1b) while it is −44°C for the ice state (Figure 1h). Strong convection occurs in the ice-free state throughout polar night and causes optically thick mid-tropospheric convective clouds (Figure 1c). The surface CRF resulting from these convective clouds averages 51 W m^{-2} during polar night (Figure 1d), whereas the surface CRF averages only 3 W m^{-2} during polar night in the ice state (Figure 1j). CRF, which is negative during summer and positive during winter, provides a significant dampening of the seasonal cycle in the ice-free state (Figure 1d). The convection that produces mid-tropospheric clouds during the winter in the ice-free state transports 14 W m^{-2} of total heat upward from the lowest 100 mb of the atmosphere, which is only a small fraction of the positive radiative forcing the convective clouds produce. Warmth and high surface evaporation allow the ice-free state to stay moist (Figure 1e) through polar night. Moisture and convective clouds vastly increase the winter optical depth and downward longwave radiation in the ice-free state (c.f. Figures 1f and 1l).

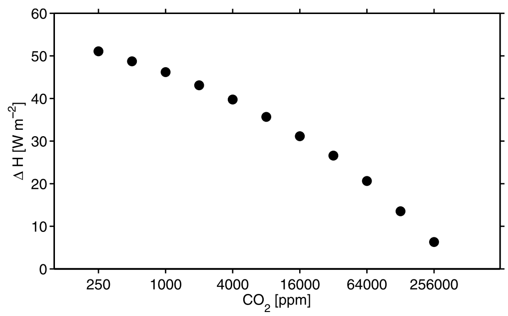

Figure 2. The amount of externally imposed heat transport required by the surface to maintain the ice-free state (ΔH) as a function of CO_2 concentration. ΔH is the annually-averaged heat flux from the ocean surface to the atmosphere at equilibrium with OHT = AHT = 0, the sea ice parameterization off, and the SST not allowed to drop below the freezing temperature.

[10] The radiative effects of the convective clouds and moisture are essential for the maintenance of the ice-free state. In the ice-free state, the SST falls only 5.4°C from its maximum to its minimum, during which time surface loses an average of 59 W m^{-2}. We calculate that without winter CRF the ice-free state would be unstable and sea ice would develop after only two years and without the winter radiative forcing of water vapor the ice-free state would be destroyed in a single season (not shown).

3. Sensitivity to Heat Transport

3.1. Idealized Heat Transport Constraints

[11] Convective clouds and moisture are a radiative blanket that can keep the ocean warm enough that sea ice does not form during polar night by trapping heat from summer SW radiation or HT. Since HT, which we must specify, is uncertain during periods of equable climate, it is important to establish the constraints AHT and OHT place on the mechanism.

[12] One estimate of the HT required to maintain a stable ice-free state is the magnitude of the annual-mean surface heat balance deficit (ΔH) obtained by running the model with OHT = AHT = 0, sea ice artificially repressed, and the SST not permitted to drop below the freezing point of seawater. HT would be necessary to maintain an ice-free state even at very large CO_2 concentrations ($\Delta H > 0$, Figure 2). The negative curvature of ΔH as a function of $\log(CO_2)$ is due to the non-linearity of the Clausius-Clapeyron equation. At CO_2 concentrations that might be relevant for equable climates (250–4000 ppm [*Pagani et al.*, 2005; *Pearson and Palmer*, 2000]), the atmosphere and ocean would have to supply 40–50 W m^{-2} to the surface to maintain an ice-free state in the Arctic ocean.

[13] ΔH is the effect of HT into the column on the surface heat balance, rather than the total HT into the column. Because roughly half of the HT into the model's atmosphere is radiated upward to space, OHT should be roughly twice as effective at heating the surface as AHT.

3.2. Heat Transport Constraints in the Full SCAM

[14] Here we test our simple argument for the amount of heat needed by the surface to maintain the ice-free state by running SCAM with thermodynamic sea ice at various CO_2 concentrations and prescribed OHT and AHT. Figure 3 confirms that the ice-free state is viable roughly when OHT + $\frac{1}{2}$AHT exceeds ΔH (Figure 2). The current annual-mean AHT is roughly 100–110 W m^{-2} at 80°N [*Trenberth and Stepaniak*, 2003] and its value during equable climates is unknown [*Pierrehumbert*, 2002; *Caballero and Langen*, 2005]. An ice-free state is possible in SCAM with OHT = 0, AHT = 100 W m^{-2} at current CO_2 levels and with OHT = 0, AHT = 80 W m^{-2} for CO_2 = 2000 ppm and higher. For comparison, many full GCMs predict only a small amount of Arctic winter sea ice when the CO_2 concentration is slowly increased to 700–850 ppm, but not run to equilibrium [*Zhang and Walsh*, 2006].

[15] Without the radiative forcing of clouds and water vapor during winter, the ice-free state would not be stable at any of the AHT, OHT, and CO_2 combinations displayed in

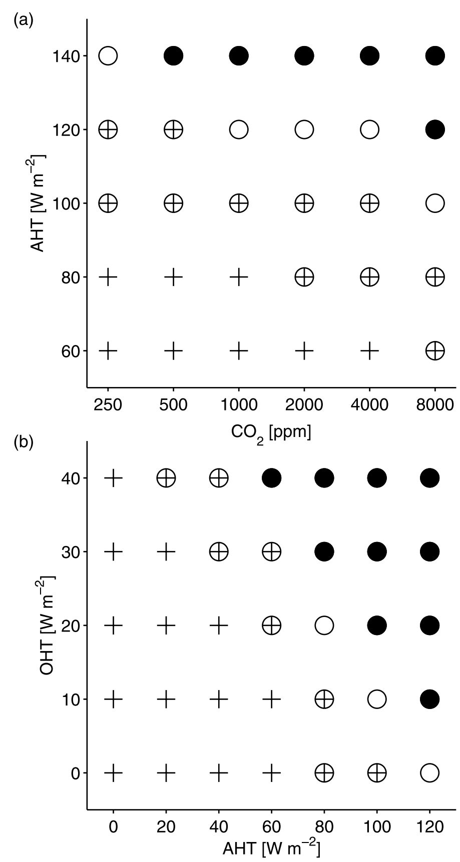

Figure 3. Stability of the ice-free and ice states as a function of the specified convergence of atmospheric heat transport (AHT), the specified convergence of ocean heat transport (OHT), and the specified CO_2. A cross indicates that the ice state is stable and a circle indicates that the ice-free state is stable. The presence of both symbols indicates that both states are stable. Filled circles indicate that the ice-free state is stable even with longwave cloud radiative forcing artificially set to zero between September 1 and April 1. (a) OHT = 0 for all runs. (b) CO_2 = 2000 ppm for all runs.

Figure 3. Winter CRF alone has a dramatic effect on the stability of the ice-free state, though clouds contribute only about 15% of the total winter downward LW flux (Figures 1d and 1f). The convergence of AHT would have to be increased by 40% above its modern value of roughly 100 W m^{-2} for the ice-free state to be stable at any CO_2 below 8000 ppm without winter LW CRF (Figure 1a).

4. Discussion

[16] The main drawback of SCAM is that it requires AHT as a specified boundary condition. Beware of the following assumptions we have made in our treatment of AHT: (1) Our applied AHT is constant in time, although we obtain similar results when we allow it to vary seasonally (not shown). (2) We have not included noise representing stochastic weather in the AHT, which might eliminate the parameter regime in which both the ice and the ice-free equilibria are possible. (3) We have presented results in which the specified AHT was dry, which is reasonable at high latitudes in the current climate [*Trenberth and Stepaniak*, 2003], although moist AHT might be important at high latitudes in an equable climate [*Pierrehumbert*, 2002]. However, substituting moist for dry AHT does not appear to significantly alter our results (Figure S2). (4) We distributed the AHT equally by mass in the troposphere, neglecting detailed vertical structure.

[17] We believe that our results are sufficiently general that they should be robust to changes in these assumptions. We also obtain qualitatively similar results with a seasonally varying ocean mixed layer depth (not shown), our results are insensitive to an increase or decrease by a factor of four in the surface winds (Figure S3), and the ice state is stable when we include leads in the sea ice model.

[18] We remain unsure as to why the feedback we describe has not been documented in coupled GCM runs, but we offer several speculative ideas here. First, signs of high-latitude convection have been observed in an atmospheric GCM forced with a low surface temperature gradient [*Korty and Emanuel*, 2007] and *Huber and Sloan* [1999] find strong winter convection in an atmospheric GCM over the Arctic ocean when they specify the SST to be high enough that there's no sea ice. These papers do not discuss the CRF feedback suggested here, its effect on surface temperatures, and its potential to help maintain an ice-free state. Second, we have suggested here that sea ice may introduce some hysteresis into the system, making the initial conditions used in coupled runs potentially important. Third, sea ice parameterizations may not yield reliable predictions in different climates [*Eisenman et al.*, 2007] and sea ice is crucial to the proposed mechanism. Finally, it is possible that climate drift due to inconsistencies between the ocean and atmosphere models, which had to be fixed with flux corrections in older models run in present-day configuration, could lead coupled GCMs away from an ice-free Arctic in equable climate runs.

[19] Although we have shown that winter convective clouds and moisture could play an important role in keeping oceans sea ice-free during periods of equable climate, we have not directly confronted the issue of above-freezing winter temperatures at high latitudes in continental interiors [e.g., *Greenwood and Wing*, 1995]. *Abbot and Tziperman* [2007] proposed that clouds and moisture due to winter convection over warm and ice-free oceans could be advected over continents, particularly if eddies were fewer and weaker, and lead to warm continental interiors. A full investigation of this idea is beyond the scope of the current work.

5. Conclusion

[20] *Abbot and Tziperman* [2007] argued that the positive radiative forcing associated with the onset of high tropospheric clouds due to deep convection could represent a strong positive feedback on increases in high-latitude surface temperature that might help to explain equable climates. We have investigated this idea using a column model with state-of-the-art atmospheric physics parameterizations, high vertical resolution, a full seasonal cycle, a thermodynamic sea ice model, and a mixed layer ocean. Depending on the CO_2 concentration, OHT, and AHT, we found high-latitude equilibria both with and without sea ice. The ice-free state has a much higher annual-mean temperature and a greatly reduced seasonal cycle. When the system is ice-free, convection occurs throughout the winter and the radiative warming effects of the clouds and water vapor associated with winter convection keep the ocean from freezing. Winter convection both depends on there being no sea ice and is essential for keeping sea ice from forming. We finally investigated various CO_2, OHT, and AHT values and found that the ice-free state is stable for values that may be reasonable for the Arctic ocean during the late Cretaceous and early Paleogene (OHT = 0, CO_2 = 250–2000 ppm, AHT = 80–100% modern).

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D. S. Abbot and E. Tziperman, School of Engineering and Applied Sciences, Harvard University, 24 Oxford Street, Cambridge, MA 02138, USA. (abbot@fas.harvard.edu)