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A mechanism for dust-induced destabilization of glacial climates

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Abstract

Abrupt transitions between cold/dry stadial and warm/wet interstadial states occurred during glacial periods in the absence of any known external forcing. The climate record preserved in polar glaciers, mountain glaciers, and widespread cave deposits reveals that these events were global in extent with temporal distribution implying an underlying memoryless process with millennial time scale. Here a theory is advanced implicating feedback between atmospheric dust and the hydrological cycle in producing these abrupt transitions. Calculations are performed using a radiative-convective model that includes the interaction of aerosols with radiation to reveal the mechanism of this dust/precipitation interaction feedback process and a Langevin equation is used to illustrate qualitatively glacial climate destabilization by this mechanism. This theory explains the observed abrupt, bimodal, and memoryless nature of these transitions as well as their intrinsic connection with the hydrological cycle.

1 Introduction

A central problem in climate science is understanding abrupt climate change such as the Dansgaard-Oeschger (D-O) transitions during glacials. These abrupt transitions are global in extent and strongly influence the hydrological cycle. Their imprint on global precipitation can be seen in polar glacier records of ice accumulation (Steffensen et al., 2008; Alley et al., 1993), midlatitude glacier records (Thompson et al., 1989), widespread cave oxygen isotope records indicating major changes in monsoonal circulations (Wang et al., 2001; Fleitmann et al., 2003; Yuan et al., 2004; Dykoski et al., 2005), and oxygen isotope and methane data that are intimately tied to tropical precipitation (Chappellaz et al., 1993). Increase in methane during abrupt warming events implies tropical precipitation changes coincident with rapid variation in midlatitude Asian monsoon precipitation (Ruth et al., 2007) and Greenland ice accumulation rates (Mayewski et al., 1993).

Greenland ice core records indicate that order-of-magnitude changes in atmospheric dust and aerosol loading are associated with the changes in precipitation during abrupt climate transitions (Lambert et al., 2008; Fuhrer et al., 1999). These records show that atmospheric dust covaries with precipitation on the same time scale (a few years, Fuhrer et al., 1999). Although less resolved compared to the Greenland record, Antarctic ice cores also show large and rapid variations in dust accumulation synchronous with temperature change (Lambert et al., 2008). Furthermore, greatly increased dust transport during glacial periods formed extensive loess deposits (Sun et al., 2006) and the Pleistocene megafauna of the northern arid steppes roamed a dry grassland which indicates dry conditions relative to the paludal tundra characterizing these areas during the Holocene (Guthrie, 2001). Increased atmospheric dust during stadials (Thompson et al., 1989; Lambert et al., 2008) is consistent with a reduction in the hydrological cycle while decreased dust during interstadials is consistent with return of pluvial conditions, due to both changes in surface moisture and the relation of atmospheric dust residence time to precipitation mediated wash out time scales (Yung et al., 1996).

These abrupt climate changes occur on time scales rapid compared to orbital, glacier ice albedo and CO_2 variation, which precludes these factors as the proximal cause of abrupt transitions. The rapidity of these changes argues for a nonlinear climate switch mechanism (Clement and Peterson, 2008; Ditlevsen, 1999). Furthermore, the exponential waiting time distribution between the D-O abrupt climate transitions and the Poisson distribution of the abrupt change intervals implies that these transitions are produced by a memoryless underlying process (Ditlevsen, 2009), while the absence of either increased variance or increased autocorrelation in the climate proxy signal on approach to the transitions implies that these transitions do not result from a bifurcation (Ditlevsen and Johnsen, 2010), but are rather noise induced transitions between stable climate equilibria.

Current theories of abrupt climate change involve nonlinear switches in the thermohaline circulation (THC) (Weaver et al., 1991), sea ice formation (Gildor and Tziperman, 2003), and storm track location (Farrell and Ioannou, 2003). The direct effect of these transition mechanisms is local to the North Atlantic region and teleconnections mediated through the ocean and atmosphere are invoked to produce the global climate changes seen in the proxy record (Seager and Battisti, 2007). Involvement of the North Atlantic THC in abrupt climate transition events is clear in the sea core record (McManus et al., 2004) but the mechanism instigating these THC changes, which is thought to be related to the freshwater/salinity balance of the North Atlantic, has not been established (Seager and Battisti, 2007). With these considerations as context we propose a mechanism for instigating the chain of events leading to abrupt climate transitions based on a dust induced destabilization of the global hydrological cycle.

2 The mechanism of dust destabilization

Transitions between climate states that are bimodal, rapid, memoryless, and not associated with increased variance or increased autocorrelation in the climate proxy signal on approach to the transition point imply a stochastically induced transition between two stable states. The rapid simultaneous change in the hydrological cycle in both low and mid latitudes implies this transition is related to a global precipitation distribution change (Rohling et al., 2003). Moreover, this transition must involve strong enough positive feedbacks to produce and maintain two stable states, one dry/cold and one wet/warm.

An analogue of glacial abrupt climate change on Earth is seen on Mars where rapid transition between a clear and a global dusty state occurs near perihelion during Martian southern spring and summer (Fernández, 1997). This analogy is apt in that the Earth's climate shares with that of Mars a vulnerable interaction among atmospheric dynamics, dust, and radiation; with the additional involvement of the hydrological cycle in the case of the Earth. We now examine the influence of dust on glacial climate variability.

Calculations with a radiative-convective model (SCAM, see Appendix A for a model description) show that both reflection and absorption by atmospheric dust reduce radiation reaching the surface (Fig. 1b), which in turn exerts a strong influence on global precipitation rate (Fig. 1a), essentially by reducing the energy available to evaporate water. A more subtle influence of radiation absorption on precipitation becomes important when the dust is increased to 5–20 times modern levels (State 2). Absorption of radiation by dust begins to replace vertical transport of heat by convection in maintaining a quasi-equilibrium state of marginal convective stability in the troposphere. This cuts off mid-tropospheric dust from wet deposition, eliminating the primary process by which dust is removed from the atmosphere, which stabilizes the high dust state. For example, when atmospheric column dust loading is increased to ten times modern levels, deep convective precipitation is reduced by a factor of 2–3 in the midtroposphere. This substantial reduction in the atmospheric dust sink means that dust input to the atmosphere would only need to be increased by a factor of 2–8 for the mid-tropospheric column dust concentrations to reach 5–20 times modern levels at which point this state would persist. This increase in atmospheric dust is well within the range of estimated dust source increase seen in the proxy record during cold Pleistocene periods (Thompson et al., 1989; Lambert et al., 2008; Fuhrer et al., 1999). If the dust is further increased to ∼30 times modern, an inversion develops (State 3, Fig. 1a). In this state deep convection shuts off completely and deep convective precipitation is reduced by more than an order of magnitude (Fig. 1a).

We believe that the state in which the role of moist convection in maintaining marginal convective stability of the troposphere is partially assumed by absorption of radiation by dust (State 2) is a model for the large-scale behavior of the atmosphere during cold, dry, glacial climates. Switch-like transitions between the cold, dry, dusty glacial climate (State 2) and the warm, wet, less dusty interglacial climate (State 1) occur when atmospheric dust load passes a threshold, as indicated in Fig. 1. Producing the increase in dust loading required to cross this threshold depends on establishing widespread drought and the subsequent occurrence of severe wind events, which is a relatively rare coincidence of weather extremes. The stochastic nature of these triggering events and the feedback stabilized cold/dry/dusty and warm/wet/less-dusty states is consistent with a two stable state system with memoryless process transitions as seen in the glacial climate record. Consistent with these statistical properties, the glacial climate can be phenomenologically modeled using a Langevin equation with a pseudo-potential having two minima representing the two stable states forced by noise representing the weather events (Ditlevsen, 1999). With suitable parameter choice, a stochastic model of this kind produces a time series of dust concentration in good agreement with the ice core record. The contribution of our theory to this Langevin model is to provide a physical identification of the model noise with extreme weather events and of the two phenomenological stable equilibrium states of the pseudo-potential with the feedback stabilized cold/dry/dusty and warm/wet/less-dusty states. As an illustrative example, using a state variable of $x = \log_{10}(\text{dust})$, we choose the interstadial state to correspond to the present dust level ($x = 0$) and a typical stadial dust level of 10 times the present dust level ($x = 1$). We then choose a potential (U) corresponding to these equilibria, with a switch between them at $x = 0.5$ (Fig. 2a). The corresponding Langevin equation is

$$\dot{x} = -\frac{\mathrm{d}U}{\mathrm{d}x} + \sigma\xi \tag{1}$$

with $\sigma = 0.1$ and ξ Gaussian distributed white noise with zero mean and unit variance. This model produces a time series (Fig. 2c) of abrupt switches between the stable states with exponentially distributed waiting time indicative of a stochastic Poissson process, consistent with the glacial records. Additional information on the noise process involved can be obtained from the ice core data and these results indicate an α-stable noise distribution consistent with that of hydrological extremes (Ditlevsen, 1999).

3 Observables

The theory advanced here predicts a number of potential observables. One prediction of the dust mechanism is abrupt hemispherically distributed changes in the hydrological cycle associated with abrupt redistribution of solar radiation absorbed between the surface and the mid-troposphere. A second prediction is that climate models with observed SST but lacking the associated atmospheric dust should be out of radiative balance. A third prediction is that reduction in precipitation scavenging in the upper troposphere during stadials should result in changes in atmospheric chemistry such as an increase in sulfate aerosol accumulation, which would also serve as a positive feedback stabilizing the stadial state.

4 Discussion

The modeling approach we have pursued is sufficient to demonstrate the dust-destabilization feedback mechanism and establish its plausibility. The fact that similar behavior has not yet been simulated in the parameter regime currently being investigated with more complex models (Mahowald et al., 2006) does not rule out this mechanism given uncertainties in modeling the dust cycle. For example, the last glacial maximum dust deposition estimates of Mahowald et al. (2006) differ from observed deposition rates in continental interiors by one to three orders of magnitude. Additionally, dust optical properties are strongly affected by uncertain mineralogical parameters, such as hematite content (Sokolik and Toon, 1999), so that our qualitative estimate of 5–20 times increased dust load to establish the colder/dustier state 2 may represent an overestimate of the required dust load depending on the dust composition.

Moreover, atmospheric dust load is a strong function of surface drying, which in turn is related to the particular sequence of global weather events. Even with identical boundary conditions, differences in the individual realizations of global weather events result in large integrated dispersion in continental scale drying on decadal and shorter time scales among the members in ensemble AGCM simulations (Schubert et al., 2004). In addition, dust lofting is a strong nonlinear function of surface wind speed (Andersen et al., 1998) which also varies among ensemble members in simulations both with and without boundary condition influences. The effect of changes in atmospheric boundary conditions, such as are associated with ENSO and the PDO in a coupled AOGCM, is to produce an additional stochastic variation in regional weather patterns that serves to enhance the variance of the stochastic process inducing the dust state transition. Explicit simulation of the dust state transition is not possible in the present generation of climate models since they do not solve for dust as a prognostic variable and since dust lofting depends crucially on small space and time scale meso and micro scale processes (Schepanski et al., 2009) that are not resolved. It follows that the calculations presented here, while indicative, cannot presently be verified by simulation of a precise a sequence of events that would cause such a transition. The important concept is that a dust transition depending on a sequence of weather events constitutes a physically plausible mechanism that would naturally satisfy the severe constraints that the transition mechanism be abrupt, bimodal, memoryless, noise induced and not associated with a bifurcation.

We have chosen to put the glacial equilibrium in Fig. 2 at 10 times present dust in agreement with observations of dust, temperature and precipitation in glacial climates (Fig. 1). We believe the far dustier and colder equilibrium indicated by the relationship between dust and precipitation as state 3 in Fig. 1 may not be accessible because dust levels cannot increase further once all potential dust source regions have been fully activated. This observation suggests that the progressive increase in the severity of stadials during the Pleistocene culminating in the particularly severe LGM interval may be related to increased availability and activation of dust source regions. Over long time scales the distribution and activation of dust source regions is clearly also related to seasonal distribution of insolation and to variations in orography.

Many Antarctic climate records show evidence for a “bipolar seesaw” signature of abrupt climate change in which the millennial time scale temperature record is antiphased between the Greenland and Antarctic ice records (e.g., Blunier and Brook, 2001). This observation is in agreement with the role of the North Atlantic THC in producing global teleconnections and as an important component of the sequence of events associated with abrupt climate change. However, the exact order of events in the sequence which begins with the instigation of an abrupt climate change event has yet to be determined. Rapid reorganization of the hydrological cycle would clearly influence the stability of North Atlantic surface water to convection with a consequent effect on THC regime stability. Conversely, reduction in the THC resulting from non-meteoric fresh water input could perhaps produce the large increases in dust seen in ice cores through its teleconnection with the Asian monsoon. Testing these predictions would poses an important challenge for climate models.

5 Conclusion

Evidence preserved in Greenland ice cores and widespread tropical and mid-latitude ice and cave deposits reveals that glacial climates were characterized by abrupt, hemispheric to global scale transitions involving both temperature and the hydrological cycle. Greenland ice core records of these transitions imply an underlying mechanism that is bimodal, noise induced, memoryless, and not associated with the variance increase and critical slowing indicative of approach to a bifurcation point. These characteristics severely constrain mechanisms of glacial abrupt climate variability. In this work we propose a mechanism for abrupt climate change that is consistent with these constraints from the record of rapid climate transitions. This mechanism is based on a precipitation/dust feedback in which weather events provide the noise that instigates transition between a stable cold/dry/dusty state and a warm/wet/less-dusty state.

Appendix A

Model description

In order to model the mechanism of dust-induced destabilization of glacial climates we use NCAR's single column atmospheric model (SCAM) (Hack et al., 2004). This model contains all aerosol, cloud, convection, and radiation representations of CAM (Collins et al., 2004; McCaa et al., 2004), NCAR's atmospheric general circulation model. We couple the model atmosphere to a mixed layer ocean with a depth of 50 m, so that the equilibrated model conserves energy, which is important for determining precipitation. We apply an ocean heat flux divergence of $-70\,\mathrm{W\,m^{-2}}$ to this slab ocean to represent heat transport to higher latitudes. We apply dust to the model by multiplying the tropical-average of the seasonally-varying standard CAM aerosol dust climatology by a "dust factor" at each model level for each of the CAM dust size bins, which represent dust particles with diameter 0.1–1.0 µm, 1.0–2.5 µm, 2.5–5.0 µm, and 5.0–10.0 µm. Each dust bin has characteristic optical properties. We use a sea salt aerosol profile taken from the tropical Pacific and set all other aerosols to zero. Collins et al. (2004) contains a detailed description of the model's aerosol scheme. We apply a surface wind speed of $8\,\mathrm{m\,s^{-1}}$ to the model. We find similar results with surface wind speeds of 4 and $12\,\mathrm{m\,s^{-1}}$. We average model results over 20 yr of converged solutions. We use a time step of 1200 s; our results are very similar when we reduce the time step to 600 s.

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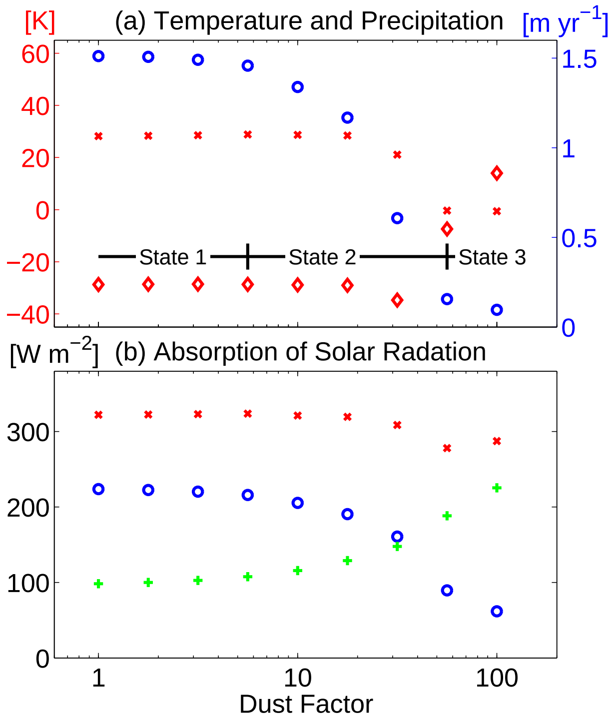

Fig. 1. Regimes in tropical stability and precipitation determined by atmospheric dust level. **(a)** The precipitation (blue circles), tropical surface temperature (red x's), and the difference between mid-tropospheric (515 mb) and surface potential temperature (red diamonds) as a function of the factor by which current tropical dust levels are increased (dust factor). **(b)** The absorption of solar radiation by the surface (blue circles), the atmosphere (green +'s), and the sum of the surface and atmosphere (red x's) as a function of the dust factor. In State 1 convection maintains the marginal convective stability of the troposphere. In State 2 absorption of solar energy by midtropospheric dust partially replaces convection in maintaining marginal convective stability. In State 3 solar absorption by dust causes an inversion.

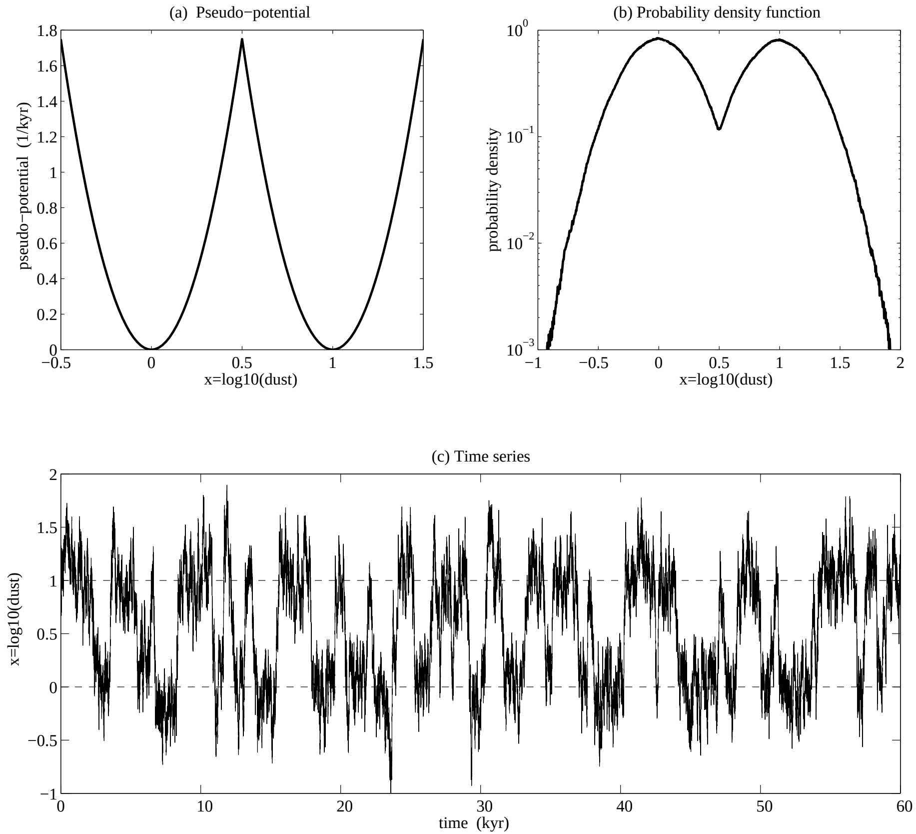

Fig. 2. Langevin model of dust transitions. **(a)** Pseudo-potential corresponding to the stadial and interstadial equilibria and to the switch between them at $x = 0.5$, where $x = \log_{10}$(dust). **(b)** Probability of occurrence of states. **(c)** Time series of transitions between states with waiting time between transitions of 1600 yr.