

## Role of Atmospheric Mass in Modulating Radiative Cooling and Surface Warming

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### ABSTRACT

The current research examines how atmospheric mass influences radiative cooling and near surface warming in an idealized, moist atmospheric aquaplanet general circulation model (GCM). The research is performed by methodically changing surface pressure by a factor of 0.5 to 10 times the current Earth value to examine the thermodynamic reactions of the atmosphere in the conditions of low levels of solar luminosity that were present on early Earth. Findings reveal that the addition of atmospheric mass has a great deal of warming effect on the near-surface temperature, most of which is caused by diminishing radiative cooling as the mass increases because of the augmented heat capacity of the atmosphere. Though moist convection does play a role in warming, it is not the primary mechanism. Radiative processes and inhibited vertical eddy heat transport are more important instead. Moreover, an increase in atmospheric mass contributes to a decrease in the meridional temperature gradients, especially with the increase in polar warming as compared to the tropics.

**Keywords:** *Atmospheric Mass, Radiative Cooling, Warming, General Circulation Model, Temperature.*

### I. INTRODUCTION

Maintaining livable built environments has emerged as one of the most significant concerns of our time, as rising global temperatures pose fundamental hazards to human civilization's economy, health, and security. 12% of the world's energy is currently used for heating and cooling buildings; by 2050, energy use for cooling in particular is predicted to increase significantly. Common cooling techniques, like air conditioners (ACs), transfer heat outside of interior spaces while using a lot of electricity, producing their own heat, and emitting both direct and indirect greenhouse gases. Additionally, heat islands with even higher temperatures are created in urban areas by the net heat from dense clusters of air conditioners and the abundance of man-made structures that trap solar heat and prevent evaporative cooling. In fact, active cooling techniques might make climate change<sup>2</sup> worse and increase the need for cooling. As a result, they are not viable options for large-scale built environment thermoregulation.

Interest in global warming has increased due to recent increases in atmospheric carbon dioxide (CO<sub>2</sub>), one of the main greenhouse gases in the atmosphere. Since water vapour is the other main greenhouse gas, atmospheric water vapour quantity also affects atmospheric temperatures. If the water vapour content rises, the temperature increase caused by CO<sub>2</sub> is intensified. Cumulus convection, which is frequently seen at low latitudes throughout much of the world, is supported by water vapour and low-level heat. Water vapour is carried higher by the cumulus convection and then dispersed out of the convection into a large subsidence area. As global warming alters cumulus convection, the distribution of humidity in the subsidence area may also vary.

One key way to lessen the need for active heating and cooling is to regulate radiative heat flows into and out of buildings. In order to do this, decades of research have investigated a variety of methods for regulating solar heat gain through various building envelope elements, such as roofs, walls, windows, and

skylights. Tailored responses to various solar spectrum components (UV, visible, and near-infrared wavelengths) have been made possible by advances in materials production and optical design. Nevertheless, the built environment radiatively emits and absorbs heat from its immediate surroundings over infrared wavelengths ( $\lambda \sim 2.5\text{--}40\ \mu\text{m}$ ) in addition to solar gain. For the most part, this ubiquitous heat exchange has not been maximised and used to increase efficiency. The radiative cooling of building surfaces facing the sky has been a significant exception.

In radiative cooling, heat from the earth is radiated into space through the long-wavelength infrared (LWIR,  $\lambda \sim 8\text{--}13\ \mu\text{m}$ ) atmospheric transmission window. The radiative heat loss can be significant if the surface emitting heat has a high emittance ( $\epsilon$ ) at the LWIR wavelengths ( $\epsilon_{LWIR}$ ) due to the earth's higher temperature ( $\sim 290\ \text{K}$ ) compared to space ( $\sim 3\ \text{K}$ ). A surface can also accomplish a net heat loss and radiatively cool to sub-ambient temperatures under sunshine if its solar reflectance ( $R_{\text{solar}}$ ) is high enough. Six Importantly, radiative cooling is a sustainable substitute for traditional active cooling systems since it is essentially passive and produces a net cooling effect. A variety of designs, including conventional white paints, porous polymers, silver-backed multilayer films, polymers, dielectric emitters, and polymer-dielectric composites, have been produced by research on radiative cooling. These designs include both broadband thermal emitters, which can operate at or close to ambient temperatures, and selective thermal emitters, which are ideal for reaching deep sub-ambient temperatures. Strategies to facilitate radiative cooling and thermoregulation under various weather and climate conditions have also been found in other studies.

## II. REVIEW OF LITERATURE

Mohamadkhani, Mohamadjavad. (2023) Radiative cooling may assist individuals stay cool without having any bad impacts because of the greenhouse gas problem that is causing global warming. By transferring heat directly into space, radiative cooling allows objects to shed heat without the need for additional energy or effort. Heat from the night may be transferred into space, as is well known. However, because it can cool things down during the day, it has been considered a potential solution to the energy shortfall in recent years. Additionally, it can benefit the global ecology. Radiative cooling materials have shown tremendous advancements thanks to nanotechnology.

Lin, Keng-Te et al., (2020) The goal of this review article is to provide a full picture of radiative cooling technology and how it may be used, particularly how radiative coolers can be used with other devices. Researchers have been very interested in radiative coolers and their uses over the last several decades since they are great for conserving energy. These primary parameters together affect the cooling efficiency of a radiative cooler. Nevertheless, a thorough examination of these primary characteristics concurrently remains unattainable. This page talks about the basic parts of radiative coolers, such as how the weather affects them in various places and how different kinds of radiative coolers may be used to control light and heat and how well they cool. The applications, obstacles encountered in this domain, and prospective developments are also examined. This article will help both academic researchers and engineers in the domains of energy harvesting, fluidic cooling, energy-efficient clothing, and architecture learn how to combine radiative coolers with practical devices.

Jeevanjee, Nadir & Fueglistaler, Stephan (2019) Atmospheric radiative cooling is a key part of the greenhouse effect on Earth, and it is directly related to how the atmosphere moves. At the same time, it's hard to understand or guess basic things about longwave radiative cooling, like its typical value of  $2\ \text{K day}^{-1}$ , its sharp drop (or "kink") in the upper troposphere, and the high values of  $\text{CO}_2$  cooling in the stratosphere. Here, we seek to achieve this comprehension by developing straightforward spectrum

models for clear-sky radiative cooling, as opposed to grey models. We make these models by putting together the cooling-to-space approximation, simplified greenhouse gas spectroscopy, and analytical formulas for optical depth. We next check these basic models using line-by-line computations. We discover that cooling rates may be represented as a product of the Planck function, a vertical emissivity gradient, and a distinctive spectral width obtained from our simplified spectroscopy.

Chemke, Rei & Kaspi, Yohai (2017) the several newly identified terrestrial exoplanets are anticipated to possess a diverse array of atmospheric masses. Here, the dynamic-thermodynamic impacts of atmospheric mass on circulation are examined using an idealised global circulation model by systematically changing the pressure at the surface of the atmosphere. An increase in atmospheric mass on an Earth-like planet reduces the Hadley circulation and makes it less wide in the north-south direction. These changes are linked to a decrease in convective fluxes and net radiative cooling, which cools the upper troposphere at mid-low latitudes and warms it at high latitudes because the atmosphere can hold more heat. These things all lower the meridional temperature gradient, the height of the tropopause, and the static stability. Lowering these parameters, which are very important for how the tropical circulation flows, makes the Hadley circulation weaker and smaller. When the meridional temperature differential is less, it also makes it harder to get mean potential energy to the eddy fields and mean kinetic energy, which makes the extratropical circulation weaker. The Rhines wavelength, which is observed to follow the meridional jet scale, is smaller as the eddy kinetic energy gets less. As the atmospheric mass grows, the jet scale shrinks in the extra tropics, which causes many jets and meridional circulation cells to form.

### III. RESEARCH METHODOLOGY

An idealised wet atmospheric aquaplanet GCM is used in a series of experiments to investigate the impact of atmospheric mass on near-surface temperature. The model, which is based on the Geophysical Fluid Dynamics Laboratory flexible modelling system, is a three-dimensional spherical coordinate primitive equation model of an ideal-gas atmosphere. This model is idealised because it is zonally symmetric and excludes processes (such as seasonal and diurnal cycles and clouds) that are less pertinent to the study of the thermodynamic influence of various atmospheric masses.

#### **Simulation Setup**

The effects of atmospheric mass on thermodynamics are investigated by systematically varying surface pressure from 0.5 to 10 times Earth's current value ( $p_{se} = 1$  bar). We present the results for this range of  $p_s$  in the main text because most data limit Earth's early surface pressure to  $0.5\text{--}4 \times p_s$ . The time average of the final 500 days of a 1500-day simulation is represented by the zonally averaged simulation results that are shown here. The time it takes the model to reach a thermal and kinetic energy statistically steady state can be significantly impacted by the air heat capacity in these simulations, and it is confirmed in every simulation that this steady state is indeed reached. Be aware that the model might not accurately depict the temperature and wind fields in the early Earth's atmosphere because of its simplicity. However, it makes it possible to examine how the kinetic and thermodynamic components of the atmosphere behave in three dimensions.

The best way to comprehend temperature changes brought on by rising air mass is to examine the model's temperature tendency equation, which is provided by

$$\frac{\partial T}{\partial t} = -\nabla \cdot (\mathbf{u}T) + Q_{\text{adiab}} + Q_{\text{conv}} + Q_{\text{cond}} + Q_{\text{rad}} + Q_{\text{surf}}, \quad (1)$$

where  $T$  is the three-dimensional temperature field,  $t$  is time,  $u = (u, v, \omega)$  is the three-dimensional wind vector in the vertical, meridional, and zonal directions, respectively, and  $Q_{\text{adiab}} = \kappa T v \omega / P$  is adiabatic heating,  $= R d C_p$ , where  $T_v$  is the virtual temperature,  $Q_{\text{conv}}$  and  $Q_{\text{cond}}$  are the convective and condensation heating per unit mass, respectively, and  $C = 1004 \text{ J kg}^{-1} \text{ K}^{-1}$  is the specific heat of air and  $R d = 287 \text{ J kg}^{-1} \text{ K}^{-1}$  is the gas constant of dry air. In equation (1), the radiative forcing term ( $Q_{\text{rad}}$ ) is provided by,

$$Q_{\text{rad}} = \frac{1}{C_p} \frac{d(S - L)}{dm}, \quad (2)$$

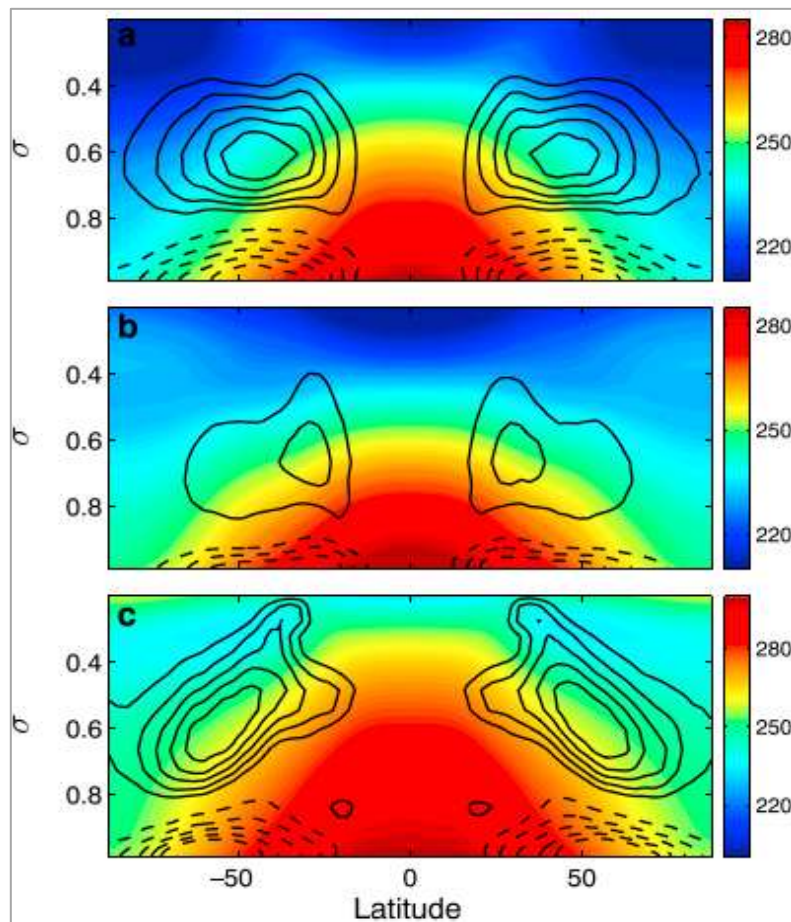
where  $g$  is the gravitational acceleration,  $dm = dp/g$  is the atmospheric mass per unit area between every two consecutive vertical levels, and  $S$  and  $L$  are the net solar and longwave radiative fluxes, respectively. Diffusion and heat fluxes from the surface to the lowest atmospheric layer are included in the surface heating ( $Q_{\text{surf}}$ ). The two types of processes in equation (1) that are most impacted by a change in  $p_s$  in a steady state ( $\partial/\partial t = 0$ ) are radiative forcing ( $Q_{\text{rad}}$ , equation (2)), which is influenced by the atmospheric heat capacity ( $C_p dm$ ), which rises with increasing atmospheric mass, and moist processes ( $Q_{\text{conv}}$ ), which involve temperature relaxation toward a moist adiabatic lapse rate. Since atmospheric mass influences the atmosphere's heat capacity and, consequently, the conversion between energy and temperature, studying the temperature tendency equation rather than the energy equation offers a clear understanding of the temperature variations caused by changes in atmospheric mass.

Three types of idealised GCM simulations are compared in order to separate the effects of atmospheric heat capacity and moisture on near-surface (lowest atmospheric level) temperature under  $p_s$  variations: (I) simulations that consider both atmospheric heat capacity and moisture effects, with an active hydrological cycle (i.e., moist convection affects the temperature tendency), and using the radiative forcing term in equation (2). (II) Moist convection-free simulations using the radiative forcing term in equation (2), and (III) moist convection-free simulations using a forcing scheme based on a Newtonian cooling ( $T_{\text{relax}} - T/\lambda$ , instead of equation (2)) that is independent of atmospheric mass and in which the temperature is relaxed toward a fixed profile ( $T_{\text{relax}}$ ) with a relaxation time  $\lambda$  (the interior relaxation time is 150 days, and the near-surface relaxation time is 15 days). Convection relaxes the temperature in these dry simulations, resulting in a constant convective profile of about  $6.8 \text{ K km}^{-1}$ .

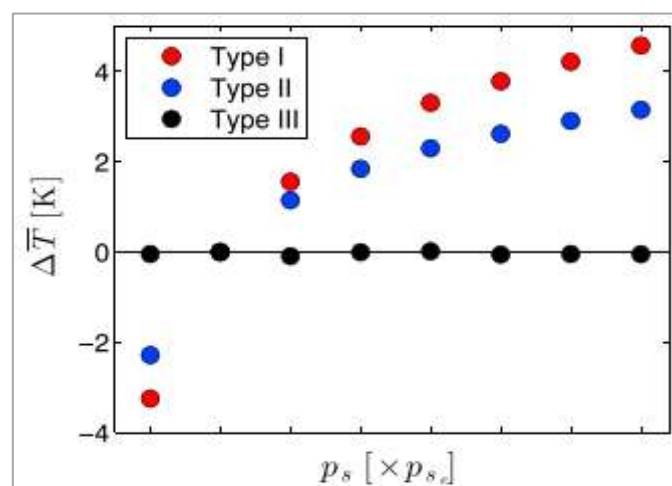
#### IV. RESULTS AND DISCUSSION

The global mean near-surface temperature drops to 275 K when solar flux is reduced to 80% of its current level, and the ice line latitude is pushed equatorward (the latitude where the near-surface temperature equals the temperature at the triple point of water,  $T_0 = 273.16 \text{ K}$ , Figure 1a). The mean near-surface temperature change in type I simulations compared to the current reference simulation (pse) is depicted in Figure 2. The global mean near-surface temperature (Figure 1b) rises by approximately 4.5 K (at  $4 \times$  pse, red circles in Figure 2) when both moisture and atmospheric heat capacity effects are taken into account (type I simulation). Because of an increase in the wet adiabatic lapse rate, convective fluxes may decrease as  $p_s$  increases, raising the near-surface temperature. We used type II simulations to investigate the impact of moisture on the mean near-surface temperature. Convection mechanisms are absent from these simulations, and the atmospheric mass solely influences the radiative forcing term (equation (2)) via the atmospheric heat capacity ( $C_p dm$ ). These simulations show that moist convection is not the main reason for the rise in mean near-surface temperature with atmospheric mass, as the temperature increases with surface pressure to approximately 70–75% of the temperature increase in the moist, type I simulations (blue circles in Figure 2). The mean near-surface temperature does not vary with  $p_s$  when

using a radiation strategy independent of pressure (type III simulation) (black circles in Figure 2). Therefore, changes in atmospheric mass mostly affect the mean near-surface temperature through changes in the atmospheric heat capacity (equation (2)).



**Figure 1: Zonal Mean Temperature and Eddy-Induced Vertical Temperature Advection across Climate Simulations**

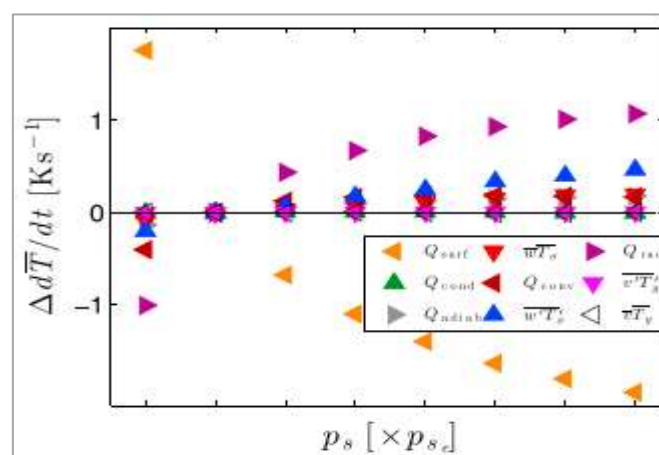


**Figure 2: Surface Pressure Effects on Near-Surface Temperature and Moisture Parameters**

Stronger worldwide net radiative cooling in the lower atmosphere (i.e.,  $Q_{rad} < 0$ ) results from a dimmer Sun in Earth's early history. The mean near-surface temperature rises as  $p_s$  increases due to the inverse relationship between  $Q_{rad}$  and atmospheric mass (equation (2)), which reduces net radiative cooling (Figures 1a, 1b, and 2). Although the warming itself acts to increase the net radiative cooling, the existence of temperature in the radiative forcing term (in the net longwave radiative flux) opposes this warming impact. Nevertheless, the

overall effect is still a surface warming. The meridional temperature gradient decreases with increasing atmospheric mass, according to an analysis of the vertical and meridional temperature distributions (see Figures 1a and 1b). When the atmospheric mass is quadrupled, the near-surface temperature increases by around 4 K in the tropics and by about 10 K at the poles. As was previously mentioned, the meridional distribution of solar energy causes a net radiative warming at low latitudes, a net cooling at high latitudes, and an overall world net cooling. Higher atmospheric mass therefore helps to flatten the meridional temperature gradient by suppressing high-latitude cooling and low-latitude radiative warming. As demonstrated below, this may reduce midlatitude vertical eddy temperature fluxes and limit baroclinic instability processes, trapping heat at the surface and further flattening the meridional temperature gradient (Figures 1a and 1b), which acts to destabilise the atmosphere. The gradient's flattening is caused by radiative processes and lower vertical eddy fluxes rather than net meridional advection.

We compute the mean values of the various components in equation (1) for each value of  $p_s$  and compare the outcomes to the current reference simulation ( $p_{se}$ ) in order to gain a better understanding of their influence on the mean near-surface temperature at steady state. Figure 3 illustrates these findings by showing how the amplitude of various components in the temperature tendency equation increases as atmospheric mass increases. When a result, when mass increases, these elements work to warm the near-surface. At a steady state, a drop in surface fluxes (orange) balances the increase in the magnitude of the warming components, resulting in less near-surface warming; however, this balance is reached at higher near-surface temperatures with increasing  $p_s$ . Near-surface warming is mostly caused by the radiative component (purple), which includes the impact of the atmospheric heat capacity ( $C_{pdm}$ , equation (2)). As  $p_s$  increases, it gradually cools the lower layers of the atmosphere, making it less negative. As  $p_s$  increases, a corresponding decrease in vertical eddy advection (blue) adds to warming by trapping more heat in the lower atmosphere (see Figures 1a and 1b's black contours). The adiabatic term (grey), mean vertical temperature advection (red), and convection (maroon) all contribute to surface warming with air mass, albeit to a lesser extent than the radiation and vertical eddy temperature fluxes. The results for convection (increasing warming with increasing  $p_s$ ) are comparable to the proposed propensity of convective fluxes to decrease with  $p_s$  at a fixed surface temperature when the moist adiabatic lapse rate increases. However, convective fluxes become progressively insignificant in reasonably huge atmospheres (beyond  $3.5 \times p_s$ ), leading to a weaker warming with increasing  $p_s$ . On the one hand, convection alone accounts for a small portion of the temperature tendency equation (maroon circles in Figure 3), but on the other hand, convection accounts for nearly a third of the warming effect (Figure 2), indicating that it initiates additional processes that contribute to the warming. The sensible and diffusive heat fluxes from the ocean (orange) are suppressed by these warming effects in the lower atmosphere. As  $p_s$  increases, changes in the other factors in equation (1) are less significant (Figure 3).



**Figure 3: Mean Components of Near-Surface Temperature Tendency (Type I Simulation)**

## V. CONCLUSION

Surface heat is increased as surface pressure rises because radiative cooling is significantly reduced. The findings demonstrate that temperature changes linked to changes in atmospheric mass are mostly driven by radiative mechanisms rather than moist convection alone. The analysis also shows that stronger warming at higher latitudes relative to the tropics is caused by increased air mass, which lowers meridional temperature gradients. Because of the suppression of vertical eddy heat transport caused by this gradient reduction, heat is trapped in the lower atmosphere and surface warming is strengthened. In high-pressure environments, convective processes have less of a direct impact on the overall energy balance. Significantly, models using pressure-independent radiative forcing reveal very little temperature change, emphasising the crucial role that atmospheric heat capacity plays in connecting atmospheric mass to climate dynamics.

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