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Inverse insolation dependence of Venus' cloud-level convection

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ABSTRACT

It is generally accepted that convection in planetary atmospheres is enhanced in low latitudes and in the daytime where incoming solar radiation is intense. Here we demonstrate, using a local convection model, that this tendency is reversed for Venus' cloud-level convection, which is driven by heating of the cloud base by upwelling infrared radiation. The dense lower atmosphere of Venus serves as a heat reservoir, whose temperature is horizontally well homogenized by large-scale dynamics, and thus upwelling infrared flux heats the cloud base almost equally over the entire planet. Since solar radiation preferentially heats the upper part of the cloud and has a stabilizing influence on the atmosphere, convection is relatively suppressed in low latitudes and in the daytime. The inverse insolation dependence seen in the numerical model explains observations of the latitudinal dependence of the convective layer depth and the gravity wave activity. The mechanism suggested in this study should be taken into account in climate modeling of Venus and cloudy exoplanets. How the combination of the opposite effects of the infrared heating and the solar heating determines the global distribution of the convective activity is an issue of universal importance. A long-lifetime Venus balloon floating at cloud heights would be useful for understanding these dynamical processes and the associated material transport.

1. Introduction

Venus, which is almost the same size as the Earth, is known for its extremely hot environment that reaches 740 K near the surface due to the greenhouse effect of the massive carbon dioxide atmosphere (Schubert et al., 1980), and concentrated sulfuric acid clouds floating at 47–70 km altitudes where the temperature drops to 230–370 K (Esposito et al., 1983). The clouds cover the whole planet with optical thicknesses of 20–40 in the visible spectral range and play crucial roles in the radiative energy balance: they reflect 80% of the incident sunlight back to space to cool the planet, and at the same time absorb thermal infrared radiation to enhance the greenhouse effect (Pollack et al., 1980). Such interaction with the radiation field is also essential for the existence of the clouds themselves. Clouds are formed photochemically in the presence of solar ultraviolet radiation (Yung and Demore, 1982), and stirred by convection, which is driven by infrared heating of the cloud base (Pollack et al., 1980). Convection is confined to the lower part of the cloud (46–58 km) and thought to enhance condensation of sulfuric acid, analogous to Earth's tropospheric clouds (James et al., 1997; Imamura and Hashimoto, 2001; McGouldrick and Toon, 2007). The occurrence of convection in this height region has been suggested by observations of neutrally stable (adiabatic) layers (Schubert et al., 1980; Hinson and Jenkins, 1995) and fluctuating vertical winds (Blamont et al., 1986). Baker et al. (1998, 2000) studied this convection using numerical fluid dynamical models, and suggested unique features such as cold, narrow downwellings that penetrate the underlying stable layer and the excitation of gravity waves below the cloud.

The global distribution of the convective activity is poorly constrained. Recently, the radio occultation experiments on ESA's Venus Express provided surprising results: the vertical extent of the neutrally stable layer increases with latitude from ~5 km at equatorial latitudes to ~10 km at polar latitudes (Tellmann et al., 2009), and the activity of gravity waves with vertical wavelengths of <4 km in the overlying stable layer is enhanced at high latitudes (Tellmann et al., 2012). The radio scintillation measurements on NASA's Pioneer Venus (Woo et al., 1980) also showed that small-scale density fluctuations with scales of <1 km, which might be manifestations of convectively-generated gravity waves (Leroy and Ingersoll, 1996), are enhanced at high latitudes. A natural

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explanation for these would be enhancement of convection and convectively-generated waves at high latitudes. However, considering that convection in the Earth's atmosphere is more vigorous at lower latitudes where incoming solar radiation (insolation) is more intense, the suggested latitudinal tendency is controversial.

Here we propose that the combined influence of solar radiation and thermal radiation on clouds leads to an anomalous insolation dependence of convection vigor, based on numerical experiments of local convective motions. The model is forced by solar heating based on in situ measurements and infrared heating based on a radiative–convective equilibrium computation. The model allows studies of the diurnal cycle of convection at different latitudes. Section 2 describes the method of calculation, Section 3 presents model results, and Section 4 gives conclusions and implications for climate modeling.

2. Description of the convection model

2.1. Fluid dynamical model

We developed a two-dimensional, nonlinear, local model of the Venus' cloud-level atmosphere located at latitudes 0°, 30° and 60°, using CReSS (Cloud Resolving Storm Simulator) version 2.3 which is described further by Tsuboki and Sakakibara (2002, 2007). The basic-state temperature and pressure, which are close to the Venus International Reference Atmosphere (Seiff et al., 1985), satisfy hydrostatic equilibrium. The basic-state wind velocity is taken to be zero. The dependent variables are horizontal velocity u, vertical velocity w, perturbation potential temperature θ, and perturbation pressure p. The governing equations are:

$$\frac{\partial \bar{\rho} u}{\partial t} = -\bar{\rho}\left(u\frac{\partial u}{\partial x} + w\frac{\partial u}{\partial z}\right) - \frac{\partial p'}{\partial x} + Turb \cdot u,$$

$$\frac{\partial \bar{\rho} w}{\partial t} = -\bar{\rho}\left(u\frac{\partial w}{\partial x} + w\frac{\partial w}{\partial z}\right) - \frac{\partial p'}{\partial z} + \bar{\rho} g\left(\frac{\theta'}{\bar{\theta}} - \frac{p'}{\bar{\rho} c_S^2}\right) + Turb \cdot w,$$

$$\frac{\partial \bar{\rho} \theta'}{\partial t} = -\bar{\rho}\left(u\frac{\partial \theta'}{\partial x} + w\frac{\partial \theta'}{\partial z}\right) - \bar{\rho} w\frac{\partial \bar{\theta}}{\partial z} + \bar{\rho}\frac{d\theta}{dt} + Trub \cdot \theta,$$

$$\frac{\partial p'}{\partial t} = -\left(u\frac{\partial p'}{\partial x} + w\frac{\partial p'}{\partial z}\right) + \bar{\rho} g w - \bar{\rho} c_S^2\left(\frac{\partial u}{\partial x} + \frac{\partial w}{\partial z}\right) + \frac{\bar{\rho} c_S^2}{\theta}\frac{d\theta}{dt},$$

where x and z are the horizontal and vertical coordinate, respectively, t is the time, $\bar{\rho}$ and $\bar{\theta}$ are the basic-state density and potential temperature, respectively, g is the gravitational acceleration, c_s is the sound speed, θ is the total potential temperature, and $d\theta/dt$ is the diabatic heating which is the sum of solar heating and infrared heating. $Turb \cdot u$, $Turb \cdot w$ and $Turb \cdot \theta$ represent subgrid-scale diffusion terms. The eddy diffusion coefficient used in these diffusion terms is taken to be proportional to the turbulence kinetic energy, which develops according to a prognostic equation (Klemp and Wilhelmson, 1978).

The physical domain spans altitudes from 40 to 60 km, with overlying and underlying 5 km-depth sponge layers to suppress wave reflection. The physical domain covers the convective region located around 47–55 km, and does not cover the bulk of the upper cloud layer, in which most of the incoming solar energy is deposited. The horizontal domain width is 100 km. Rigid wall boundary conditions are applied to the top and bottom boundaries, while periodic boundary conditions are applied to the lateral boundaries. Rotational effects are neglected since we focus on mesoscale convection in which the Coriolis and other metric terms are unimportant. Latent heating by evaporation and condensation is also neglected because the mass loading of Venus' clouds is insignificant (Knollenberg and Hunten, 1980).

The vertical and horizontal grid widths are 125 m and 200 m, respectively. The Arakawa-C and Lorenz staggered grids are used for horizontal and vertical grid arrangement, respectively. The terms related to sound waves are integrated with a time step of 0.2 s using an explicit forward–backward scheme in the horizontal and an implicit Crank–Nicolson scheme in the vertical, and other terms are integrated with a time step of 1 s using a leap-frog scheme with the Asselin time filter. Effects of sound waves are weakened by adding reduction factors for divergence terms. To further suppress numerical instability, fourth-order numerical smoothing of the dependent variables is applied. Reducing the grid size to half hardly changes the typical scale of convection cells and the convection strength, although finer structures are enhanced in convection.

2.2. Thermal forcing

The influence of radiation is given by prescribed solar heating profiles based on in situ measurements (Tomasko et al., 1980) and an infrared heating profile calculated by a radiative–convective equilibrium model for a globally-averaged state (Ikeda, 2011) (Fig. 1). The detail of the radiative–convective equilibrium computation is given in Appendix.

The adopted radiative forcing profiles represent the following physics. The incident solar flux is partially absorbed by the cloud layer, preferentially heating the upper part of the cloud, and transmitted to the lower atmosphere to establish a hot sub-cloud atmosphere via the greenhouse effect. The opaque nature of the cloud to upward infrared radiation leads to heating of the cloud base and occurrence of an unstable layer around 47–55 km in radiative equilibrium, and then convective adjustment occurs to establish a neutrally stable layer (Pollack et al., 1980; Eymet et al., 2009). This convective heat transport raises the temperature at 50–55 km, leading to excessive infrared cooling, and lowers the temperature at 47–49 km, leading to excessive infrared heating. The resultant energy flow is as follows: solar flux reaching the lower atmosphere is thermalized and converted to upward infrared flux; the infrared flux is absorbed by the cloud base at 47–49 km; convection develops and transports heat upward; and the heat deposited above 50 km is further transported upward by infrared radiation because above this height the atmosphere becomes less opaque.

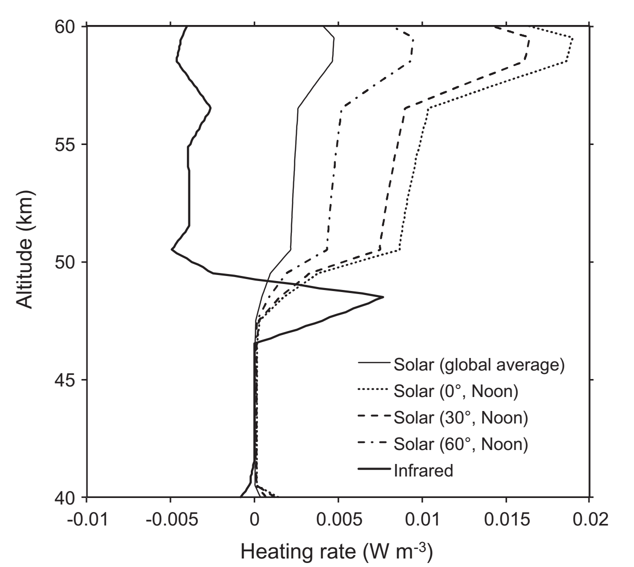

Fig. 1. Globally-averaged solar heating profile, local-noon solar heating profiles for latitudes 0°, 30° and 60°, and infrared heating profile used in the model.