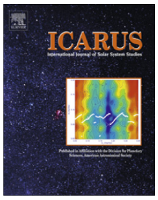
Icarus 229 (2014) 71–91

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus



Numerical simulations of Jupiter's moist convection layer: Structure and dynamics in statistically steady states ☆

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ARTICLE INFO

Article history:
Received 21 March 2013
Revised 16 September 2013
Accepted 12 October 2013
Available online 24 October 2013

Keywords:
Jovian planets
Jupiter, atmosphere
Atmospheres, dynamics
Atmospheres, structure

ABSTRACT

A series of long-term numerical simulations of moist convection in Jupiter's atmosphere is performed in order to investigate the idealized characteristics of the vertical structure of multi-composition clouds and the convective motions associated with them, varying the deep abundances of condensable gases and the autoconversion time scale, the latter being one of the most questionable parameters in cloud microphysical parameterization. The simulations are conducted using a two-dimensional cloud resolving model that explicitly represents the convective motion and microphysics of the three cloud components, H_2O, NH_3, and NH_4SH imposing a body cooling that substitutes the net radiative cooling. The results are qualitatively similar to those reported in Sugiyama et al. (Sugiyama, K. et al. [2011]. Intermittent cumulonimbus activity breaking the three-layer cloud structure of Jupiter. Geophys. Res. Lett. 38, L13201. doi:10.1029/2011GL047878): stable layers associated with condensation and chemical reaction act as effective dynamical and compositional boundaries, intense cumulonimbus clouds develop with distinct temporal intermittency, and the active transport associated with these clouds results in the establishment of mean vertical profiles of condensates and condensable gases that are distinctly different from the hitherto accepted three-layered structure (e.g., Atreya, S.K., Romani, P.N. [1985]. Photochemistry and clouds of Jupiter, Saturn and Uranus. In: Recent Advances in Planetary Meteorology. Cambridge Univ. Press, London, pp. 17–68). Our results also demonstrate that the period of intermittent cloud activity is roughly proportional to the deep abundance of H_2O gas. The autoconversion time scale does not strongly affect the results, except for the vertical profiles of the condensates. Changing the autoconversion time scale by a factor of 100 changes the intermittency period by a factor of less than two, although it causes a dramatic increase in the amount of condensates in the upper troposphere.

The moist convection layer becomes potentially unstable with respect to an air parcel rising from below the H_2O lifting condensation level (LCL) well before the development of cumulonimbus clouds. The instability accumulates until an appropriate trigger is provided by the H_2O condensate that falls down through the H_2O LCL; the H_2O condensate drives a downward flow below the H_2O LCL as a result of the latent cooling associated with the re-evaporation of the condensate, and the returning updrafts carry moist air from below to the moist convection layer. Active cloud development is terminated when the instability is completely exhausted. The period of intermittency is roughly equal to the time obtained by dividing the mean temperature increase, which is caused by active cumulonimbus development, by the body cooling rate.

1. Introduction

It is now an established fact that convective clouds are common entities in Jupiter's atmosphere (Vasavada and Showman, 2005). For example, Galileo and Cassini observed a number of small (∼500–2000 km) convective clouds near the locations of lightning strikes (Little et al., 1999; Gierasch et al., 2000; Dyudina et al., 2004). Convective clouds are considered to play an important role

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0019-1035/$ - see front matter © 2013 The Authors. Published by Elsevier Inc. All rights reserved.
http://dx.doi.org/10.1016/j.icarus.2013.10.016

in transferring heat from the interior of the planet to the upper troposphere (Gierasch et al., 2000). In due course, the mean vertical structure in the moist convection layer of Jupiter's atmosphere is thought to be maintained by the statistical contribution of a large number of clouds driven by internal and radiative heating/cooling over multiple cloud life cycles.

The mean vertical structure, i.e., the mean vertical profiles of temperature, condensates, and condensable gases, in the moist convection layer has been estimated using one-dimensional equilibrium cloud condensation models (ECCMs), where the profiles are derived from the thermodynamic equilibrium values of an adiabatically ascending air parcel from the deep atmosphere (Weidenschilling and Lewis, 1973; Atreya and Romani, 1985; Sugiyama et al., 2006). However, the results obtained by ECCMs should not be accepted without caution because they have neglected the effects of fluid dynamical and cloud microphysical processes associated with various atmospheric disturbances including convective clouds.

Although numerous attempts have been made to determine the vertical structure of Jupiter's atmosphere, many of the important properties of convective clouds are far from being constrained (reviewed by, e.g., West et al., 1986; Atreya et al., 1999; Vasavada and Showman, 2005), since the thick cloud deck prevents the vertical structure of the moist convection layer from being observed by remote sensing. Examples are the mean profiles of condensates and condensable gases; the Galileo probe is the first, and so far the only, spacecraft that carried out an in situ observation of the vertical structure of Jupiter's atmosphere from the level of visible clouds to approximately 20 bars. The results show an unexpectedly small amount of water vapor (Wong et al., 2004). However, the representativeness of the observed vertical structure is considered poor since the Galileo probe's entry site was one of the 5-μm hot spots which are atypical cloud-free regions in Jupiter's atmosphere. The mean atmospheric structure and its relationship to moist convection still remain unclear.

In order to investigate the possible structure and dynamics of the moist convection layer maintained by the statistical contribution of a large number of clouds over multiple cloud life cycles, numerical simulations using a cloud resolving model with long-term integration periods are indispensable. Such attempts have been rather rare, since most studies using cloud resolving models have focused on the evolution of a single cloud, in which the onset and initial expanding phase of a single cloud are considered under simplified and arbitrary initial conditions with short-term integration periods (e.g., Yair et al., 1992, 1995; Hueso and Sanchez-Lavega, 2001).

The purpose of our studies (Nakajima et al., 2000; Sugiyama et al., 2009, 2011) has been to investigate idealized mean profiles of condensable gases and condensates, which were formerly investigated by the use of ECCMs, and the temporal-spatial characteristics of convective motions that produce such profiles. For this purpose, we have been developing a two-dimensional cloud resolving model and performing long-term numerical simulations. The atmospheric structure obtained by Nakajima et al. (2000) is characterized by a thin but strong stable layer near the H_2O lifting condensation level that acts as a barrier for vertical convective motions, which is caused mainly by the change of mean molecular weight of atmospheric gases. This study suffered from two major limitations in that it considered only H_2O as a condensable component and employed unrealistically intense body cooling as a substitute for radiative cooling. Sugiyama et al. (2009) included, in addition to the condensation of H_2O, the condensation of NH_3 and the production reaction of NH_4SH, and Sugiyama et al. (2011) investigated the possible structure and dynamics of the moist convection layer using a body cooling whose cooling rate was of the order of that expected in Jupiter's atmosphere. The results suggested that the activity of moist convection is not steady but experiences a prominent quasi-periodic variation with a period of several tens of days. Around the levels where NH_3 condensation and NH_4SH chemical reaction occur, weak but definite stable layers develop and act as dynamical and compositional boundaries during the period of weak convective activity.

Although Sugiyama et al. (2011) succeeded in obtaining an insightful image of the structure and dynamics of the moist convection layer in Jupiter's atmosphere, the dependence of the structure and dynamics on parameters that are poorly constrained by observations remains to be examined. One of the most important parameters to be considered is the deep abundances of condensable gases. Not only the altitudes at which condensation and chemical reaction occur but also dynamical properties should be affected by this parameter, since the vertical profile of static stability is governed by the deep abundances of condensable gases (Sugiyama et al., 2006). The deep abundance of H_2O gas is the most ambiguous. The Galileo probe could not provide a confident estimate (Wong et al., 2004), and indirect evidence suggests that the deep abundance of H_2O gas is higher than the solar abundance (Atreya et al., 1999). We therefore perform a parameter experiment on the deep abundances of condensable gases.

Also poorly constrained are details of cloud microphysical processes. There have been some attempts (e.g., Rossow, 1978; Carlson et al., 1988) to estimate the time scales involved in such processes. Gibbard et al. (1994) and Yair et al. (1998) also considered cloud microphysical processes in order to investigate lightning in Jupiter's convective clouds observed by spacecraft, and succeeded in demonstrating its existence. However, there have been no quantitative measurements of the amount, size, type, and composition of cloud particles, to which the representation of cloud microphysics in numerical models can be compared. Thus, we hesitate to use a highly sophisticated bulk microphysical parameterization scheme such as that implemented in the EPIC model (Palotai and Dowling, 2008). Instead, we implement a simple bulk parameterization scheme, as will be fully described in Section 2, and perform a parameter experiment on the autoconversion time scale. The reason we chose the autoconversion time scale as the parameter to be varied is that it is the most ambiguous parameter of all those controlling the rate of condensate removal from an air parcel. For instance, at least for the case of Earth-like conditions, Nakajima and Matsuno (1988) showed by the use of long-term numerical calculations that switching off the autoconversion process destroys the asymmetry between narrow, strong, cloudy updrafts and wide, weak, dry downdrafts, which is a distinct characteristic of the troposphere of Earth, and produces a troposphere completely filled with condensate. Switching on/off other processes such as evaporation of precipitating condensate and negative buoyancy of condensate does not result in such an extreme change.

In this study, a number of long-term numerical simulations are performed in order to examine the dependence of the idealized structure and dynamics of the moist convection layer in statistically steady states on the autoconversion time scale and on the deep abundances of condensable gases. We also examine the mechanism of the most significant characteristic, the intermittent emergence of vigorous cumulonimbus clouds, obtained in most of our calculations. In Section 2, we present a brief description of our cloud resolving model and the settings for the parameter experiments. In Section 3, we summarize the characteristics of the structure and dynamics of the moist convection layer obtained by a control experiment in which the settings are identical to those of Sugiyama et al. (2011). In Sections 4 and 5, we demonstrate the dependences of the structure and dynamics of the moist convection layer on the autoconversion time scale and on the deep abundances of condensable gases, respectively. We discuss the