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Modeling Jupiter's cloud bands and decks 2. Distribution and motion of condensates

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ABSTRACT

A simple jovian cloud scheme has been developed for the Oxford Planetary Unified model System (OPUS). NH_3-ice, NH_4SH-solid, H_2O-ice and H_2O-liquid clouds have been modeled in Southern hemisphere limited area simulations of Jupiter. We found that either three or four of the condensates existed in the model. For a deep atmospheric water abundance close to solar composition, an NH_3-ice deck above 0.7 bar, an NH_4SH-solid deck above 2.5 bar and a H_2O-liquid deck with a base at about 7.5 bar and frozen cloud tops formed. If a depleted deep water abundance is assumed, however, a very compact cloud structure develops, where an H_2O-ice cloud forms by direct sublimation above 3 bar. The condensates constitute good tracers of atmospheric motion, and we have confirmed that zonal velocities determined from manual feature tracking in the modeled cloud layers agree reasonably well with the modeled zonal velocities. Dense and elevated clouds form over latitudes with strong atmospheric upwelling and depleted clouds exist over areas with strong downwelling. In the NH_3-ice deck this leads to elevated cloud bands over the zones in the domain and thin clouds over the belts, which is consistent with the observationally deduced distribution. Due to changes in the vertical velocity pattern in the deeper atmosphere, the NH_4SH-solid and water cloud decks are more uniform. This modeled cloud structure thus includes the possibility of more frequent water cloud observations in belts, as this deeper deck could be more easily detected under areas with thin NH_3-ice clouds. Large scale vortices appeared spontaneously in the model and were characterized by elevated NH_3-ice clouds, as expected from observations. These eddies leave the most discernible imprint on the lighter condensate particles of the uppermost layer.

1. Introduction

Jupiter's large scale atmospheric motions have been deduced mainly from tracking of movements in the visible upper cloud layer of the planet (e.g. Limaye, 1986; Vasavada et al., 1998; Porco et al., 2003). Being the primary source of information about jovian dynamics, Jupiter's cloud structure has been observed since the 18th century and numerically investigated since the 1970s. Based on early numerical experiments by Weidenschilling and Lewis (1973) thermochemical-equilibrium models have established the predominant view of a triple layered vertical cloud distribution in the upper troposphere, consisting of an NH_3-ice layer between 0.2 and 0.8 bar, an NH_4SH-solid layer between 1 and 3 bar and a possible deep aqueous or icy water layer between 1 and 8 bar (Lewis, 1969; Atreya et al., 1999; Sugiyama et al., 2006).

Spectroscopic observations from the Voyager (Conrath and Gierasch, 1986), Galileo (Banfield et al., 1998; Irwin et al., 2001; Simon-Miller et al., 2001) and Cassini (Matcheva et al., 2005) missions place the proposed globally averaged NH_3-ice cloud layer between 0.2 bar and 1 bar. Retrievals from both Galileo's Near-Infrared Mapping Spectrometer (NIMS) (Irwin et al., 2001) and Cassini's Composite Infrared Spectrometer (CIRS) (Matcheva et al., 2005) support the existence of a second cloud layer below 1 bar, which could be interpreted as the NH_4SH-deck predicted in the one-dimensional thermochemical models. A tenuous cloud layer at this altitudes was also detected by the Galileo probe nephelometer (de Pater et al., 2001). The deeper water clouds have only been spectroscopically detected locally (Banfield et al., 1998) and are likely associated with moist convection sites (Gierasch et al., 2000). Roos-Serote et al. (2004) have shown that NIMS spectra can be fitted with cloud profiles containing a deep water cloud and that the Galileo probe measurements could be consistent with the existence of a deep cloud below 14 bar.

The spatial distribution of clouds has been inferred from the banded appearance of the planet. Large scale upwelling in Jupiter's zones and downwelling in belts at altitudes between 1 and 0.1 bar has been inferred from radiometric observations of the temperature structure and parahydrogen fraction (Ingersoll and Cuzzi, 1969; Gierasch et al., 1986; Conrath et al., 1990; West et al., 1992; Moreno and Sedano, 1997). A corresponding distribution of high and dense NH_3-ice clouds in zones and relatively cloud free belts

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is usually assumed (e.g. West et al., 1986) and has been supported by spectroscopic observations (Simon-Miller et al., 2001; Matcheva et al., 2005). Ground based radiometric observations of Jupiter found a global depletion of NH_3-ice particles in the layer from 0.6 bar to 2 bar but also suggested a stronger depletion in belts (de Pater et al., 2001; Showman and de Pater, 2005). Recent observations of lightning storms occurring mainly in belts suggest a reversed pattern for the spatial distribution of deep water clouds (Banfield et al., 1998; Gierasch et al., 2000).

The cloud structure of Jupiter's large scale discrete features has mainly been studied from observations of the Great Red Spot. Spectroscopic observations have been used to construct a three layer model of clouds above the Great Red Spot, which consists of a stratospheric haze layer, dense and elevated NH_3-ice clouds in the troposphere and an anomalously thin cloud layer below (Simon-Miller et al., 2002).

Numerical modeling of the spatial distribution of jovian condensates has so far primarily been undertaken with one-dimensional models as referred above or has focused on small scale cloud structure (Yair et al., 1992, 1995; Hueso and Sanchez-Lavega, 2001; Nakajima et al., 2000) and microphysics (Rossow, 1978; Ackerman and Marley, 2001). Palotai and Dowling (2008) have investigated Jupiter's ammonia and water cloud layer in large domain two-dimensional models but so far no results from large scale, three-dimensional models of Jupiter's cloud structure have been published.

We have developed a simple jovian cloud model for the Oxford Planetary Unified model System (OPUS), a sophisticated three-dimensional GCM, which has been used in several numerical studies of Jupiter's dynamics (e.g. Yamazaki et al., 2004). OPUS is based on the UK Met Office's Unified Model. The cloud scheme models the four jovian condensate species, NH_3-ice, NH_4SH-solid, H_2O-liquid and H_2O-ice, as semi-active tracers advected with the ambient atmospheric motion. The vertical location and extent of the clouds depends on the specified deep abundance of the source species. We have used the model to simulate both solar oxygen based (Carlson et al., 1992) and depleted (by a factor of 10^{-3}) (Bjoraker et al., 1986; Lellouch et al., 1989) water profiles, and obtained a qualitatively different water cloud distribution in each case. A deep liquid water cloud deck with frozen cloud tops forms for solar abundance, while a water ice cloud with a base above 3 bar is generated by direct sublimation in the depleted scenario. In the depleted case, the condensates for all three species were confined within a compact layer between 0.2 and 3 bar.

OPUS was employed in the first part of this study to investigate the formation of jet scale circulation cells in response to radiative and momentum forcing in Jupiter's atmosphere (Zuchowski et al., 2009). In that companion paper we presented model results, which featured two different set of circulation cells in the upper and lower atmosphere, with partly divergent vertical velocities. By coupling the cloud scheme to this dynamical scenario we were able to simulate both the vertical structure of Jupiter's major cloud decks as well as to investigate the formation of cloud bands over belts and zones in response to the simulated circulations. The modeled condensate diagnostics are directly comparable to observations of Jupiter's clouds. We thus show below that the scenario described by Zuchowski et al. (2009) is associated with a modeled cloud structure which is in good agreement with previous numerical models and spectroscopic cloud observations. Specifically, we obtained high and dense NH_3-ice cloud bands over zones and thin, depressed clouds in belts. A more uniform latitudinal distribution was found in the deeper decks, consistent with more frequent observations of water clouds in belts. This agreement with observations in the upper troposphere provides further evidence for the hypothesis that divergent jet scale circulation cells, induced by radiative and momentum forcing, provide an explanation consistent with the observed jovian clouds.

In Section 2 we briefly introduce the atmospheric model and describe the principles underlying the formulation of the bulk cloud scheme. Section 3 contains the modeled results, including a discussion of the vertical and spatial distribution of clouds, an investigation of the role of condensates as atmospheric tracers in the model and a presentation of the clouds within a large scale vortex. In Section 4 we summarize our findings and discuss our final conclusions.

2. Model set-up and initialization

2.1. Atmospheric dynamics

The atmospheric model used for this study and the generation of jet scale meridional circulation cells through radiative and momentum forcing in Jupiter's atmosphere have been extensively discussed by Zuchowski et al. (2009). We were thus able to couple the cloud scheme to a model with well studied atmospheric dynamics. The run used here features a latitudinal channel, extending from 15° S to 40° S, in which two sets of meridional circulation cells develop. In the stratosphere the jet scale cells are well aligned with the jet centers and lead to upwelling over the South Tropical and Temperate Zones as well as to downwelling over the respective belts. The tropospheric set of cells includes an additional clock-wise rotation cell at the Northern boundary. Therefore the vertical velocity direction in the South Tropical Belt is partly reversed in the deep atmosphere and the velocity profile is shifted southward in temperate latitudes. These differences between the upper and deep atmosphere lead converging flows in belt regions as predicted, e.g. by Ingersoll et al. (2000). The model used here is designated Run 3 in the companion paper.

The model does not include any parametrization of sub-grid scale cumulus convection. Sub-grid scale turbulence has been parameterized by a Richardson number dependent mixing procedure (Yamazaki et al., 2004). Circulations initiated by latent heat release through condensation can significantly alter the atmospheric dynamics (e.g. Palotai and Dowling, 2008) and might lead to vertical transport different from the one we now obtain in response to the Newtonian forcing terms.

2.2. Bulk cloud model

Simple bulk cloud schemes were previously developed in Oxford for both martian and venusian GCMs (Boettger et al., 2005; Lee et al., 2005, 2007), using simple representations of cloud condensation and simulating the advection of vapor and condensates with highly simplified microphysics. In the present study we have effectively adapted these schemes for the jovian planets for each of the occurring condensate species.

Our scheme represents vapor and condensate phases of a cloud species as passive tracers, advected within the atmosphere by horizontal and vertical winds through OPUS's intrinsic tracer scheme (Robinson, D., Clark, P.A., Malcom, A., 2004. Unified model user guide—Atmospheric tracers. Technical report, UK Met Office). NH_3-ice, NH_4SH-solid, H_2O-liquid and H_2O-ice clouds are the condensates likely to exist on Jupiter (e.g. Atreya et al., 1999) and have been modeled here. It is usually assumed that motion in the upper cloud deck is diagnostic for the general atmospheric motion, such that the NH_3-ice condensate fits the description of a passive tracer reasonably well. This simple model at present lacks a parametrization of the chemical reaction forming the NH_4SH-solid cloud deck, so that the depletion of NH_3-ice deduced from ground based observations (de Pater et al., 2001) is not represented by the scheme.