Simulating Moist Convection on Jupiter and Saturn with WRF

I. Introduction

It is well known that cloud systems and associated moist convection (MC) play a very important role in the global atmosphere circulation and climate system (Arakawa and Schubert 1974; Randall et al. 2003; Arakawa 2004). Recent observations (Sanchez-Levega 1999; Gariesh et al. 2000; Ingersoll et al. 2000; Porco et al. 2003, 2005) show that moist convection also plays an important role in the large-scale dynamics of Jupiter’s and Saturn’s atmospheres. Some numerical models have been developed to simulate the moist convection and the interactions between MC and the large-scale dynamics in Jupiter and Saturn (Stoker 1986; Yair et al. 1992, 1995; Hueso & Sanchez-Levage 2001, 2002, 2004; Li & Ingersoll, submitted). However, there are a lot of spaces can be improved in the above-mentioned numerical models (see details in part II). In this report, we propose to simulate MC and the associated large-scale dynamics by modifying a matured Earth’s Weather Research and Forecast (WRF) model.

II. Previous Works on MC and Associated Dynamics

The previous numerical simulations of MC on Jupiter and Saturn include a one-dimensional (1-D) model (Stoker 1986), two-dimensional (2-D) models (Yair, 1992, 1995; Nakajima et al. 2000), and a recently-developed three-dimensional (3-D) single-cell model (Hueso & Sanchez-Levage, 2001). In these models, the dynamical and physical processes are relatively simple, even for the 3-D MC model developed by Sanchez-Levage’s group. More importantly, these MC models are run for small domain in the order of $10^2$ km with short time in the order of hour due to computational limits. Therefore, these models can not reproduce many of the important observational features of convective storms (e.g., size in a few thousand kilometers and lifetime in a few days) on Jupiter and Saturn. Recently, Sanchez-Levage’s group develops a 2-D model of convective storms to expand the simulating domain to a few thousand kilometers (Hueso et al. 2002) by utilizing the outputs from their previous 3-D single-cell MC model (Hueso & Sanchez-Levage, 2001). A real 3-D mesoscale model of convective storms with domain size in a few thousand kilometers and simulating time beyond a few days is urgently needed for the Jupiter and Saturn.

The study on the role of MC in the large-scale dynamics of Jupiter and Saturn are relatively limited. Some important conclusions have been drawn from observations (Gariech et al. 2000; Ingersoll et al. 2000; Sanchez-Levage et al. 1999). However, the numerical simulation of the interactions between MC and the large-scale dynamics is a relatively new field partly due to the tremendous scale difference between the mesoscale processes and the large-scale dynamics. A reduced-gravity quasi-geostrophic (QG) model with a simple parameterization of MC based on observations has been applied to this question (Li & Ingersoll, submitted). No doubt, more numerical works should be addressed on this topic considering the important role of MC in the large-scale circulation of Jupiter and Saturn.
III. Motivation and Possibility to Study MC with WRF

As a flexible, state-of-the-art atmospheric simulation system, the WRF model is constructed for use in a broad range of applications across scales ranging meters to thousands of kilometers. The applications include idealized simulations of convection, parameterization research, and coupled-model study. The two-way nesting feature of WRF model (information can be transported between the low-resolution large domain and embedding small high-resolution regions) makes it possible to study micro-scale, mesoscale and large-scale processes in a single model. Thus, we try to modify the WRF model to study the important mesoscale and large-scale dynamics of the atmospheres of Jupiter and Saturn, including:

1. *Simulating the mesoscale convective storms in Jupiter and Saturn*

   Obviously, WRF is a good candidate to simulate the mesoscale convective storms in Jupiter and Saturn. There are two choices for this kind of simulation. The first one is that a few single-cell MCs with domain in the order of 10 km randomly dispersed in the domain of the mesoscale model (a few thousand kilometers). Lightning has been shown to occur at several places in the same cloud systems seems to supporting the idea that mesoscale convective storms is composed of smaller convective cells (Little et al. 1999). Our simulation will be different with the work of Sanchez-Levaga’s group (Heuso et al. 2002). Firstly, the 3-D WRF model allows us to study more dynamical and physical processes by incorporating these existing different schemes of physics including moist convection and cloud microphysics in WRF. Furthermore, the two-way nesting feature of WRF makes it possible to study the interactions between different single-cell MCs, and the interaction between the single-cell MC and the mesoscale circulation. The other choice is that we set a single initial warm air bubble has large size in the order of 100 km and strong stability (temperature difference with environment is ~ K) so that the single unstable air bubble can develop into a mesoscale convective storms with size in the order of 1000 km.

2. *Simulating the Equatorial regions of Jupiter and Saturn*

   Equatorial regions of Jupiter and Saturn display a lot of important features (e.g., the Great Red Spot (GRS), the South Equatorial Belt (SEB), and strong eastward jets). Current QG models of the giant planets (Panetta 1993; Huang & Robinson 1998; Marcus 2000; Li & Ingersoll, submitted) are not suitable to study the equatorial regions. Shallow Water (SW) models can not generate eastward equatorial jets either (Cho & Polvani, 1996). Using a SW model, Downing and Ingersoll (1989) successfully generated the GRS from initial small disturbances. However, the zonal wind profiles are prescribed in their SW model. The results of our reduced-gravity QG model with simple parameterization of MC (Li & Ingersoll, submitted) suggest that multiple jets can be developed and maintained by moist convection in middle latitudes. Observations (Little et al. 1999; Sanchez-Levage et al. 1999; Porco et al. 2003, 2005; Li et al. 2004) show that MC is active in the equatorial regions of Jupiter and Saturn. Therefore, the modified WRF model will be a good tool to test our idea (moist convection as an energy source and driving force) in the equatorial regions. We want to capture the GRS or the strong eastward equatorial jets or both by the MC driving idea in the equatorial regions. In the simulation of the strong eastward
equatorial jets of Jupiter and Saturn we probably have to involve deep flow, which should be easy in the 3-D WRF model. There are also two choices for the simulations of the equatorial regions: 1) a 3-D low-resolution WRF model in a large domain including the equatorial regions (30° N – 30° S) with a simple parameterization of MC based on the output from the simulation of the mesoscale convective storms in motivation 1 and 2) a 3-D WRF model with two-way nesting including high-resolution MC regions in a low-resolution large domain (30° N – 30° S) to simulate the mesoscale convective storms and the large-scale dynamics (the GRS and the equatorial jets) at the same time.

3. Developing global WRF model for Jupiter and Saturn

Based on the global WRF model for Mars that is developing in Mark’s group, we expect to develop a global WRF model for Jupiter and Saturn. The first simple test is that we only consider the interaction between the mesoscale convective storms and the large-scale circulation if we assume the mesoscale convective storms are the most important mesoscale processes by the first-order approximation. Then we disperse these mesoscale convective storms (high-resolution) in the global domain to drive the large-scale circulation. We expect that the global circulation can be generated from MC and these mesoscale convective storms only appear in these regions with large-scale vorticity is cyclonic, which is consistent with observations (Little et al. 1999; Porco et al. 2003), after large-scale global zonal jets are developed. The simple test is same with the idea of our previous work (Li & Ingersoll, submitted), but with the global domain.

However, a real Global Circulation Model (GCM) has to involve different cloud processes, which means every big grid cell of GCM has to be simulated with a mesoscale model. Traditional cumulus parameterization can not offer the reliable prediction for the global circulation and climate changes (Randall et al. 2003; Arakawa, 2004). In the review paper by Randall et al. (2003), the authors discussed two new directions on cloud-resolving GCM: 1) global Cloud System-Resolving Models (CSRM), which means to expand the current CSRM's domain to the global area. This idea is difficult in current computation ability (increase 10^6 time of the current GCM computation time) due to high space and time resolution and 2) a so-called “super-GCM” (Grabowski et al. 1999, 2001). The later one is attracting more attention because of its relatively fast computation speed. Super-GCM uses a CSRM with much smaller domain compared to the grid cell of the GCM to represent a ‘sample’ of the grid cell of the GCM, analogous to a population sample used in an opinion poll. The CSRM computes statistics (precipitation rate and fractional cloudiness, and so on) for the sampled portion of the grid cell column of the GCM, and then these statistics are applied to the entire grid cell column. Some preliminary experiments by Grabowski show that such idea is very successful (Grabowski et al. 2001).

The “super-GCM” idea can be incorporated in our construction of the global WRF models for Jupiter and Saturn in current computation ability. We can use a mesoscale WRF model in small portion of each grid cell of global WRF model as a sample or use the mesoscale WRF model in small portion of the grid cell of other good GCMs of Jupiter and Saturn (e.g., EPIC 4.0 developed by Tim Dowling).
4. Other applications
No doubt, a successful modified WRF model can be used to study other important features of atmospheres of Jupiter and Saturn (e.g., white Ovals and large-scale waves). In addition, the modified WRF model will be expected to study the atmospheric processes in the other two giant planets (Uranus and Neptune).

References:


