Icarus 229 (2014) 355–377

Contents lists available at ScienceDirect

Icarus

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

Intercomparison of general circulation models for hot extrasolar planets

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ARTICLE INFO

Article history:
Received 11 April 2013
Revised 20 November 2013
Accepted 20 November 2013
Available online 1 December 2013

Keywords:
Extra-solar planets
Atmospheres, dynamics
Meteorology

ABSTRACT

We compare five general circulation models (GCMs) which have been recently used to study hot extrasolar planet atmospheres (BOB, CAM, IGCM, MITgcm, and PEQMOD), under three test cases useful for assessing model convergence and accuracy. Such a broad, detailed intercomparison has not been performed thus far for extrasolar planets study. The models considered all solve the traditional primitive equations, but employ different numerical algorithms or grids (e.g., pseudospectral and finite volume, with the latter separately in longitude–latitude and 'cubed-sphere' grids). The test cases are chosen to cleanly address specific aspects of the behaviors typically reported in hot extrasolar planet simulations: (1) steady-state, (2) nonlinearly evolving baroclinic wave, and (3) response to fast timescale thermal relaxation. When initialized with a steady jet, all models maintain the steadiness, as they should—except MITgcm in cubed-sphere grid. A very good agreement is obtained for a baroclinic wave evolving from an initial instability in pseudospectral models (only). However, exact numerical convergence is still not achieved across the pseudospectral models: amplitudes and phases are observably different. When subject to a typical 'hot-Jupiter'-like forcing, all five models show quantitatively different behavior—although qualitatively similar, time-variable, quadrupole-dominated flows are produced. Hence, as have been advocated in several past studies, specific quantitative predictions (such as the location of large vortices and hot regions) by GCMs should be viewed with caution. Overall, in the tests considered here, pseudospectral models in pressure coordinate (PEBOB and PEQMOD) perform the best and MITgcm in cubed-sphere grid performs the worst.

1. Introduction

Carefully testing general circulation models (GCMs) of extrasolar planets is important for understanding the physical properties of the atmospheres and for attaining confidence in the complex models themselves. Intercomparison of full GCMs, as well as benchmarking of dynamical cores and testbed models against 'standard solutions', are common in Earth studies (e.g., Held and Suarez, 1994; Boer and Denis, 1997; Polvani et al., 2004; Jablonowski and Williamson, 2006). Intercomparisons are also becoming more common for circulation models of other Solar System planets (e.g., Lebonnois et al., 2013). However, similar intercomparisons have not been performed for models of hot extrasolar planets. Given that the conditions of many extrasolar planets are markedly different than the Earth—and much more exacting on the circulation models—it is useful to subject the models to tests which are appropriate for extrasolar conditions (e.g., Thrastarson and Cho, 2011).

Thus far, only Rauscher and Menou (2010) and Heng et al. (2011) have explicitly attempted to intercompare simulations of hot extrasolar planets performed with different GCMs. The former study attempts to compare their results using the Intermediate General Circulation Model (Blackburn, 1985) with those reported in Cooper and Showman (2005) using the ARIES/GEOS model (Suarez and Takacs, 1995). However, while qualitatively similar features were observed, the comparison was somewhat inconclusive because the model setup was not identical. In their studies using the Community Atmosphere Model (Collins et al., 2004); Thrastarson and Cho, 2010, 2011 have shown sensitivity to initial condition, as well as thermal relaxation and explicit numerical dissipation specifications. A clearer comparison than in Rauscher and Menou (2010) has been presented in Heng et al. (2011). In the latter study, time-mean zonally-averaged (i.e., longitudinally-averaged) fields are presented from simulations with the Flexible Modeling System (Anderson et al., 2004), using two different types of numerical algorithm (pseudospectral and finite volume). However, while zonal and temporal averaging is somewhat justifiable for rapidly rotating planets, the procedure is less useful for the more slowly rotating planets, such as those considered in the

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0019-1035/$ - see front matter
http://dx.doi.org/10.1016/j.icarus.2013.11.027

study: the averaging can destroy dynamically-significant flow structures, as well as conceal subtle numerical and coding errors.[1]

In addition to the setup not being same or systematic across different models, the inconclusiveness of the past comparisons and the general variability of the model results stem from the fact that the models employ different numerical algorithms, grids, and coordinates to solve the governing equations—as we shall show in this work. Moreover, the numerical parameters of the model calculations are often not described explicitly in the literature, or even in the technical documentations of the models themselves. Thus, it has been difficult to ascertain which differences between model outputs are due to the model and which are due to the setup. Here, we perform a careful comparison of five GCMs recently used to study hot extrasolar planet atmospheres. The GCMs are: BOB[2], CAM[3], IGCM[4], MITgcm[5], and PEQMOD[6]. They have been used, for example, in the following extrasolar planet circulation studies: BOB (Beaulieu et al., 2011; Polichtchouk and Cho, 2012), CAM (Thrastarson and Cho, 2010, 2011), IGCM (Menou and Rauscher, 2009; Rauscher and Menou, 2010), MITgcm (Showman et al., 2009; Lewis et al., 2010), and PEQMOD (Cho and Polichtchouk, in preparation).

The five GCMs are submitted to three tests which are useful for assessing model convergence and accuracy. The tests are chosen to specifically address three features that have been typically reported in hot extrasolar planet atmospheric flow simulations: (1) steady flow, (2) nonlinear baroclinic wave, and (3) response to a fast timescale thermal relaxation. We stress that, in addition to their good range and relevance, the tests are purposely chosen with reproducibility of the results in mind: the tests are not difficult to set up and full descriptions of the test cases (as well as the GCMs tested) are provided, along with all of the model parameter values used in the simulations (see Appendix A)—as per our usual practice. We are also happy to share all source codes and input files/parameters used in this study. Note that the emphasis in this work is on models tested in their 'default configuration' (i.e., essentially as they are unpacked), modulo minor modifications to facilitate equatable (as well as equitable)[7] comparisons.

The overall plan of the paper is as follows. In Section 2, we review the governing equations solved by the five GCMs and describe the discretization and dissipation schemes used in the models. In Section 3, the three test cases are carefully described and the results from the tests are presented in turn. Both *inter*-model and *intra*-model comparisons are presented in detail, where the former comparison refers to 'between different models' and the latter comparison refers to 'within a single model'. The aim of this section—indeed, of this entire paper—is to permit one to go beyond broad-brush comparisons based on strongly dissipated/constrained or averaged fields. In Section 4, summary and conclusions are given, along with some discussion of implications of this work.

2. Dynamical cores and test cases

2.1. Dynamical cores

The GCMs—or, more precisely, their 'dynamical cores'—discussed in this work all solve the hydrostatic primitive equations for the 'dry' atmosphere. The dynamical core is essentially that part of the GCM which remains when all the sophisticated physical parameterizations (e.g., convection, radiation, wave-drag, etc.) have been stripped away: it is the engine of the GCM. In this paper, we refer to 'GCMs' and 'dynamical cores' interchangeably, as the distinction is not particularly important here. None of the sophisticated physical parameterizations are used in any of the models for the comparisons: only a crude heating/cooling scheme is used in one of the test cases. In general, it is prudent to test and characterize the core before moving onto the full GCM.[8]

The equations solved govern the large-scale dynamics of planetary atmospheres (e.g., Holton, 1992; see also Cho (2008) for some discussions relevant to the current work). Given that the GCMs tested solve the equations in different vertical coordinate systems (e.g., pressure, sigma, eta—see below), we first present and discuss the equations in the generalized vertical coordinate, s. In the s-coordinate, the hydrostatic primitive equations read (Kasahara, 1974):

$$\frac{\mathrm{D}\mathbf{v}}{\mathrm{D}t} = -\frac{1}{\rho}\nabla_s p - g\nabla_s z - f\mathbf{k}\times\mathbf{v} + \mathcal{F}_{\mathbf{v}} + \mathcal{D}_{\mathbf{v}} \tag{1a}$$

$$\frac{\mathrm{D}\theta}{\mathrm{D}t} = \frac{\theta}{c_p T}\dot{q}_{\mathrm{net}} + \mathcal{D}_\theta \tag{1b}$$

$$\frac{\partial p}{\partial s} = -\rho g\frac{\partial z}{\partial s} \tag{1c}$$

$$0 = \frac{\partial}{\partial s}\left(\frac{\partial p}{\partial t}\right)_s + \nabla_s\cdot\left(\mathbf{v}\frac{\partial p}{\partial s}\right) + \frac{\partial}{\partial s}\left(\dot{s}\frac{\partial p}{\partial s}\right), \tag{1d}$$

where

$$\frac{\mathrm{D}}{\mathrm{D}t} \equiv \left(\frac{\partial}{\partial t}\right)_s + \mathbf{v}\cdot\nabla_s + \dot{s}\frac{\partial}{\partial s}.$$

Here, $\mathbf{v}(\mathbf{x},s,t) = (u,v)$ is the (zonal, meridional) velocity in the frame rotating with $\boldsymbol{\Omega}$, the planetary rotation vector, and $\mathbf{x}\in\mathbb{R}^2$; $\dot{s}\equiv \mathrm{D}s/\mathrm{D}t$ is the generalized vertical velocity; $z = z(\mathbf{x},s,t)$ is the physical height, directed locally upward (in the direction of the unit vector $\mathbf{k}$); ∇_s is the two-dimensional (2D) gradient operator, operating along constant surfaces of $s = s(\mathbf{x},z,t)$; $\rho(\mathbf{x},s,t)$ is the density; $p(\mathbf{x},s,t)$ is the pressure; $f = 2\Omega\sin\phi = 2\boldsymbol{\Omega}\cdot\mathbf{k}$ is the Coriolis parameter, where ϕ is the latitude; $\mathcal{F}_{\mathbf{v}}(\mathbf{x},s,t)$ represents momentum sources; $\mathcal{D}_{\mathbf{v}}(\mathbf{x},s,t)$ and $\mathcal{D}_\theta(\mathbf{x},s,t)$ represent momentum and potential temperature sinks, respectively; g is the gravitational acceleration, assumed to be constant and to include the centrifugal acceleration contribution; $\theta(\mathbf{x},s,t) = T(p_{\mathrm{r}}/p)^\kappa$ is the potential temperature, where $T(\mathbf{x},s,t)$ is the temperature, p_{r} is a constant reference pressure, and $\kappa = \mathcal{R}/c_p$, with $\mathcal{R}$ the specific gas constant and c_p the constant specific heat at constant pressure; and, $\dot{q}_{\mathrm{net}}(\mathbf{x},s,t)$ is the *net* diabatic heating rate (i.e., heating minus cooling).

The set of equations, (1a)–(1d), is closed with the ideal gas equation of state, $p = \rho\mathcal{R}T$. The equation set is also supplemented with the boundary conditions,

$$\dot{s} = 0 \qquad \text{at} \quad s = s_T \tag{2a}$$

$$\dot{s} = \frac{\partial s_B}{\partial t} + \mathbf{v}_B\cdot\nabla s_B \qquad \text{at} \quad s = s_B. \tag{2b}$$

Here, s_T is the boundary surface at the top; s_B is the boundary surface at the bottom, at a fixed altitude above the reference height ($z = 0$); and, $\mathbf{v}_B$ is horizontal velocity at the bottom surface. Boundary conditions (2) imply no mass transport through the upper and lower boundary surfaces. Note, if the lower boundary coincides with a constant s-surface (i.e., $s_B \neq s_B(\mathbf{x},t)$), then the boundary condition (2b) simply reduces to

$$\dot{s} = 0 \quad \text{at} \quad s = s_B. \tag{3}$$

[1] During the preparation of this manuscript another study, by Bending et al. (2013) appeared that compares their results with those of Menou and Rauscher (2009). The authors of the new study report that they are not able to reproduce precisely the results of the older study, although both studies use the same dynamical core (Section 2.1).

[2] *Built on Beowolf* (Scott et al., 2003).

[3] *Community Atmosphere Model – version 3.0* (Collins et al., 2004).

[4] *Intermediate General Circulation Model* (Blackburn, 1985).

[5] *MIT general circulation model – checkpoint64d* (Adcroft et al., 2012).

[6] *Primitive Equations Model* (Saravanan, 1992).

[7] Equitable refers to 'impartial' or 'fair', and equatable refers to 'equivalent' or 'comparable'.

[8] Note that, in comparisons of full GCMs for the Earth, model differences generally increase when physics parameterizations are included (e.g., Blackburn et al., 2013).