The dynamical range of global circulations — II

Gareth P Williams

Geophysical Fluid Dynamics Laboratory/NOAA, Princeton University, Princeton, NJ 08542, USA

Abstract. The dynamical range of global atmospheric circulations is extended to specialized parameter regions by evaluating the influence of the rotation rate (Ω) on axisymmetric, oblique, and diurnally heated moist models. In Part I, we derived the basic range of circulations by altering Ω for moist and dry atmospheres with regular and modified surfaces. Again we find the circulations to be composed of only a few elementary forms. In axisymmetric atmospheres, the circulations consist of a single jet in the rotational midrange (Ω* = 1/2-1) and of double jets in the high range (Ω* = 2-4), together with one or two pairs of Hadley and Ferrel cells; where Ω* = Ω/ΩE is the rotation rate normalized by the terrestrial value. These circulations differ from those predicted by first-order symmetric-Hadley (SH1) theory because the moist inviscid atmosphere allows a greater nonlinearity and prefers a higher-order meridional mode. The axisymmetric circulations do, however, resemble the mean flows of the natural system — but only in low latitudes, where they underlie the quasi-Hadley (QH) element of the MOIST flows. In midlatitudes, the axisymmetric jets are stronger than the natural jets but can be reduced to them by barotropic and baroclinic instabilities. Oblique atmospheres with moderate to high tilts (θp = 25°-90°) have the equator-straddling Hadley cell and the four basic zonal winds predicted by the geometric theory for the solstitial-symmetric-Hadley (SSH) state: an easterly jet and a westerly tradewind in the summer hemisphere, and a westerly jet and an easterly tradewind in the winter hemisphere. The nonlinear baroclinic instability of the winter westerly produces a Ferrel cell and the same eddy fluxes as the quasi-geostrophic QG element, while the instability of the summer easterly jet produces a QG-Hadley (QGH) element with a unique, vertically bimodal eddy momentum flux. At high θp and low Ω*, the oblique atmospheres reach a limiting state having global easterlies, a pole-to-pole Hadley cell, and a warm winter pole. At low tilts (θp < 10°), the oblique circulations have a mix of solstitial and equinoctial features. Diurnal heating variations exert a fundamental influence on the natural-Hadley (NH) circulations of slowly rotating systems, especially in the singular range where the zonal winds approach extinction. The diurnality just modifies the NH element in the upper singular range (1/4s < Ω* < 1/6), but completely transforms it into a subsolar-antisolar Halley circulation in the lower singular range (0 ≤ Ω* < 1/6). In the modified NH flows, the diurnality acts through the convection to enhance the generation of the momentum-transferring planetary waves and, thereby, changes the narrow polar jets of the non-diurnal states into broad, super-rotating currents. Circulation theory for these specialized flows remains rudimentary. It does not explain fully how the double jets and the multiple cells arise in the axisymmetric atmospheres, how the QGH element forms in the oblique atmospheres, or how waves propagate in the slowly rotating diurnal atmospheres. But eventually all theories could, in principle, be compared against planetary observation: with Mars testing the QGH elements; Jupiter, the high-range elements; Titan, the equinoctial and solstitial axisymmetric states; and Venus, the diurnally modified NH flows.

1 Introduction

We continue the presentation, begun in Part I (Williams 1988), of the circulation set generated by varying some of the fundamental external pa-
rameters and internal physical factors that control the dynamics of a terrestrial global circulation model (GCM). The solutions are developed for two purposes: (1) to study basic circulation dynamics by altering the scale and mix of the jets, cells and eddies; and (2) to broaden the perspective on planetary and terrestrial climates by defining the dynamical range and the parametric variability of global circulations. In presenting the solutions, we again explore the hypothesis that circulation variability is limited to the mix of a few elementary components that can be understood in terms of standard theories.

In Part I, we derived the basic range of circulations by altering the rotation rate ($\Omega$) and, hence, the Rossby and Froude numbers of moist and dry models driven by a symmetric annual-mean heating. The resulting flows were described in terms of four elementary components, and interpreted in terms of standard symmetric-Hadley (SH) and quasi-geostrophic (QG) theories. We found that a natural-Hadley (NH) element and a tropical quasi-Hadley (QH) element prevail at low and high $\Omega$, respectively, and that a momentum-traversing (QG$_s$) element and a momentum-converging (QG$_v$) element occur in baroclinically unstable midlatitudes at medium and high $\Omega$, respectively. The scales and interactions of these elements lack a full theoretical explanation and deviations occur at transitions and at parameter extremes.

Now, in Part II, we extend the parameter range into three specialized regions, all unrelated but all involving some form of latitudinal or longitudinal asymmetry, by evaluating the influence of $\Omega$ on axisymmetric, oblique, and diurnally heated GCMs. The three solution sets are obtained for three basic (but diverse) purposes: (1) to isolate the SH modes of the moist GCM; (2) to define the dynamics of the tropical easterly jets; and (3) to examine the transitions undergone by the NH element as $\Omega \to 0$. The solutions also examine how the axisymmetric flows differ from the natural ones when the barotropic and baroclinic instabilities are suppressed, how the solstitial flows differ from the equinoctial ones when an extreme seasonality is allowed, and how the diurnal flows differ from the nondiurnal ones at very low $\Omega$. As in Part I — to which the reader is referred for notation and terminology — we assume that the GCM is valid in these parameter ranges and that a qualitative comparison between the solutions and the theory is meaningful. We also use the same standard methods for defining and analyzing the circulations, although these are clearly less useful for the eddy-free axisymmetric states and the eddy-dominant Halley flows.

We begin in §2 with the AXISYMMETRIC set, created by omitting the large-scale longitudinal variations from the basic GCM and by varying the rotation rate over the main range of interest, from $\Omega^* = \frac{1}{2}$ to 4; where $\Omega^* = \Omega/\Omega_E$ is the rotation rate normalized by the terrestrial value. To explain the solutions, we turn to the first-order symmetric-Hadley (SH$_1$) theory of Held and Hou (1980) — the most successful attempt at defining the symmetric-Hadley state for Earth’s atmosphere since Lorenz’s (1969) review (see §1-3.1). This SH$_1$ theory allows for latent heating implicitly, by localizing the cell upflow at the equator, but moisture is not included in the associated numerical modeling. Our AXISYMMETRIC model, on the other hand, includes latent heating explicitly, so we can define the SH modes of moist atmospheres and estimate their contribution to the natural MOIST circulations.

The AXISYMMETRIC solutions turn out to have a more complex bearing on the MOIST states than expected because the thermodynamic forcing changes greatly — the baroclinicity doubles — when the eddies are suppressed in a model that determines its own surface temperature ($T_s$). The AXISYMMETRIC solutions are also more complex than the SH$_1$ states because the meridional circulations are more nonlinear when the free atmosphere is fully inviscid, and when the latent heating amplifies the upflows; the SH$_1$ theory explains only the simplest symmetric states. Axisymmetric circulations are generally more sensitive than natural circulations to the subgrid formulations and the surface conditions, so bridging the gap between the two systems requires a hierarchy of models with different parameterizations.

We proceed to the OBLIQUE set in §3 to examine the dynamics of the solstitial circulations. Only the summer flows are really sensitive to the interhemispheric heating asymmetries and, in the solstitial limit, they contain a negative baroclinicity, an unstable easterly jet, and an equator-straddling Hadley cell. To define the main range of solstitial circulations and to isolate their invariants, we vary the obliquity $\theta_p$ from $10^\circ$ to $90^\circ$ and the rotation rate $\Omega^*$ from $\frac{1}{2}$ to 4 for a moist GCM. The equinoctial or minimal-tilt states, on the other hand, are adequately described by a GCM forced by an annual-mean heating, as in Part I.

To understand the OBLIQUE solutions, we must first define the solstitial-symmetric-Hadley (SSH) state for the hot-pole limit by modifying the geometric (equinoctial) SH$_1$ theory. Then, to