An Introduction to

The Global Circulation of the Atmosphere

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About the Cover

This image (actually pieced together from multiple images) was acquired on December 8, 1992, by NASA’s Galileo spacecraft, as it swung by Earth on its way out to Jupiter. It shows a wonderful but physically impossible view of the Southern Hemisphere. A substantial fraction of the image should be in darkness, even though the image depicts a time near the summer solstice of the Southern Hemisphere. This view was created by patching together a mosaic of several images taken by Galileo over a 24-hour period, and remapping them as they would be seen from above the pole. South America, Africa, and Australia are respectively seen at the middle left, upper right, and lower right.

Of particular interest are the beautiful cloud patterns associated with extratropical cyclones in the storm track ringing Antarctica. This picture is reminiscent of photos of “dishpan” experiments, in which aspects of the global circulation are simulated in a rotating, differentially heated laboratory tank.
Announcements

Subject: The global circulation of the atmosphere
Text: Class notes
Course grade: Based entirely on homework, including some projects
Schedule: Classes will be missed occasionally. Make-ups will be scheduled. A calendar showing class meetings will be distributed early in the semester, and past experience suggests that not many changes will be needed.

An Introduction to the Global Circulation of the Atmosphere
Web page for AT605

http://kiwi.atmos.colostate.edu/group/dave/at605.html

QuickStudies are available at

http://kiwi.atmos.colostate.edu/group/dave/QuickStudies.html
### Handy Numbers

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius of the Earth</td>
<td>$6.37 \times 10^6$ m</td>
</tr>
<tr>
<td>Angular velocity of the Earth’s rotation</td>
<td>$7.29 \times 10^{-5}$ s$^{-1}$</td>
</tr>
<tr>
<td>Acceleration of Earth’s gravity</td>
<td>$9.81$ m s$^{-2}$</td>
</tr>
<tr>
<td>Globally averaged surface pressure</td>
<td>$984$ hPa</td>
</tr>
<tr>
<td>Density of air near sea level</td>
<td>$1.2$ kg m$^{-3}$</td>
</tr>
<tr>
<td>Annual mean incident solar radiation</td>
<td>$340$ W m$^{-2}$</td>
</tr>
<tr>
<td>Global albedo</td>
<td>$0.30$</td>
</tr>
<tr>
<td>Outgoing longwave radiation</td>
<td>$240$ W m$^{-2}$</td>
</tr>
<tr>
<td>Globally averaged surface air temperature</td>
<td>$288$ K</td>
</tr>
<tr>
<td>Globally averaged precipitable water</td>
<td>$25$ mm ($= 25$ kg m$^{-2}$)</td>
</tr>
<tr>
<td>Globally averaged precipitation rate</td>
<td>$3$ mm day$^{-1}$</td>
</tr>
<tr>
<td>Latent heat of condensation at $0$ °C</td>
<td>$2.52 \times 10^6$ J kg$^{-1}$</td>
</tr>
<tr>
<td>Stefan-Boltzman constant</td>
<td>$5.67 \times 10^{-8}$ W m$^{-2}$ K$^{-4}$</td>
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<tr>
<td>$c_p$ for dry air</td>
<td>$1000$ J kg$^{-1}$ K$^{-1}$</td>
</tr>
<tr>
<td>Gas constant for dry air</td>
<td>$287$ J kg$^{-1}$ K$^{-1}$</td>
</tr>
<tr>
<td>Molecular viscosity of air</td>
<td>$1.5 \times 10^{-5}$ m$^2$ s$^{-1}$</td>
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</table>
General References


Preface

This is a graduate-level introductory overview of the global circulation of the atmosphere, a subject that is closely tied to atmospheric dynamics. A course on dynamics tends to focus on basic physical concepts and methods for their analysis, however, while a course on the global circulation must focus on what the atmosphere actually does, and why. Graduate-level studies in atmospheric dynamics are essential as preparation for reading this book, and students will learn some additional dynamics in the process of reading the book.

It is difficult to draw a line between the global circulation and climate. The two subjects are growing closer together, as the roles of heating and dissipation in the global circulation emerge as key issues. Such topics as monsoons, the hydrologic cycle, and the planetary energy budget can be included under either “climate” or “global circulation,” although perhaps with different slants. Climate is the bigger subject. This book skirts the edges of physical climatology.

The subject is much too broad to cover in one book, so I have had to make choices. Several parts of the book stress the role of cloud systems and other small-scale processes in the workings of the global circulation. Isentropic coordinates are used extensively. Energetics are discussed in some detail. There is a chapter on the global circulation as turbulence, including an extended section on the chaotic nature of the circulation.

This is a graduate-level book, based on classes that I have taught at Colorado State University over the past twenty-five years. The level of difficulty is set so as to maximize the potential benefit to the strongest students in the class; if they work very hard, they should just barely be able to master the material. It will be worth the effort. This is a beautiful subject.

A lot of work is involved in putting together these course notes. For several years, Michelle Beckman very professionally made many additions and corrections to the notes. She also developed and applied the formatting that you see, and combined the many separate documents into a unified “book.” The notes would be much less useful without her contributions.

Mark Branson, Don Dazlich, Kelley Wittmeyer, and Mike Kelly have ably assisted in the production of some of the figures. Mark in particular made a huge contribution. Mike Kelly, Cara-Lyn Lappen, Katherine Harris, Stefan Tulich, Anning Cheng, Mike Toy, Kyle Wiens, Cristiana Stan, Jason Furtado, Maike Ahlgrim, Luke Van Roekel, Levi Silvers, and Matt Masarik performed superbly as Teaching Assistants for the course, and both the students and I learned as a result of their efforts.

Mick Christi, Kate Musgrave, and Kevin Mallen pointed out numerous typos and other errors in the text.

Finally, I am grateful to the many students who took my global circulation over the years; their questions and suggestions have led to major improvements.

David Randall
Tuesday, January 14, 2014
Outline of the class content

1. Introduction
The nature of the subject
A brief overview

2. What makes it go?
The Earth’s radiation budget: An “upper boundary condition” on the general circulation
Surface boundary conditions
Energy and moisture budgets of the surface and atmosphere

3. An overview of the observations
The global distribution of atmospheric mass
Zonal wind
Meridional wind
Geopotential height
Vertical velocity and the mean meridional circulation.
Angular momentum
Temperature
A view in potential temperature coordinates
The global distribution of water vapor
Precipitation
A quick introduction to the effects of large-scale eddies on the zonally averaged circulation
A view from theta coordinates
Lots of questions

4. Conservation of momentum and energy
Conservation of momentum on a rotating sphere
Conservation of kinetic energy and potential energy
Conservation of thermodynamic energy
Conservation of total energy
Static energies
Entropy
Approximations
The mechanical energy equation in other vertical coordinate systems
The effects of turbulence

5. The mean meridional circulation
The observed meridional transports of energy and moisture
A simple theory of the Hadley circulation
Extension to other planetary atmospheres
Particle trajectories on the sphere: A partial explanation of “bandedness”
6. An overview of the effects of radiation and convection
Convective energy transports
Radiative-convective equilibrium
The observed vertical structure of the atmosphere, and the mechanisms of vertical energy transport
More on moist convection

7. The Energy Cycle
Available potential energy
The gross static stability
The available potential energies of three simple systems
Variance budgets
Generation of available potential energy, and its conversion into kinetic energy
Eddy kinetic energy, zonal kinetic energy, and total kinetic energy
Observations of the energy cycle
The role of heating

8. Planetary-scale waves and other eddies
Free and forced small-amplitude oscillations of a thin spherical atmosphere
Observations of stationary and transient eddies in middle latitudes
Theory of orographically forced stationary waves
Tropical waves
The response of the tropical atmosphere to stationary heat sources and sinks
Monsoons
The Walker Circulation
The Madden-Julian Oscillation

9. Wave-Mean Flow Interactions
Interactions and non-interactions of gravity waves with the mean flow
Vertical propagation of planetary waves
Vertical and meridional fluxes due to planetary waves
Sudden warmings
Eliassen-Palm Theorem-Reprise
The Eliassen-Palm theorem in isentropic coordinates
Potential vorticity fluxes
The quasi-biennial oscillation
Blocking

10. The general circulation as turbulence
Energy and enstrophy cascades
Nonlinearity and scale interactions
Two-dimensional turbulence

An Introduction to the Global Circulation of the Atmosphere
Quasi-two-dimensional turbulence
Dimensional analysis of the kinetic energy spectrum
Observations of the kinetic energy spectrum
The general circulation as a blender
The limits of deterministic weather prediction
Quantifying the limits of predictability
Climate prediction
The World’s Simplest GCM
Pushing the attractors around

11. The future of the global circulation of the atmosphere

Introduction
Hydrologic cycle
Meridional temperature gradient
Storm tracks
Hadley circulation
Tropopause height
ENSO