12.307 Weather and Climate Laboratory
Spring 2009

12.307
Project 4
General Circulation

April 2005

1 Introduction

In this final project, we draw together some of the ideas explored in Labs 1, 2 and 3 and apply them to study, using atmospheric data and a rotating annulus, aspects of the general circulation of the atmosphere.

(Background reading: Chapter 5 and 8 of 12.003 Notes)

2 Atmospheric Data/Climatology

The mean features of the meridional structure of the atmosphere will be illustrated by plotting climatological fields. The climatological data set is part of the NCEP/NCAR reanalysis project (see Kalnay et al 1996, BAMS 77,437-471). Time mean fields from 1982 to 1994 have been computed from the analyzed fields.

To display the data you will use the IRI/LDEO web interface devloped by Columbia University - see Appendix 1.

Plot the zonally averaged temperature (T), meridional wind (v), vertical velocity (ω) (in pressure coordinates - $\omega = Dp/Dt$), and zonal wind u from the NCEP climatology for the months of January (i.e. the average of all the January's between 1982 and 1994) and July (all the July's).

Making use of your plots we will first discuss the Hadley circulation in the Tropics and then go on to discuss the circulation in the extratropics.

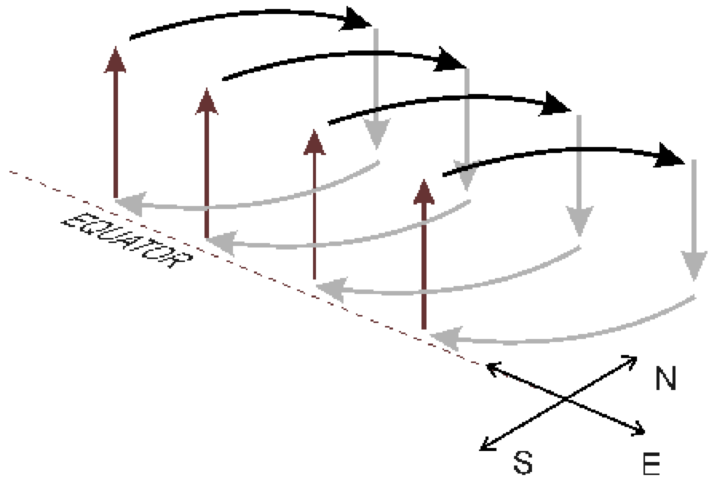


Figure 1: Schematic of the Hadley circulation (showing only the N Hem part of the circulation; there is a mirror image circulation south of the equator).

2.1 The Hadley Circulation

2.1.1 Temperature

As discussed in section 5.1 of 12.003 Notes, the net radiative budget of the Earth-atmosphere system, averaged over the year, shows a net surplus of incoming radiation over the tropics and a net deficit at high latitudes (see Fig 5.4). As a result of this the tropospheric temperature is higher in the tropics than at the poles, as should be evident from your T plot.

If the Earth were not rotating, the circulation driven by this temperature difference would be straightforward, with warm air rising in low latitudes and cold air sinking at high latitudes - see fig.1. Can we see evidence of this in your climatological plots?

2.1.2 Meridional circulation

From the meridional circulation (v, ω) we can indeed see a meridional circulation in the tropics, but notice that the sinking motion is located in the subtropics rather than at high latitudes. The circulation does not extend all the way to the pole because of angular momentum constraints. Near the equator, however, where the Coriolis effect is weak, the equatorial atmosphere acts as if the Earth were not rotating. How far the circulation extends polewards depends (according to theory) on many factors. From the observations we can see that it extends to roughly 30°N.

2.1.3 Zonal wind

Inspect your zonal average zonal wind plot and see if it is consistent with the following discussion.

Consider the upper branch of the Hadley circulation (see Fig.2). As air moves away from the equator, the Coriolis parameter becomes increasingly large, in the northern hemisphere turning the wind to the right, resulting in a westerly component to the flow. Here the flow subsides (producing the desert zone and the "trade inversion" - see discussion in Chapter 7) of 12.003 notes - and returns to the equator at low levels. At these low levels, the Coriolis acceleration, again turning the flow to the right in the northern hemisphere, produces easterly winds: the "trade winds", southeasterly in the northern hemisphere (northeasterly in the southern hemisphere). These surface winds are not nearly as strong as in the upper troposphere, because they are strongly moderated by friction in the near-surface flow. In fact, there must be low level westerlies somewhere: in equilibrium, the net frictional drag (strictly, torque) on the entire atmosphere must be zero, or the total angular momentum of the atmosphere would not be steady. So, the surface winds must be westerly at the poleward edge of the circulation cell, and easterly near the equator.

2.2 Schematic of Hadley circulation

Compare the schematic of the Hadley Circulation - see fig.2 - to the zonally averaged u,v and ω from your climatology and label your plots as in the schematic.

Note that Fig.(2) shows symmetry about the equator (annual-mean conditions). In reality, there are strong asymmetries that shift seasonally. Compare your January and July mean fields.

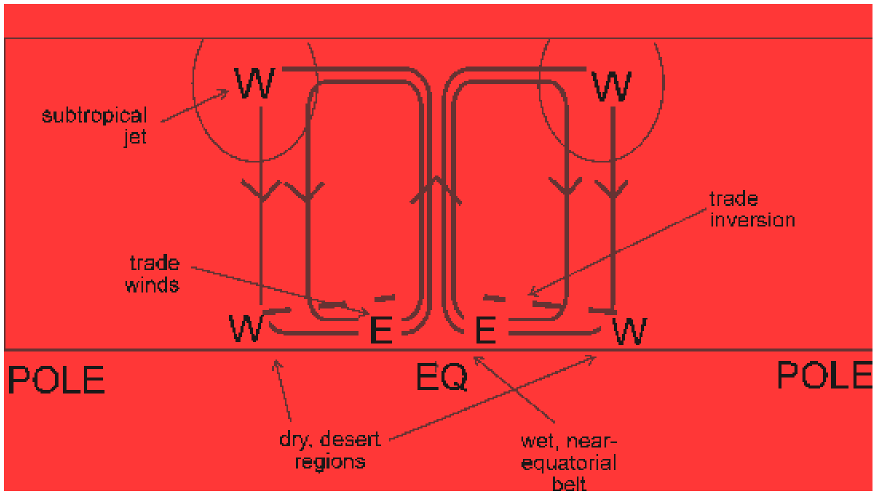


Figure 2: Westerlies are marked W; easterlies E

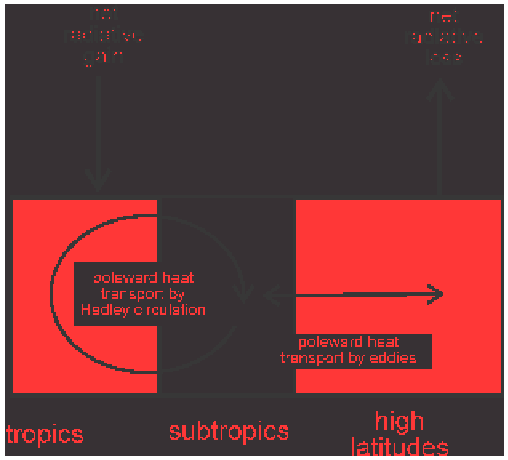
2.3 The Midlatitude circulation

Although the simple Hadley cell model depicted in Fig. 2 describes the tropical regions quite well, it predicts little action in middle and high latitudes. There, the powerful constraints of rotation are dominant, and there can be no meridional circulation. As can be seen from your T plot, however, there are nonzero gradients of temperature in middle latitudes, as well as in the vicinity of the subtropical jet. Thermal wind balance tells us that if T varies with latitude (but not longitude) then - see Lab Project 2 on the thermal wind:

$$\frac{\partial u}{\partial p} = \frac{R}{fp}\left(\frac{\partial T}{\partial y}\right)_p \;;\; \frac{\partial v}{\partial p} = 0 \,.$$

where R is the gas constant. So there is no meridional geostrophic flow (and so no geostrophic meridional circulation), but there is a zonal flow, in thermal wind balance, which since T decreases poleward implies westerly winds increasing with height (decreasing with pressure) - see zonally averaged v.

Even though the purely zonal state is balanced (in the sense that the forces balance), the midlatitude atmosphere is full of *eddies*, which manifest themselves as traveling storm systems. Where do they come from? The atmosphere still has plenty of available potential energy, as evidenced by the



horizontal temperature gradients (cf. our discussion in section 8.3 of 12.003 notes). Tapping of this energy through a meridional overturning is inhibited by rotation, but there are other ways of extracting the energy. The zonal state we have described is *unstable* through a process known as *baroclinic instability*[1]. Through this instability, longitudinally asymmetric motions are generated, within which air parcels are exchanged along sloping surfaces.

The process of baroclinic instability is responsible for the genesis of the ubiquitous waviness of the midlatitude flow; these waves often form closed eddies, especially near the surface, where they are familiar as the high and low pressure systems that control most of our weather. In the process, they also effect the poleward heat transport required to balance the energy budget. The eddies "stir" the atmosphere, tending to minimize the equator-to-pole temperature contrast.

So, in cartoon form, our picture of the low- and high-latitude energy balance looks as shown in Fig. 2.3. Together, these two components of the general circulation effect the poleward heat transport implied by the equator-to-pole radiative imbalance.

2.3.1 Eddy heat transport

As discussed above, weather systems are the primary mechanism of meridional heat transport in middle latitudes: air moving polewards tends to be

[1] "Baroclinic" (as opposed to "barotropic") means that $\rho \neq \rho(p)$— thus horizontal gradients of density and temperature occur along pressure surfaces.

warm compared to air moving equatorwards. Let's try and compute the poleward heat flux due to eddies: $\overline{v'T'}$. It is this eddy transfer that is represented by the horizontal arrow in fig 2.3.

We can use NCEP reanalysis to estimate the eddy heat transport for the month of January 1992, a month of particularly strong eddy activity:

$$\overline{v'T'} = \overline{vT} - \overline{v}\,\overline{T}$$

where the overbar is a time-mean over the month.

Plot the zonal average of $\overline{v'T'}$, $\left[\overline{v'T'}\right]$ defined by:

$$\left[\overline{v'T'}\right] = \frac{1}{x_2 - x_1} \int_{x_1}^{x_2} vT \; dx$$

where $x_2 - x_1 = 2\pi a \cos\varphi$, a is the Earth radius and φ latitude.

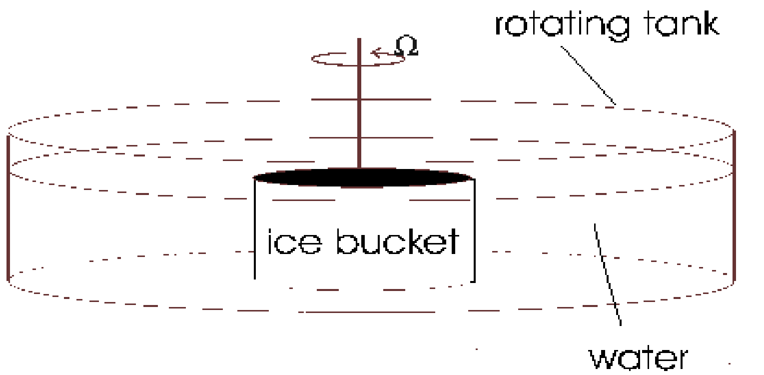
Use your figure - note the units are in $ms^{-1}K$ - to estimate the net northward heat flux by eddies across 45°N, $\mathcal{H}$:

$$\mathcal{H} = c_p \int_{x_1}^{x_2} \int_0^{\infty} \rho \, \overline{v'T'} \; dx \; dz = 2\pi a \cos\varphi \frac{c_p}{g} \int_0^{p_s} \left[\overline{v'T'}\right] \; dp$$

where we have used hydrostatic balance. Compare your estimate with the requirement (from the Earth's radiation budget) that the net (atmosphere and ocean) heat transport must be about 5×10^{15}W.

What fraction of the total is contributed by the eddies?

NOTE - *Specific heat of air at constant pressure* $= 1004\ JK^{-1}kg^{-1}$*; mean surface pressure* $= 1000hPa$*;* $g = 9.81ms^{-2}$*; mean Earth radius* $a = 6371km$*;* 1^o*latitude* $\equiv 111km$*.*



3 Laboratory Experiment

The purpose of the experiment is to observe 'Hadley' and 'eddying' regimes in a differentially heated, rotating fluid annulus. The experimental arrangement is as shown in Fig. 3. It consists of a cylindrical plexiglass tank filled with water to a depth of about 15cm and placed on a rotating table. Initially, the water is of uniform temperature. But centered on the rotation axis, we place a metal bucket filled with ice. This sets up a radial temperature gradient (decreasing "poleward") that will drive motions in the tank. Temperature variations in the tank are monitored at strategic positions using thermisters attached to data loggers. Currents are observed using paper dots, potassium permanganate crystals etc.

'Hadley' and 'eddying' turbulent regimes can be set up in the tank by adjusting the rotation rate, Ω, of the tank - Ω can be ranged from zero to 10 rpm[2] (revolutions per minute).

[2]Note that on the big table the digital readout is the rotation rate in '$milli - f$': thus 1000 is a rotation rate of $1 \times f$, where $f = 2\Omega$ and $\Omega = \frac{2\pi}{\text{period in seconds}}$. The period of rotation is thus:

$$\text{period in seconds} = \frac{4\pi}{f}$$

Thus when the reading is 1000, $f = 1$ and the period is $4\pi = 12.566s$.

3.1 Hadley Circulation

Set the table rotating cyclonically very slowly - $\Omega = 0.3$ rpm. Can you see evidence of a Hadley circulation? Dye streaks should clearly show the thermal wind shear. Can you identify bands of super-rotating fluid - 'westerlies'? Are there any easterlies? Identify the laboratory analogue of the trade wind belt - see fig.(2) where the easterlies are marked E and the westerlies W.

When rotating slowly we observe the development of an axisymmetric circulation in thermal wind balance with the radial temperature gradient. For an incompressible fluid, the thermal wind relation is

$$\frac{\partial u}{\partial z} = -\frac{g\alpha}{2\Omega}\frac{\partial T}{\partial r}$$

where u is the azimuthal current, α is the coefficient of expansion of water and r is the radius. Since T decreases toward the ice-filled bucket, we will see a thermal wind that is super-rotating ("westerlies") in the upper part of the fluid.

3.2 Turbulent eddies

Set the table rotating fast $\Omega = 10$ rpm and wait for the system to reach a steady state. With stronger rotation, meridional overturning will be inhibited. The thermal wind will remain, but will show signs of azimuthal asymmetry. We see the development of waves in the tank, through baroclinic instability, as in the picture on the next page.

Estimate typical horizontal current speeds, u. Estimate the Rossby number, $R_o = \frac{u}{2\Omega L}$ where L is a length of the typical eddying motion you observe.

3.3 Regimes

Vary the rotation rate in (smallish) stages from $\Omega = zero$ to 10 rpm. Let the flow settle down each time. Map the transition from axisymmetric flow through regular waves to turbulent eddies. Compute the Rossby at each stage. How do they compare with that of the Earth's atmosphere?