The general circulation of the atmosphere

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We consider in this note the most general features of the circulation of the atmosphere and try to show that, regardless of the details, we must obtain a circulation much as is observed.

1 Component parts of the general circulation of the atmosphere

The gross features of the observed atmospheric circulation are depicted in Fig.1.

The zonal flow is strongly westerly aloft in middle latitudes — 10 m/s rising to 30 m/s at upper levels in the westerly jetstream — a fact that we can now understand as a straightforward consequence of the decrease of temperature with latitude. Surface winds are constrained to be weak by the action of friction near the ground, and thermal wind balance implies that a poleward decrease of temperature is necessarily accompanied by increasing westerly winds with height. Taken together, these two facts require a zonal flow in middle latitudes that increases from near zero at the ground to strong westerlies at altitude.

But at the surface we cannot have westerly flow everywhere because it would imply a net torque on the Earth. So there must be easterlies at the surface somewhere. Now let's suppose, guided by observations — Fig.1 (middle) — that there are easterlies at the ground in the tropics, with westerlies in middle latitudes.

Now the winds at the surface are, to a first approximation, in geostrophic balance and so to balance the Coriolis torque we must invoke a pressure-gradient force. Thus we can deduce that there must be a SUBTROPICAL

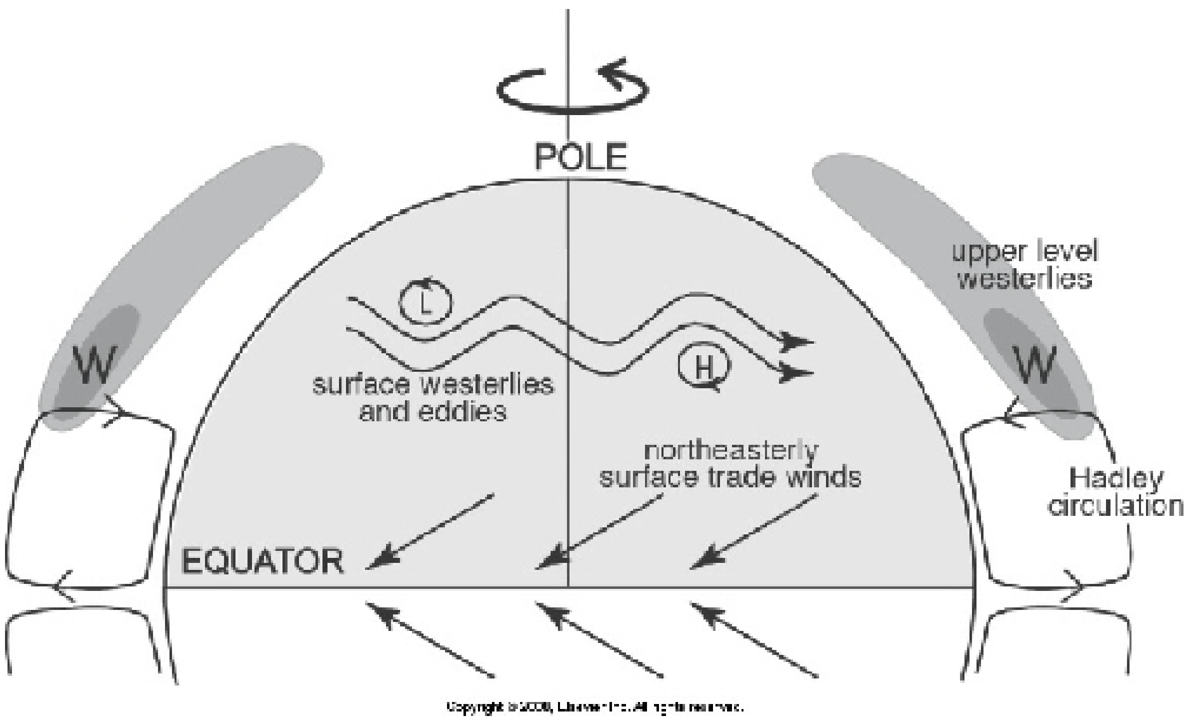
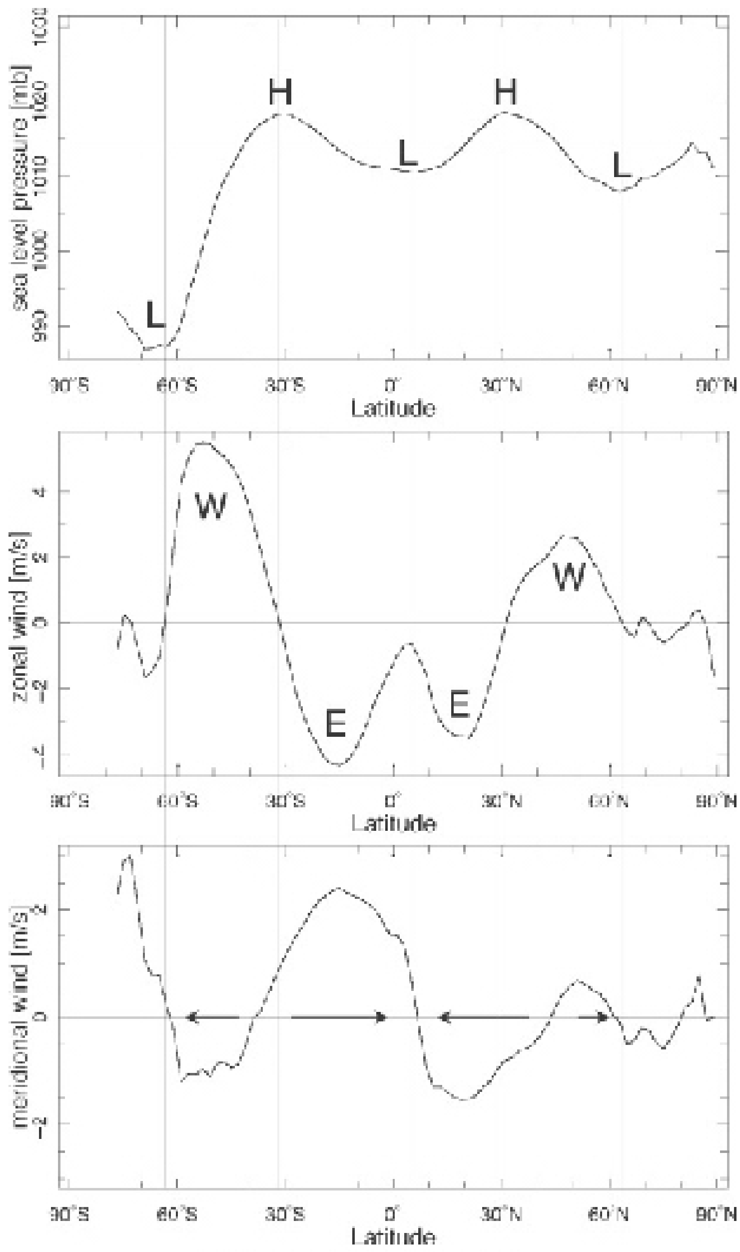


Figure 1: Schematic of the observed atmospheric general circulation for annual-averaged conditions. The upper level westerlies are shaded to reveal the core of the subtropical jet stream on the poleward flank of the Hadley circulation. The surface westerlies and surface trade winds are also marked. Only the northern hemisphere is shown. The vertical scale is greatly exaggerated.


sea level pressure [mb]
zonal wind [m/s]
meridional wind [m/s]
Latitude
H
L
W
E

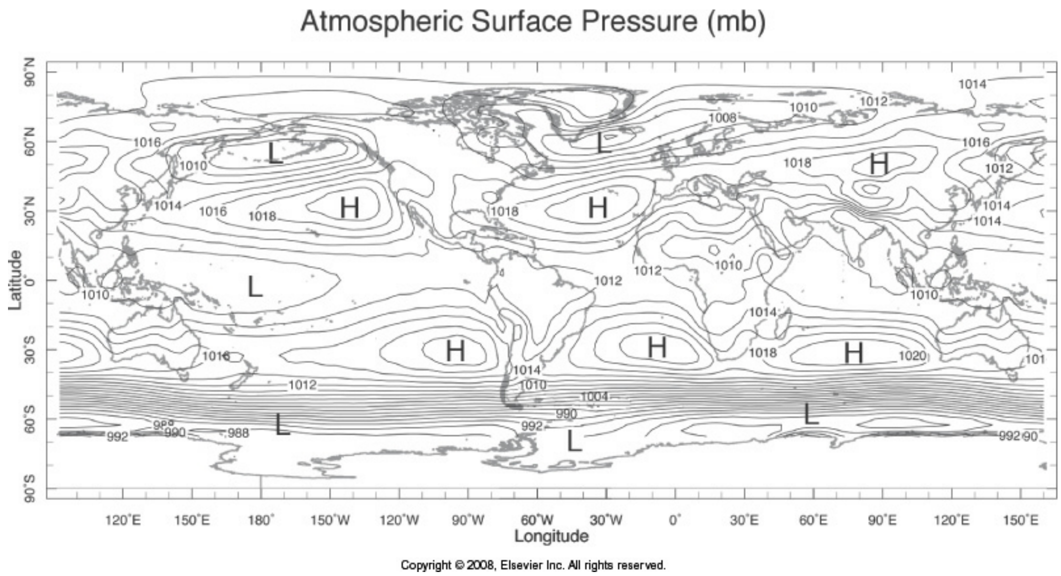


Figure 2: The annual-mean surface pressure field in mb. Contour interval 5 mb.

HIGH at the surface, with a belt of low pressure to the north, as is seen in Fig.1(top panel) and Fig.2.

In the absence of frictional processes, the wind blows along the isobars suggesting a purely zonal flow in the steady state. But the wind at the ground is affected by the nature of the underlying surface and so, particularly over land where frictional drag can be strong, the surface wind is sub-geostrophic i.e. not quite strong enough for Coriolis torques to completely balance the pressure-gradient force. Air parcels thus 'fall down' the pressure gradient slightly, from high to low pressure. Thus the observed surface wind has a pronounced component across the pressure gradient directed from high to low (Fig.1 — bottom panel) This frictionally-induced surface flow drives a meridional circulation (a circulation in the north-south plane) — forming the Ferrel Cell and, in part, the Hadley Cell too. This can be seen in Fig.3.

Thus we see that in:

- middle-latitudes — low-level convergence forces ascent — lows and CYCLONES — precipitation
- subtropics — low-level divergence and descent — highs and ANTICYCLONES — deserts.

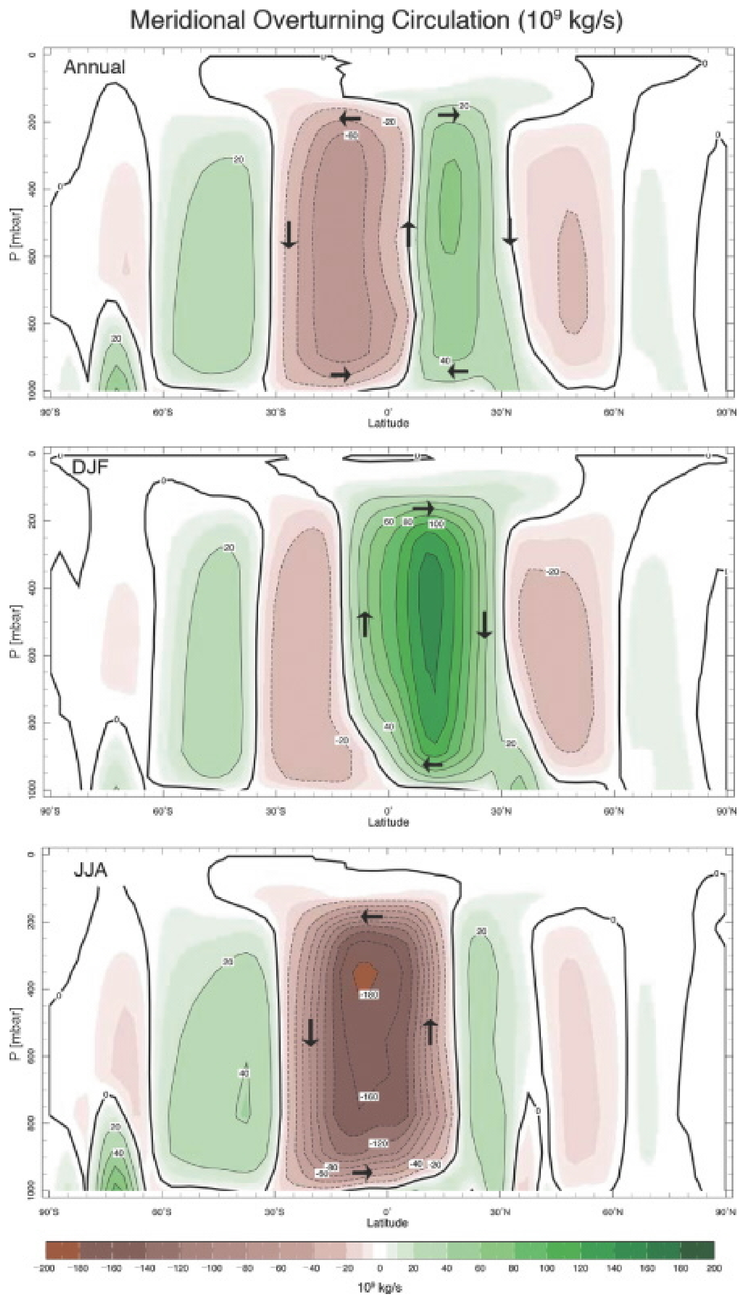


Figure 3: The meridional overturning streamfunction of the atmosphere in annual mean, DJF and JJA conditons. Units are in 10^{10}kg/sec. Flow circulates around positive (negative) centers in a clockwise (anti-clockwise) sense. Thus, in the annual mean, air rises just north of the equator and sinks around $\pm 30^o$.

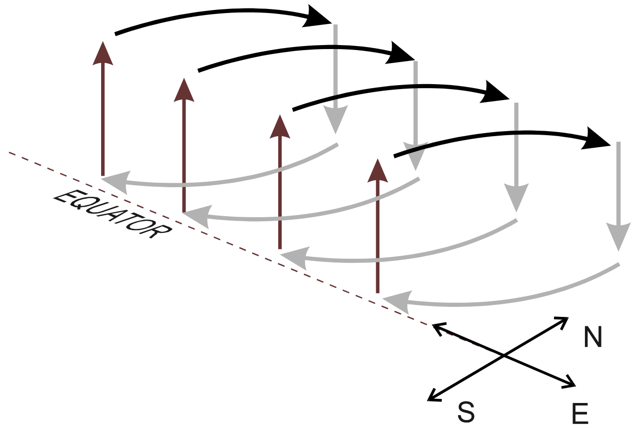


Figure 4: Schematic of the Hadley circulation (showing only the N Hem part of the circulation; there is a mirror image circulation south of the equator).

1.1 Hadley Circulation

In the Hadley circulation there is a tendency to conserve angular momentum with westerlies aloft as air moves polewards and surface easterlies — the trades — as air moves equatorward at the ground — see Fig.4. The TRADE WINDS (rather steady both in direction and speed) in the northen hemisphere are thus north-easterly, in the southern hemisphere they are south-easterly. In the region where they meet — the Doldrums — we find low pressure, light irregular winds, lots of vigorous convective activity and generally upward motion — the Inter-Tropical-Convergence-Zone — known as the ITCZ.

So, as shown in Fig.5, the surface winds are expected to be westerly at the poleward edge of the circulation cell, and eastward near the equator. This is similar to the observed pattern (see Fig.1 middle panel), but not quite the same: in reality the surface westerlies are located poleward of the subtropical jet.

1.2 The extra-tropical circulation

On the poleward side of the subtropical high we observe generally westerly winds extending all the way down to the ground. The flow is not axisymmetric, however. There are large-amplitude waves, troughs and ridges with scales of typically a few thousand kilometers. This is the main region

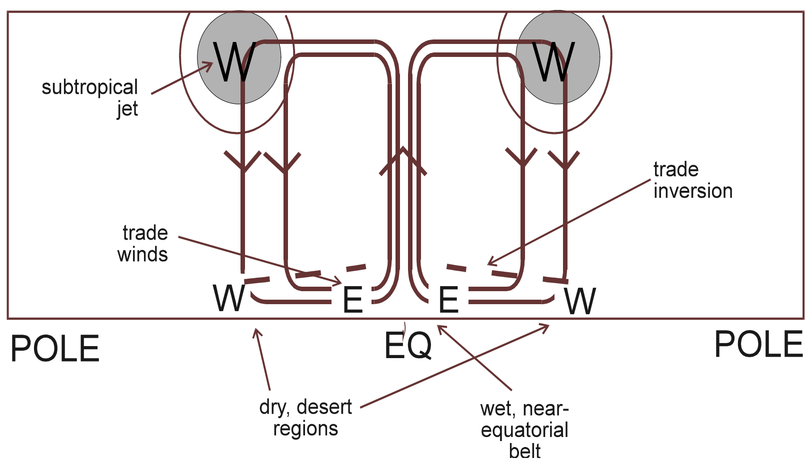


Figure 5: A schematic diagram of the Hadley circulation and its associated zonal flows and surface circulation.

of frontal and cyclonic activity - we see a succession of migrating cyclones — WEATHER SYSTEMS — causing frequent changes in wind direction. The weather systems organise themselves to efficiently transfer heat and angular momentum from the equator to middle latitudes.

Superimposed on these high-frequency weather systems there are large-scale zonal (longitudinal) variations in patterns of winds (they are called PLANETARY WAVES) induced by topography (mountain ranges such as the Rockies) and the thermal contrast between the land and sea. Finally there are MONSOONal circulations driven by seasonal variations in the thermal contrasts between large continental land masses such as Asia and the adjacent ocean. These are so strong that they may induce cross-equatorial flow (as in the SW monsoon over Asia during summer).

2 Heat and momentum transport

The simplest observed global characteristic of the atmosphere is that the tropics are much warmer than the poles. Since both regions are, on an annual average, in equilibrium, there must be a process acting to transport excess energy from the tropics to make up the deficit in high latitudes, as depicted schematically in Fig. 6(a).

The implied transport of some $6 \times 10^{15} W$ — see Fig.8 — must be effected

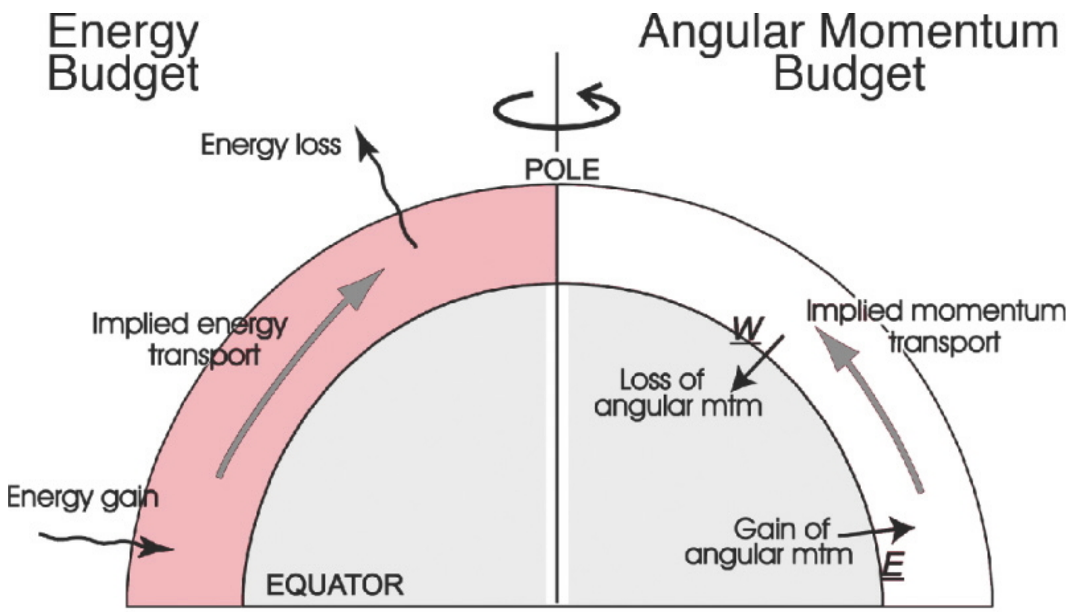


Figure 6: Latitudinal transport of (left) heat and (right) angular momentum implied by the observed state of the atmosphere. In the energy budget there is a net radiative gain in the tropics and a net loss at high latitudes; in order to balance the energy budget at each latitude, a poleward heat flux is implied. In the angular momentum budget the atmosphere gains angular momentum in low latitudes (where the surface winds are easterly) and loses it in middle latitudes (where the surface winds are westerly) — a poleward atmospheric flux of angular momentum is implied.

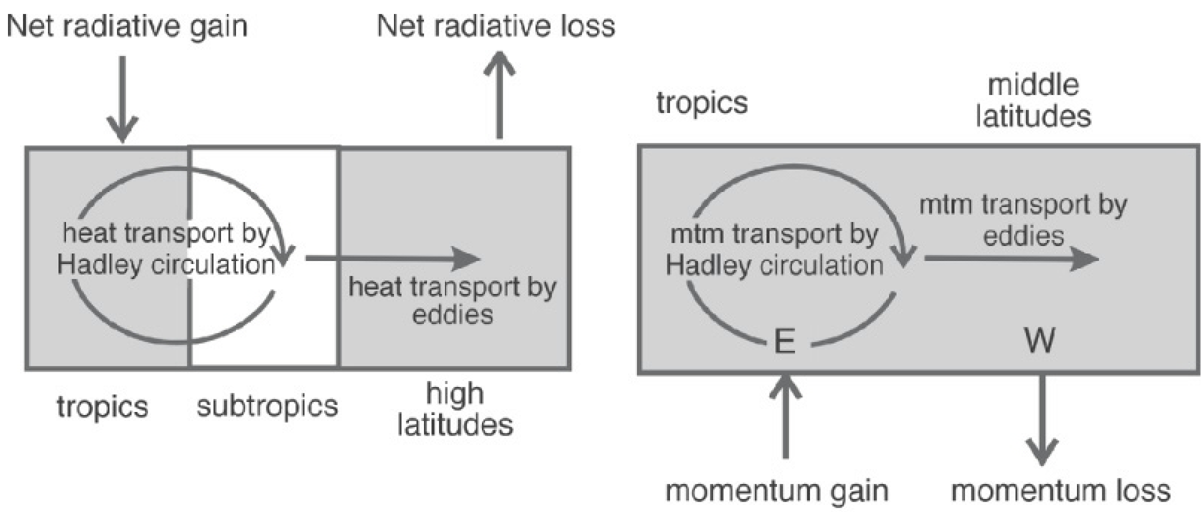


Figure 7: Schematic of the transport of (a) energy and (b) momentum by the atmospheric general circulation. Transport occurs through the agency of the Hadley circulation in the tropics, and baroclinic eddies in middle latitudes.

by the atmospheric (and to a lesser degree, oceanic) circulation, carrying warm air poleward and cold air equatorward. As a result, the tropics are cooler, and polar regions warmer, than they would be in the absence of such transport. Thus, in this as in other respects, the atmospheric general circulation plays a key role in climate.

In cartoon form, our picture of the low- and high-latitude energy balance is as shown in Fig.7a.

3 Illustrative Laboratory experiments

3.1 GFD Lab VII: Experiment on the Hadley Circulation

A number of aspects of this Hadley Circulation are revealed in Expt VII of the Marshall and Plumb text. The apparatus is just a rotating cylindrical tank, containing plain water, at the center of which is a metal can filled with ice. The consequent temperature gradient (decreasing "poleward") drives motions in the tank, the nature of which depends, *inter alia,* on the rotation

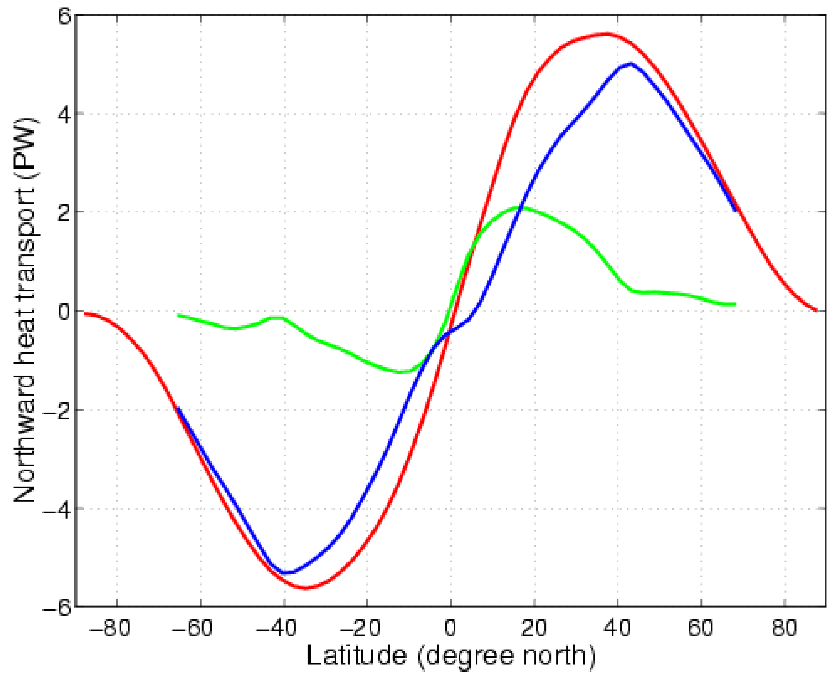


Figure 8: The Ocean (green) and Atmospheric (blue) contributions to the northwards heat flux based on the NCEP reanalysis (in PW=$10^{15}W$) by (i) estimating the net surface heat flux over the ocean (ii) the associated oceanic contribution, correcting for heat storage associated with global warming and constraining the ocean heat transport to be -0.1 PW at 68°S (iii) deducing the atmospheric contribution as a residual. The total merdional heat flux, as in Fig.5.9, is also plotted (the red curve). From Trenberth, K. E., and J. M. Caron, 2001: Estimates of meridional atmosphere and ocean heat transports. J. Climate., 14, 3433-3443.

rate. When weakly rotating ($\Omega \lesssim 0.3$ rpm), we see the development of a strong "eastward" (*i.e.*, super-rotating) flow in the upper part of the fluid which can be revealed by paper dots floating on the surface.Dye streaks clearly show the thermal wind shear — see Fig. 9 — especially near the cold can where the density gradient is strong.

The jet observed in the experiment, which is analogous to the creation of the subtropical jet by the Hadley circulation discussed above, is maintained by angular momentum advection by the meridional circulation. Water rises at the outer wall, moves inward in the upper layers, conserving angular momentum as it does so, thus generating strong "westerly" flow, and rubs against the cold inner wall, becoming cold and descending. Potassium permanganate crystals, dropped into the fluid, settle on the bottom and give an indication of the flow in the bottom boundary layer. In Fig.9 we see flow moving radially outwards at the bottom and being deflected to the right[1]: note the two dark streamers moving outward and clockwise (opposite to the sense of rotation). This flow is directly analogous to the easterly and equatorward trade winds of the lower atmosphere.

3.2 GFD Lab XI — baroclinic instability

To illustrate the phenomenon of middle latitude cyclone development, we describe a laboratory experiment of the phenomenon. The apparatus is identical to that of Lab VII just used to study the thermal wind and the Hadley circulation. In the former experiments the table was rotated very slowly, at a rate of $\lesssim 0.3$ rpm. This time, however, the table is rotated much more rapidly, at $\Omega \sim 3$ rpm, representing the considerably greater Coriolis parameter found in middle latitudes. At this higher rotation rate something remarkable happens. Rather than observing a steady axisymmetric flow, as in the Hadley regime shown in Fig.9, meridional overturning is now inhibited by the stronger rotation. The thermal wind remains, but breaks down through instability, as shown in Fig.10. We see the development of eddies in the tank which sweep (relatively) warm fluid from the periphery to the cold can at one azimuth and, simultaneously, carry cold fluid from the can to the periphery at another. In this way a radially-inward heat transport is achieved, offsetting the cooling driven by the melting ice.

For the case shown, the eddies are of wavenumber 3 (*i.e.*, 3 complete

[1]Assuming the tank rotation is clockwise, like the northern hemisphere of the Earth.

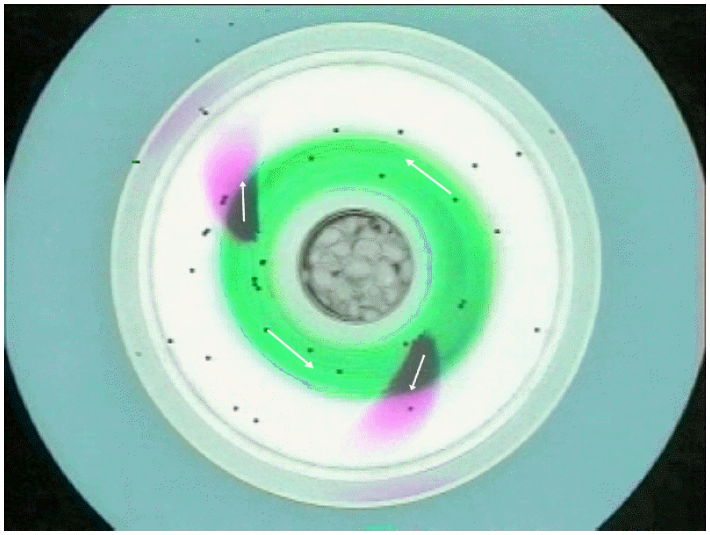


Figure 9: The Hadley regime studied in GFD Lab VII. Bottom flow is revealed by the two outward spiralling streaks showing anti-cyclonic (clockwise) flow; the black paper dots and collar of dye mark the upper level flow and circulate cyclonically (anti-clockwise).

wavelengths around the tank — see the view from above shown in Fig.10, bottom panel). By experimenting with the rotation rate of the tank we can observe that the scale of the eddies decreases (wavenumber increases), and the flow becomes increasingly irregular, as Ω is increased.

Figure 10: (Top) Baroclinic eddies in the 'eddy' regime viewed from the side. (Bottom) View of the wavenumber 3 baroclinic instability from above.