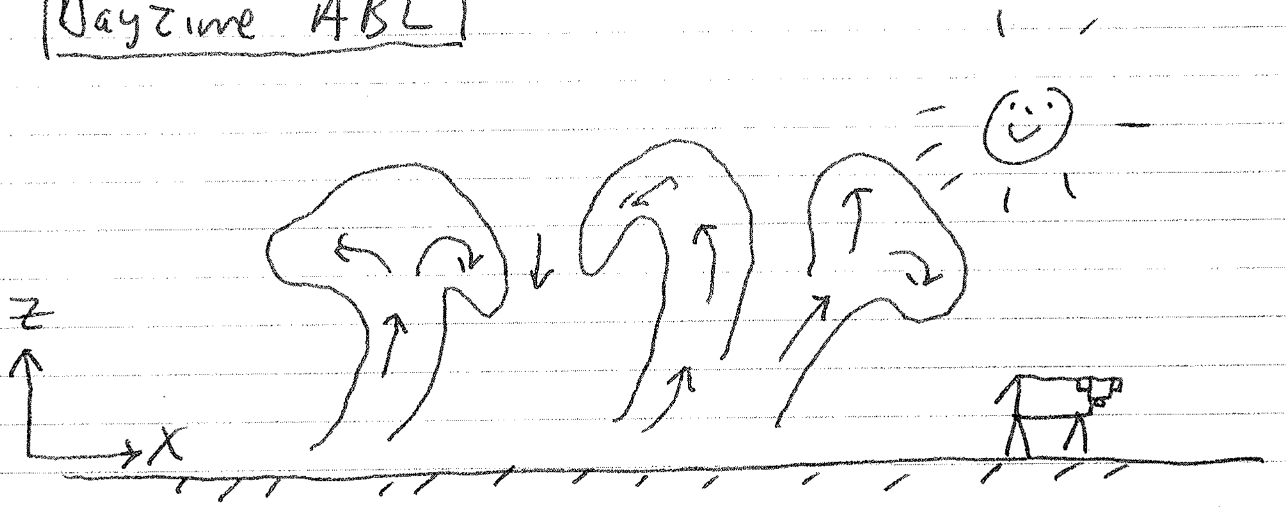
Let's take a quick look at the *Atmospheric Boundary Layer* (ABL). Consider diurnal cycle during fair weather over land. Focus on effect of heating/cooling of earth's surface. Consider surface characteristics and forcings to be independent of x, y (horizontal homogeneity). *Ignore synoptic-scale influences* (p.g.f./winds).

Daytime ABL



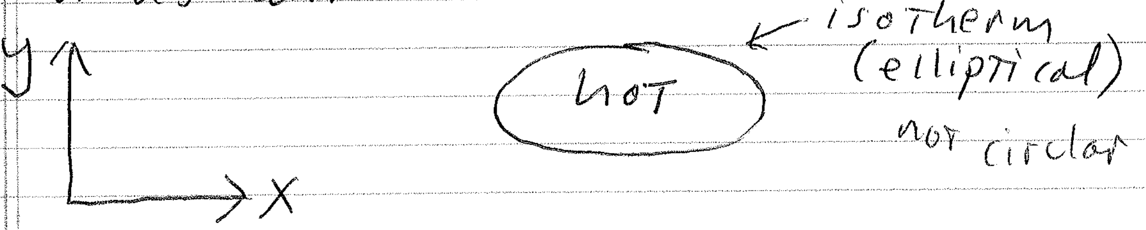
- sun heats surface
- thermal instability
- thermals carry hot air upward
- lots of turbulent mixing, lots of *baroclinic generation* of *horizontal* vorticity on edges of thermals → but it's random. Also *vertical vorticity generated* through tilting of the baroclinically-generated horiz vorticity. Get dust devils.

If we "average-out" the turbulent fluctuations, what does thermal structure (e.g. potential temperature) look like as f^n of z? [*Digression*: what do we mean by average? Ideally it would be an *ensemble average*: an average over many *identical* experiments (apart from the randomness). So imagine N *identical* universes (apart from randomness) and go to same point x, y, z at same time t, and average Θ over the N universes. Well, can't really do that so in practice must fudge the average, e.g. average over short but not too-short time intervals. Want to average-out the short-term turbulent fluctuations but leave in longer-term (diurnal) trends].

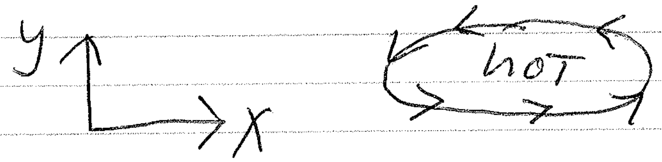
Vertical vorticity generation by asymmetric thermal bubbles rising in a shear-free environment.

For details, see Shapiro and Kanak, 2002, J. Atmos. Sci.

Consider an asymmetric bubble of hot air rising in an environment without windshear.



Early on, before advection effects become important, the horizontal vorticity is largely coincident with the baroclinic vorticity generation term. This baroclinic vorticity is largely tangent to the isotherms:



so isotherm is also a vortex line (ring vortex).

The perturbation pressure in this evolving flow can be shown to satisfy a Poisson eq^{n} (which follows from taking the 3D divergence $\nabla\cdot$ of the Boussinesq eq^{ns} of motion:

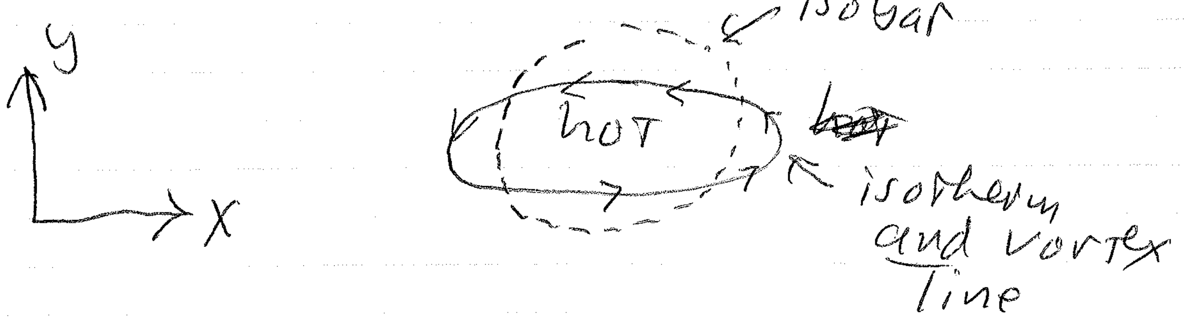
$$(1)\quad \frac{\partial \vec{v}}{\partial t} + (\vec{v}\cdot\nabla)\vec{v} = -\frac{1}{\underset{\text{const ref density}}{\rho_0}}\nabla \underset{\text{pert pressure}}{p'} + \overset{\text{buoyancy}}{b\hat{k}} + \nu\nabla^2\vec{v}$$

Taking $\nabla\cdot(1)$ and using fact that $\nabla\cdot\vec{v}=0$ in a Boussinesq flow [so that $\frac{\partial}{\partial t}(\nabla\cdot\vec{v})=0$ and $\nu\nabla^2(\nabla\cdot\vec{v})=0$) we get a <u>Poisson eq^{n}</u> for pert pressure:

$$\nabla^2 p' = -\rho_0\nabla\cdot\left[(\vec{v}\cdot\nabla)\vec{v}\right] + \frac{db}{dz}$$

This Poisson eqⁿ (a type of elliptic p.d.e.) tends to have <u>smooth solutions</u>, even though the forcing terms on the r.h.s. (including buoyancy) may be highly variable and have sharp gradients. In other words, the pressure isolines will tend to be "less sharp/curvy" than the buoyancy/temperature lines. Graphically, we can draw this as:

Fig 1

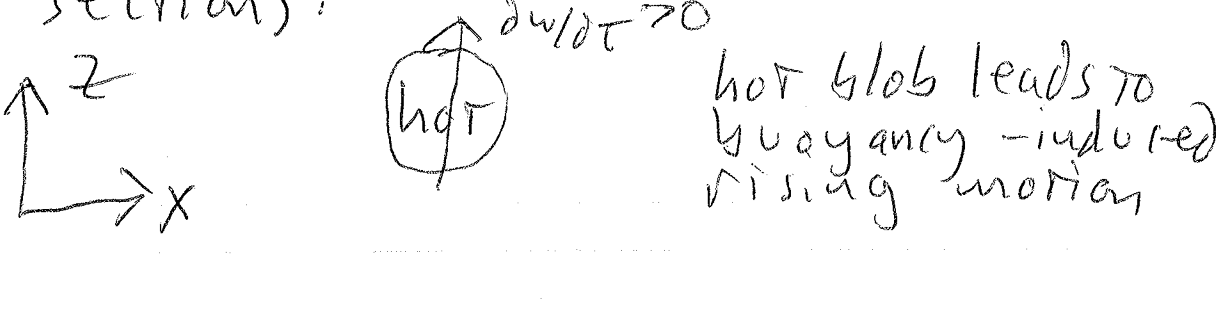


Next consider the vertical eqⁿ of motion:

$$\frac{\partial w}{\partial t} = \text{nonlinear advection} - \frac{1}{\rho_0}\frac{\partial p'}{\partial z} + b\hat{k} + \text{friction}$$

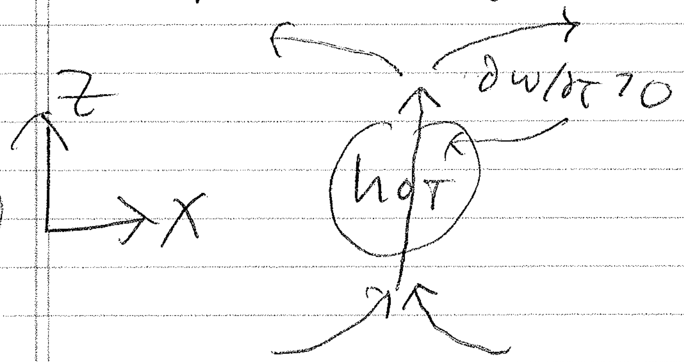
The $b\hat{k}$ term produces a vertical acceleration (upward) that has the same pattern as the temp field (i.e. highly asymmetric). But the $\frac{1}{\rho_0}\frac{\partial p'}{\partial z}$ term is "broader" than the b field. What about the direction of that term? Reason as follows (and use vert cross-section):

Fig 2



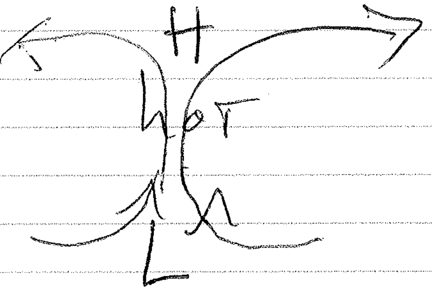
In order for mass to be conserved, there has to be a compensating <u>inflow</u> into base of updraft and a compensating <u>outflow</u> at upper end of thermal disturbance:

Fig 3



This in-up-out circulation is associated with <u>low</u> perturbation pressure beneath hot blob and <u>high</u> perturbation pressure above hot blob:

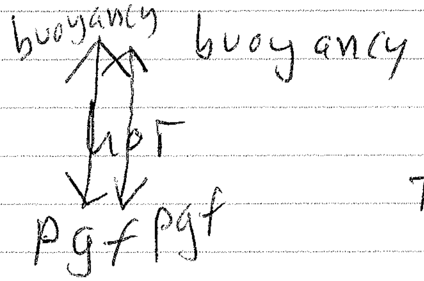
Fig 4



The L and H here are <u>perturbation</u> pressure anomalies.

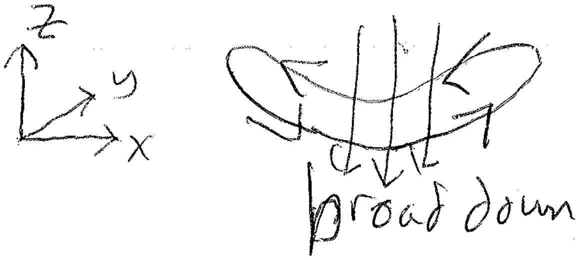
associated with this high-over-low pert pressure distribution is a <u>downward</u> directed vertical pgf. So the <u>vertical</u> pgf acts to <u>oppose</u> the buoyancy and tends to drive a fairly symmetric downward forcing (vert pgf).

Fig 5



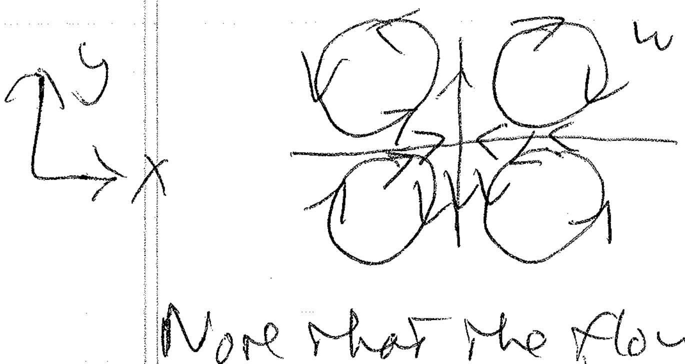
So, as the blob rises due to (positive buoyancy) some of this buoyant forcing is <u>opposed</u> by a <u>relatively broad</u> downward directed pgf. This pgf acts like a giant thumb, pushing <u>down relatively symmetrically</u> on the asymmetric vortex ring. The effect is to distort the ring as follows.

Fig. 6



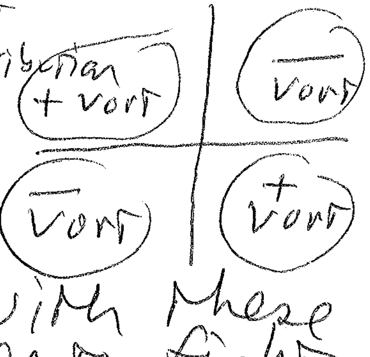
Tilting of the vortex ring by the part of the w field associated with the vert pgf.

The distorting of the vortex ring leads to a clover-leaf pattern of alternating + and − vertical vorticity blobs:

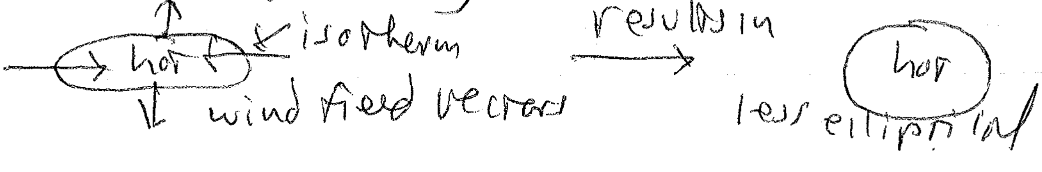


wind vectors

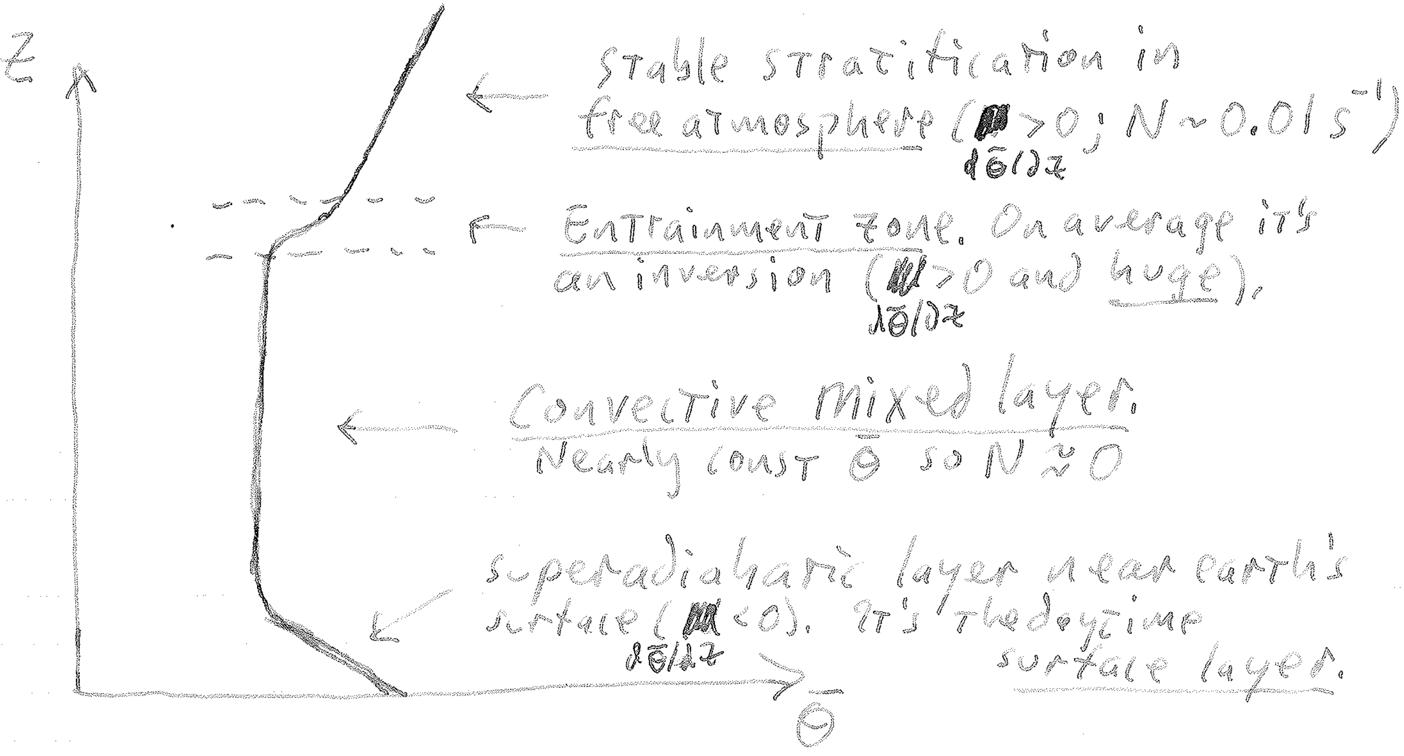
vert vort distribution



Note that the flow associated with these counter-rotating vortices tries to <u>fight the thermal asymmetry</u>.



$\bar{\theta}$ in the daytime ABL:



Stable stratification in free atmosphere ($d\bar{\theta}/dz > 0$; $N \sim 0.01\,s^{-1}$)

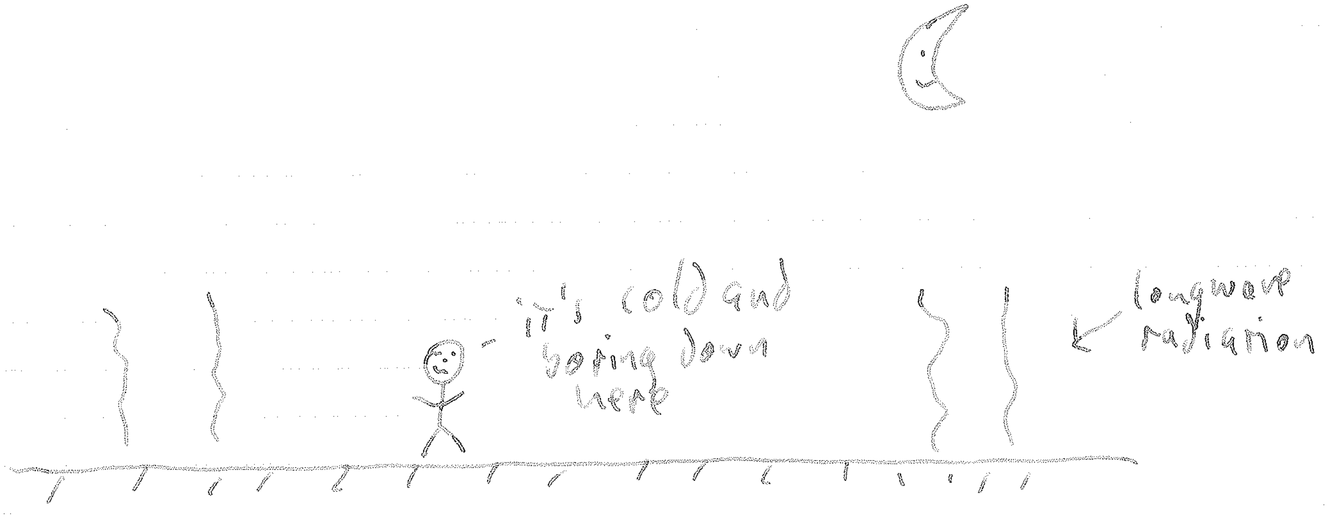
Entrainment zone. On average it's an inversion ($d\bar{\theta}/dz > 0$ and huge).

Convective mixed layer. Nearly const $\bar{\theta}$ so $N \approx 0$

superadiabatic layer near earth's surface ($d\bar{\theta}/dz < 0$). It's the daytime surface layer.

[With compressibility accounted for, Brunt-Väisälä frequency is: $N = \sqrt{\frac{g}{\theta_r}\frac{d\theta}{dz}}$]

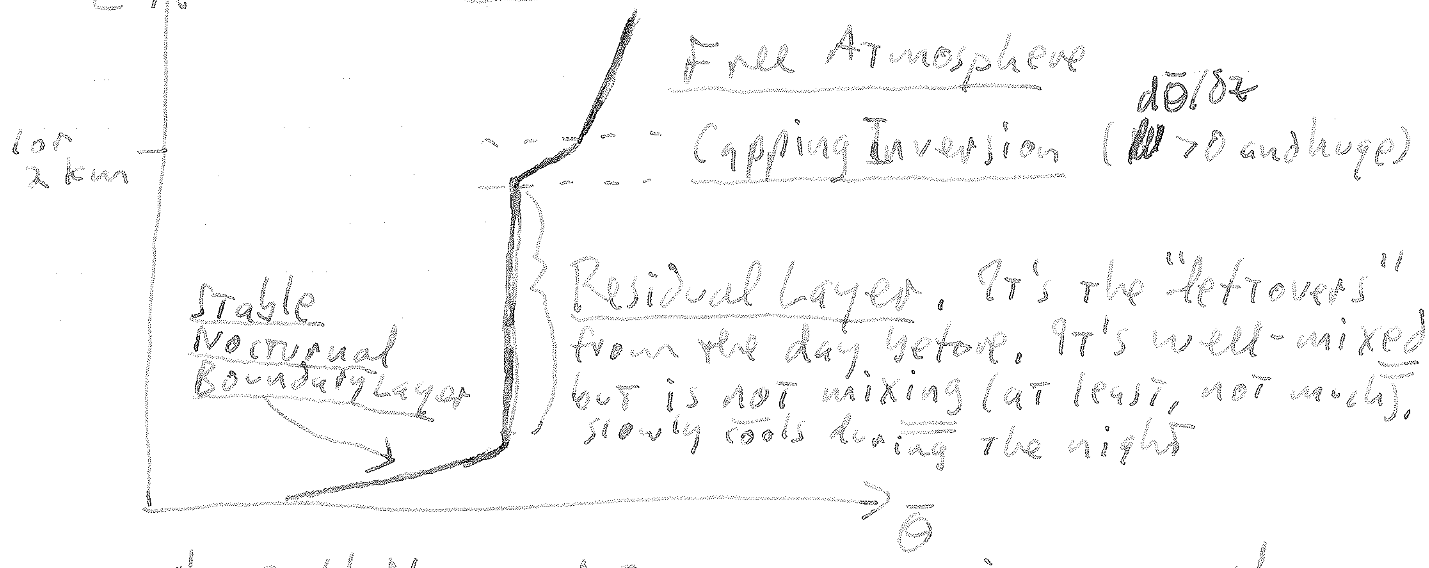
Night-time ABL



- no solar radiation at night
- but longwave radiation from earth's surface continues (day and night)
- so there's a net energy loss ∴ cooling of surface
- cooling sets in quickly around sunset (or before)
- production of thermals ceases
- turbulent mixing is very very weak (but still there)

Mean potential temp $\bar{\theta}$ profile looks similar to the daytime profile, except near the surface:

$\bar{\theta}$ in the night-time ABL:



Residual Layer. It's the "leftovers" from the day before. It's well-mixed but is not mixing (at least, not much). slowly cools during the night

The Stable Nocturnal Boundary Layer is generally 0 - 200 m deep. It grows during the night. Sometimes it's called a radiation inversion (don't confuse it with the Capping Inversion)

If there was a synoptic-scale pressure gradient force then a low-level jet would develop in the stable nocturnal b.l. and in the lower part of the residual layer. We'll examine the low-level jet later on.