Thermal and shear instabilities:
Introduction

Kelvin-Helmholtz (K-H) waves &
horizontal convective rolls (HCRs)
HCRs

- Boundary layer phenomenon
- Pairs of counterrotating vortices
  - Alternating updrafts & downdrafts
- Ubiquitous over land on sunny, warm afternoons
- Cloud streets may form along roll updrafts
  - Parallel streets w/ typical separation of about 2-8 km or so
  - Wavelengths from 0.2 km (Ferrare et al. 1991) to 20 km (Asai 1966) have been noted
HCR schematic

Roll axes shown parallel to both wind and vertical shear vector

Dailey and Fovell (1999)
Hurricane Claudette
Florida HCRs - appeared in afternoon

Not all bands are HCRs

too far aloft

too wide
ARPS simulation

Surface heat flux w/ random perturbations
Vertical velocity at 1.5 km AGL
$w \text{ (cm/s)} \quad \text{time} = 66 \text{ min}$
Animation

$w (\text{cm/s}) \quad \text{time} = 3 \text{ min}$
Vertical profiles of $\theta$
K-H waves made visible by clouds

Brian Tang
DTDM simulation

perturbation potential temperature

airflow vectors
K-H waves can form clouds

Fig. 16. Schematic diagram summarizing mechanisms of convection initiation and organization due to the outflow boundary, K–H waves, and IG waves within multi-Doppler box shown in Fig. 7.

Weckwerth & Wakimoto 1992
Open and closed cells over the Eastern Pacific (Bjorn Stevens)
Organization of mesoscale instabilities

• Three basic forms
  – Open cells (ascent/cloudiness on edges; subsidence/clear at center)
  – Closed cells (ascent/cloudiness at center; clear at edges)
  – Linear rolls (parallel, roughly straight counterrotating vortices)

• Two types of rolls
  – Longitudinal rolls - parallel to wind and/or vertical wind shear vector
  – Transverse rolls - perpendicular to wind and/or vertical shear vector
Early observations of rolls

• Woodcock (1942)
  – Deduced rolls by watching gliding pattern of sea gulls

• Langmeier (1939)
  – Noted ocean seaweed tended to form lines parallel to wind
  – When wind shifted, so did seaweed lines
Forcing mechanism for rolls & billows

- Thermal instability
  - Unstable atmosphere, buoyancy driven
- Dynamical instability (shear)
  - Parallel instability
  - Inflection-point instability
  - “Richardson number” instability ($R_i < 1/4$)
  - “Critical level” instability
- Combination of the two
Some history

• Benard (1901)
  – Heated thin (~1 mm) fluid layer from below
  – Observed “closed cells”
  – Later determined to be driven by surface tension rather than buoyancy
    • Occurs on painted ceilings (Pearson 1958)
Some history

• Rayleigh (1916)
  – Formulated Rayleigh number Ra (Houze p. 63)

\[
Ra = \frac{h^4 \Gamma g \tilde{\alpha}}{\hat{D} \hat{K}}
\]

\(\Gamma\) = lapse rate (large for heated fluid)
\(h\) = depth of heated layer
\(g\) = gravity acceleration
\(\alpha\) = thermal expansion coefficient
\(K, D\) = fluid conductivity and viscosity

- More unstable, less viscous, less conductive - Ra larger
Some history

- Rayleigh found thermal convection occurred when a critical Rayleigh number \((Ra)_c\) was exceeded.
- He showed

\[
Ra = \frac{(k^2 + l^2 + m^2)^3 h^4}{k^2 + l^2}
\]

where

\[
k = \frac{2\pi}{L_x}, \quad l = \frac{2\pi}{L_y}, \quad m = \frac{2\pi}{L_z}
\]

- Many combinations of \(k, l\) can result in \(Ra > (Ra)_c\).
- Cells: \(k = l\); Rolls: \(k = 0, l \neq 0\) or \(l = 0, k \neq 0\)
Thermal instability

• Tends to produce rolls aligned along wind and/or vertical wind shear that drift with the mean wind
  – In case of unidirectional flow (wind, shear parallel), rolls stationary relative to ground

• How important is wind? How important is shear? Which is more important?
Thermal instability

- Kuo (1963), Asai (1979a,b; 1972)
  - Theoretical studies
  - For unstable environment with unidirectional shear, most unstable mode is stationary, longitudinal rolls parallel to wind & shear
  - Transverse mode (rolls perpendicular to shear) suppressed by shear
  - Shear is all-important
Thermal instability

• Kuettner (1971)
  – Transverse mode suppressed by gradient of vertical shear (i.e., shear has to vary with height)

• Plank (1966), Miura (1986)
  – Variable vertical shear not necessary

• Miura (1986)
  – Rolls required at least shear of .001 s\(^{-1}\) (\(\Delta u = 1 \text{ m/s over 1 km}\))

• Tsuchiya and Fujita (1967)
  – Mode selection between 2D rolls and 3D cells depended on shear magnitude (larger favors rolls)
Thermal instability

• Sykes and Henn (1989)
  – Increasing speed shear caused 3D convection to become 2D rolls
• Sun (1978)
  – Rolls obtained most easily when there was no speed shear, but instead large directional shear in a shallow layer
• Surface flux and non-calm flow near ground needed
  – Min surface wind 3.2 m/s (Kropfli and Kohn 1978), 5 m/s (Christian 1987)
  – Ferrare et al (1991), Wilczak and Businger (1983) showed rolls can exist in winds < 2 m/s
Dynamic instability

• Parallel instability
  – Exists owing to vertical shear along roll axes, Coriolis force and viscosity
  – Requires Reynolds number (ratio of inertia and viscosity) small
  – Atmosphere… Re large

\[ Re = \frac{h \bar{u}}{\hat{D}} \]
Dynamic instability

- Inflection point instability (IPI)
  - Requires an inflection point (curvature change) in cross-roll wind
  - Observations insisting it’s important and observations failing to detect inflection points exist

- Lenschow (1970), LeMone (1973) found both IPI and thermal instability
- Brown (1970) argued neutrality of PBL means rolls are shear-induced (but consequence of rolls is mixing!)
Dynamic instability

- Richardson number instability

\[ Ri = \frac{N^2}{(u_z)^2} < \frac{1}{4} \]

- Ri is ratio of stability frequency and vertical shear (both squared)
- Thermal instability is Ri < 0 (since \( N^2 < 0 \))
- Necessary condition for instability can be shown to be Ri < 1/4 (will derive soon)
- Ri < 1/4 results in “rolls” (K-H billows) perpendicular to shear vector
- Instabilities appear to survive as long as Ri < 1 or so