Horizontal Convective Rolls

Asai papers &
Simulations w/ ARPS

Asai (1970a)

- Effect of vertical shear on roll orientation
- Boussinesq derivation - equations similar to shear instability derivation
  - **Negative** Richardson numbers (reported as positive numbers) represent unstable environments
  - Presumed solutions similar to before, but solved numerically
- Figure 2
  - Most unstable mode is stationary relative to flow and becomes smaller in size as -Ri increases

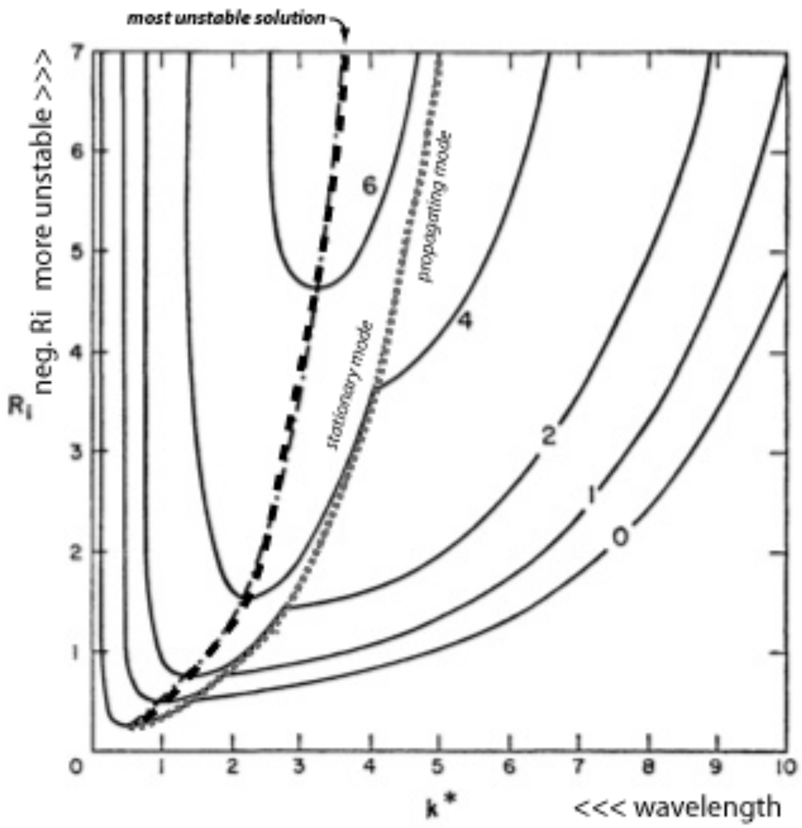


Fig. 2. Amplification rate of perturbation as a function of the Richardson number R_i (ordinate) and the wavenumber k^* (abscissa). Solid lines are isopleths of amplification rate (in units of 10), dash-dotted line indicates the maximum amplification rate, and dotted line separates the stationary unstable perturbation from the transitive one.

Asai (1970a) Fig. 2

- -Ri vs. k (thermal instability increases upward; wavelength increases to left)
- Left of dotted curve represents waves (rolls) stationary with respect to flow; propagating rolls to right
- Wavelength of **most unstable mode** (fastest growing solution that will dominate) becomes smaller as environment becomes more unstable [dashed curve]
- *Most unstable solution is stationary with respect to flow for all unstable environmental conditions*

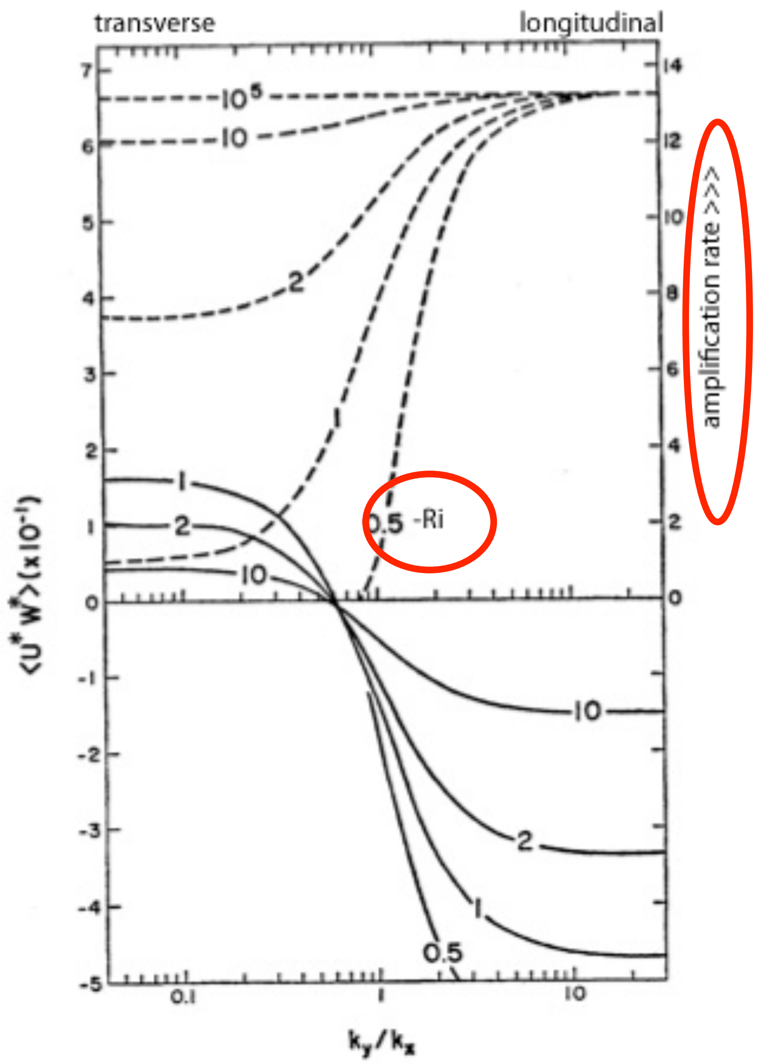


Fig. 8. Variations of vertical momentum transfer $\langle U^*W^* \rangle^\dagger$ (solid line) and amplification rate of perturbation σ^* (broken line) with the ratio between the wavenumbers in the x and y directions., k_y/k_x, for different values of R_i. The numeral labelled at each curve denotes the value of R_i. These are for the case of $R_a=10^4$ and $k^*=2$.

Asai (1970a) Fig. 8

- Consider roll wavelengths Lx and Ly. Rolls aligned along x-axis have Lx >> Ly.
- Consider vertical shear oriented along the x-axis
- Horizontal axis is $k_y/k_x = L_x/L_y$ representing *roll orientation*
- Large L_x/L_y means rolls parallel with the vertical shear vector (*longitudinal rolls*). Small L_x/L_y means rolls oriented perpendicular to shear (*transverse rolls*)
- Vertical axis (labeled at right) is amplification rate for various roll orientations

More…

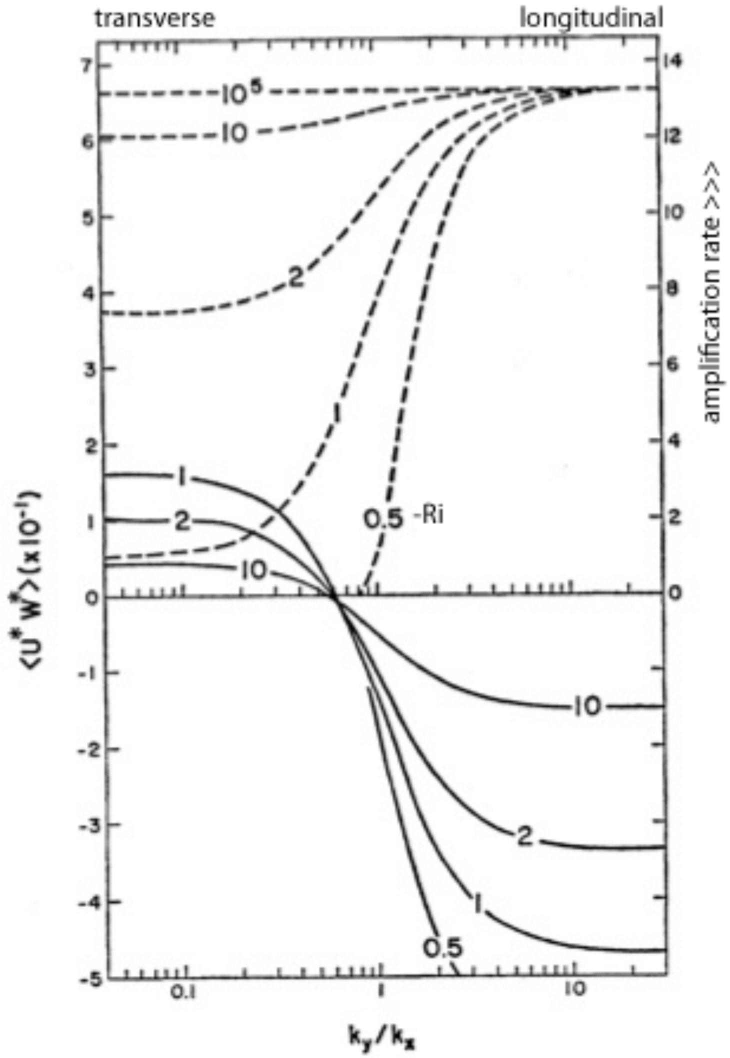


Fig. 8. Variations of vertical momentum transfer $\langle U^* W^* \rangle$† (solid line) and amplification rate of perturbation σ^* (broken line) with the ratio between the wavenumbers in the x and y directions., k_y/k_x, for different values of R_i. The numeral labelled at each curve denotes the value of R_i. These are for the case of $R_a = 10^4$ and $k^* = 2$.

Asai (1970a) Fig. 8 (continued)

- Amplification rate vs. roll orientation for various values of -Ri (thermal instability; dashed curves)
- Shear-parallel rolls always have largest growth rate
- For marginally unstable environments (-Ri = 0.5), shear-perpendicular rolls are suppressed
- For very unstable environments (-Ri > 10) *all* orientations are unstable
- (Ignore solid curves)

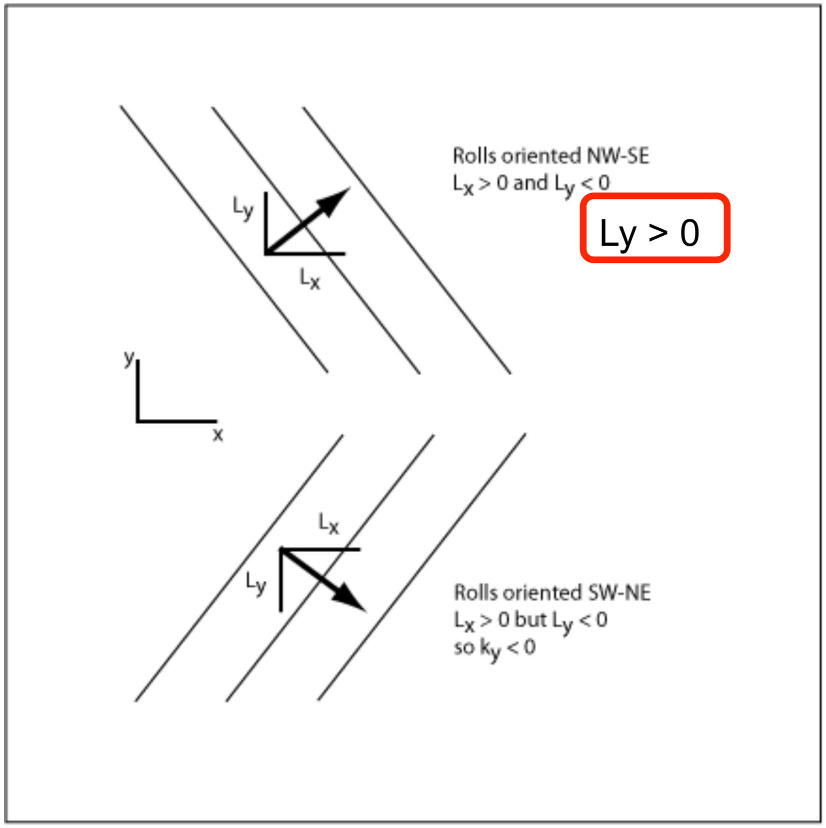
Asai (1970a)

- Figure 8 summary
  - Shear-parallel (longitudinal) rolls always favored
  - Small instability - shear-perpendicular (transverse) rolls have very small growth rates
  - Large instability - all possible orientations grow quickly
    - Cells?

Asai (1972)

- Thermally unstable but -Ri not varied
- Directional and speed shear
- Case I - shear vector still constant w/ z
  - Shear vector is NW-SE in example
  - Figure 2: growth rate max for Lx = Ly
  - Rolls still line up parallel to shear vector
- Case 2 - shear vector *turns* with height
  - Figure 6: three maxima (two shown)
    - Parallel to shear in upper part of shear layer
    - Parallel to shear in lower part of shear layer
    - Perpendicular to shear (inflection point instability)

Asai (1972) sign convention



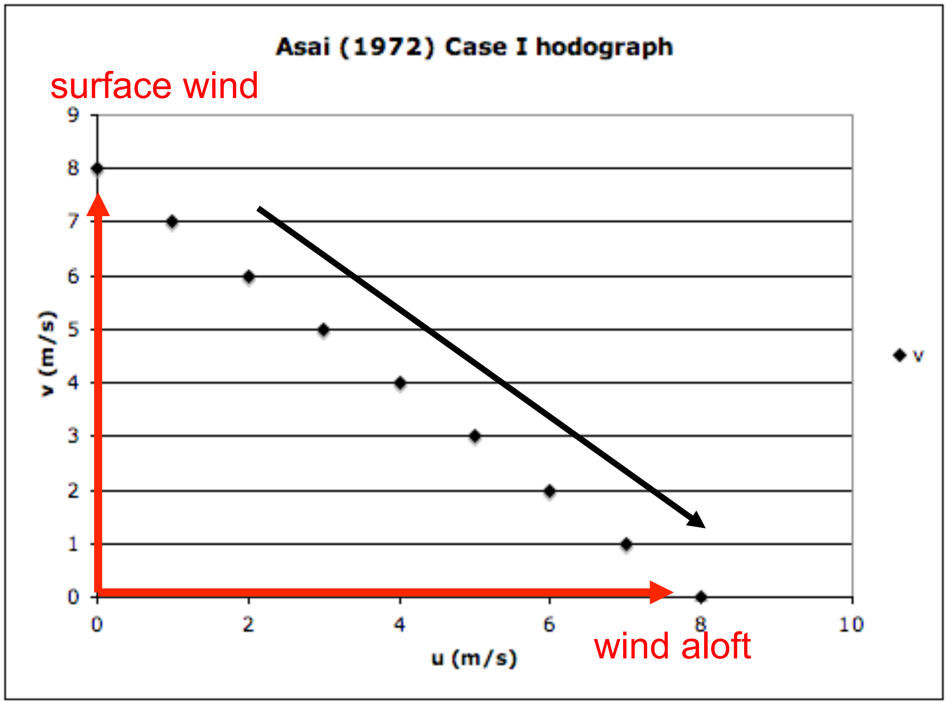
Wavelengths are Lx, Ly

Wavenumbers are Kx, Ky

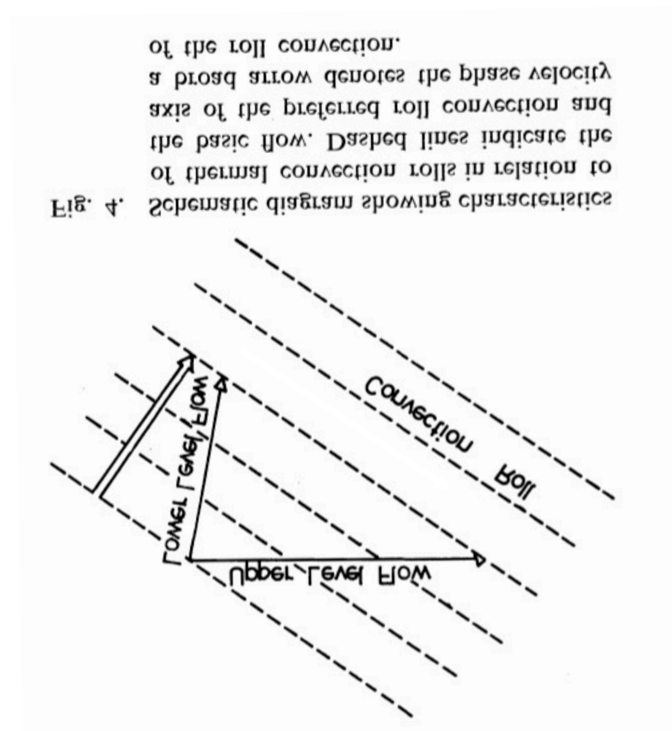
Both can be negative depending on roll orientation

For NW-SE rolls Kx, Ky >0 and Lx, Ly > 0

Asai (1972) Case I



Asai Case 1: Shear NW-SE (above)



Schematic showing result: rolls parallel to shear vector and not to winds at any level

Asai (1972) Case I

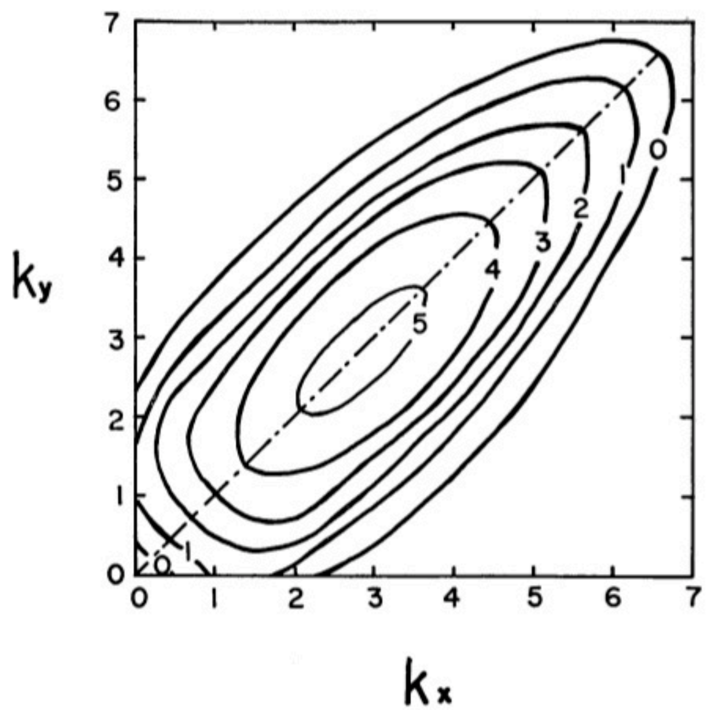
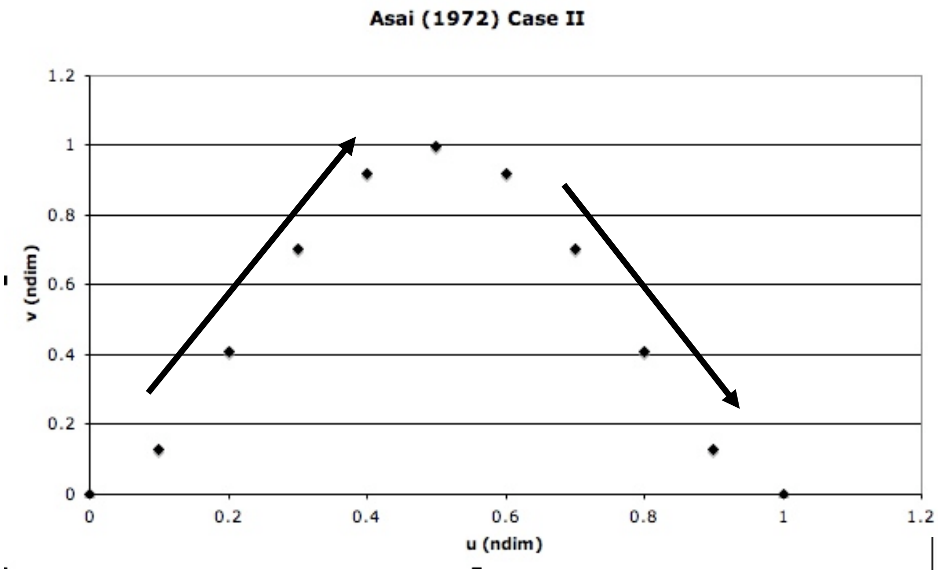


Fig. 2. Amplification rates in units of 0.1 as a function of the wavenumbers, k_x and k_y, for Case (I) with $a_1=1$, $R_i=1$ and $R_a=10^4$. A dash-dotted line indicates a maximum amplification rate for a given wavenumber.

- Axes are E-W and N-S wavenumbers
- Contoured is amplification rate
- Shear oriented NW-SE
- Largest growth rate for rolls with Lx = Ly > 0; i.e., *aligned along shear vector*
- Growth rate max for <u>inter-mediate</u> wavelengths

Asai (1972) Case II

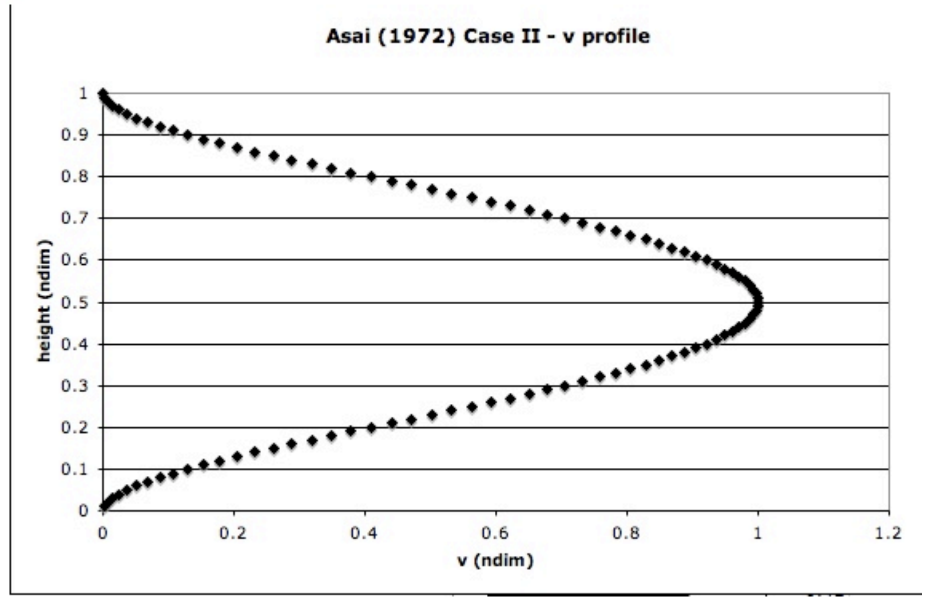


Shear vector varies w/ Height

Upper layer shear remains NW-SE

Note V component has inflection point(s) [at z=.25 and .75] >>>

U component does not (not shown)



Asai (1972) Case II

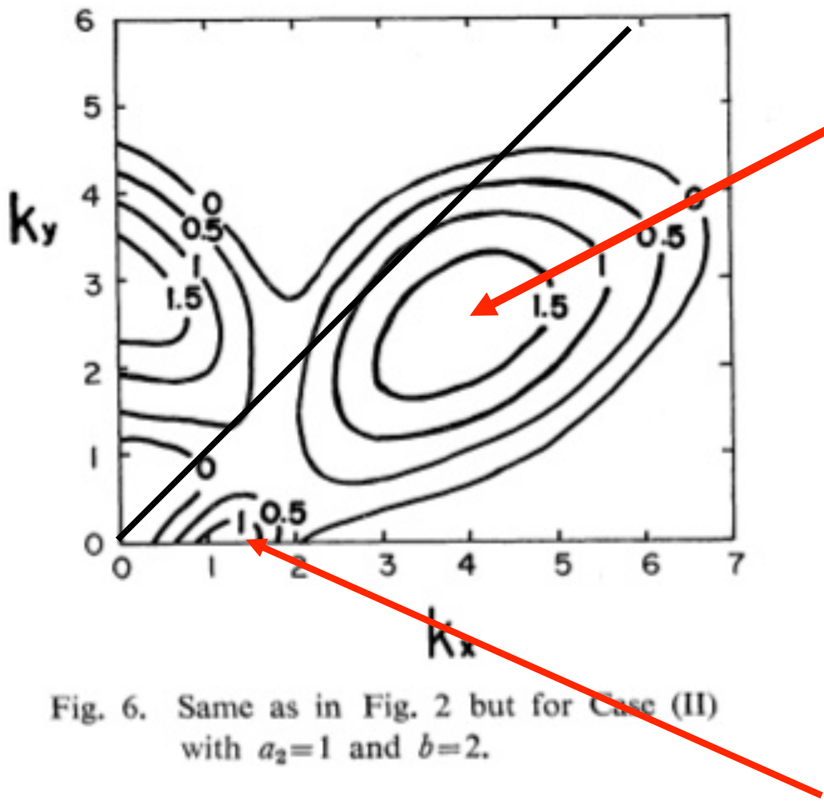


Fig. 6. Same as in Fig. 2 but for Case (II) with $a_2=1$ and $b=2$.

More…

- Fig. 6 - largest amplification rate again "nearly parallel" to shear vector (i.e., Kx = Ky) in upper part of layer (actually, they're turned at some CCW angle to shear vector)

- Rolls "parallel" to shear vector in *lower* part of layer also appeared but are NOT shown (Ky < 0)

- Also a local max in amplification rate for rolls parallel to y-axis (Ky = 0) with long wavelengths (unexplained by Asai)

Asai (1972) Case II

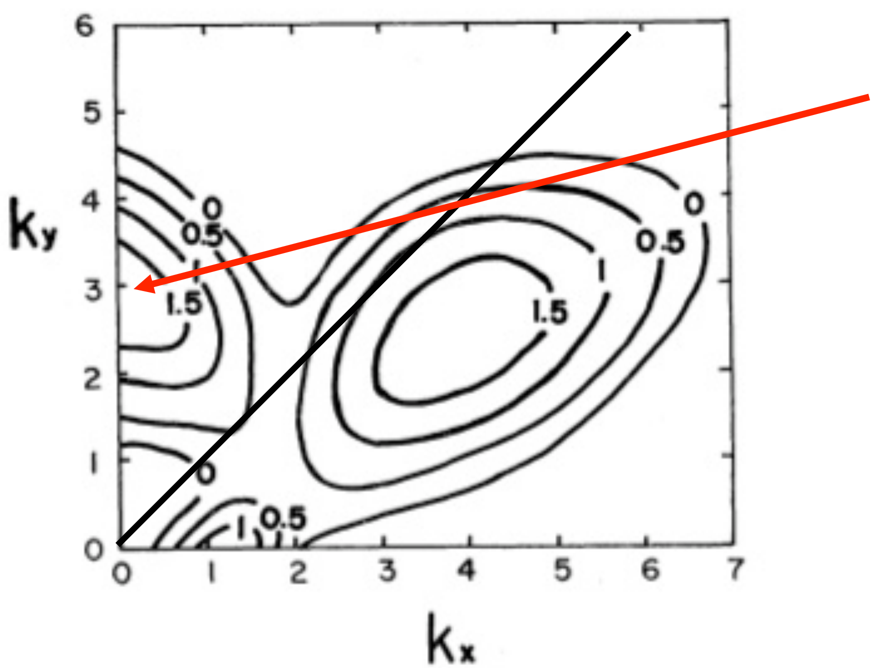


Fig. 6. Same as in Fig. 2 but for Case (II) with $a_2=1$ and $b=2$.

- Another locally large amplification rate occurs for Kx = 0 (rolls parallel to x-axis, at angle to shear)

> That is inflection point instability which produces rolls oriented perpendicular to the wind component with the inflection point (here, the v component)

Asai (1970a) Case II

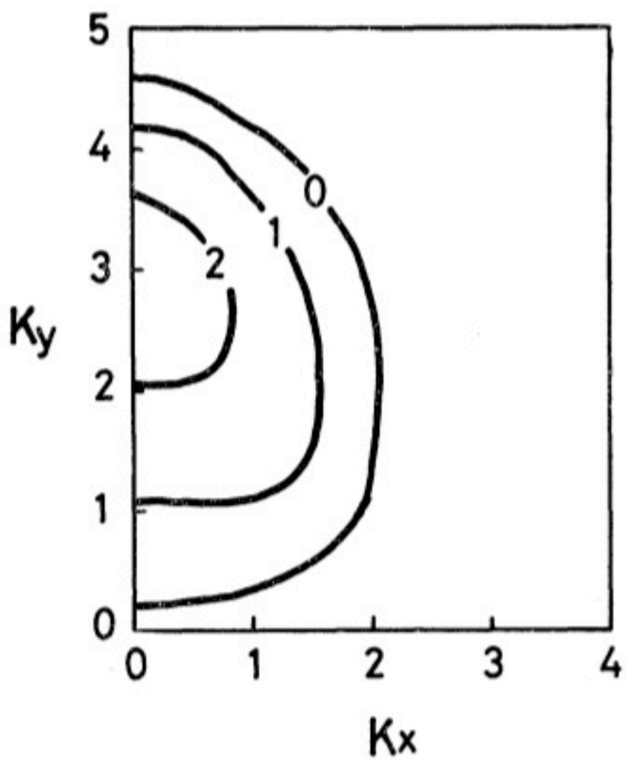
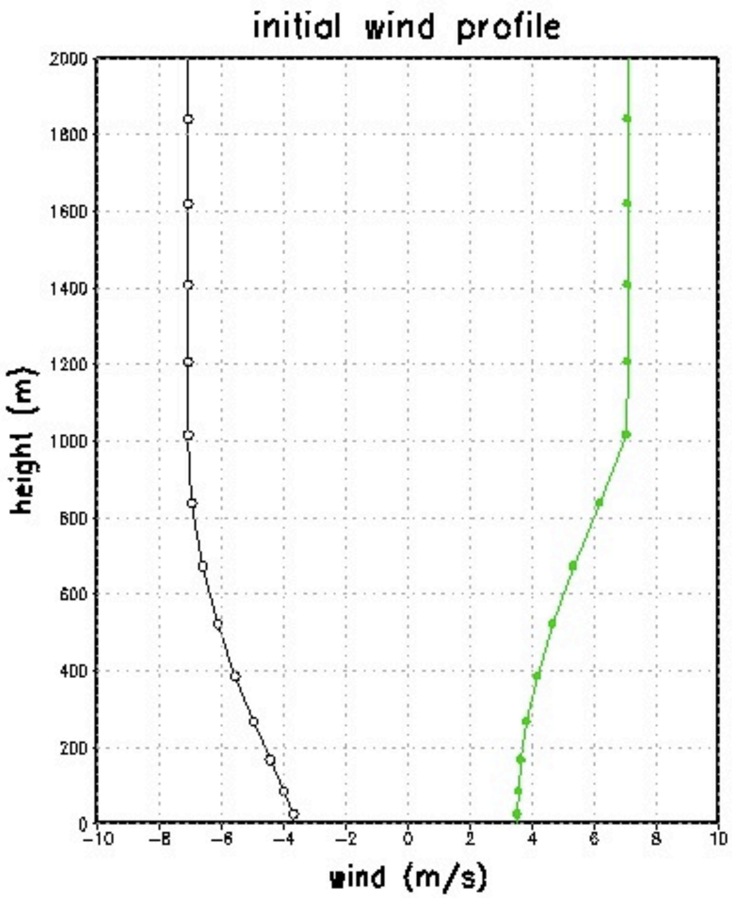


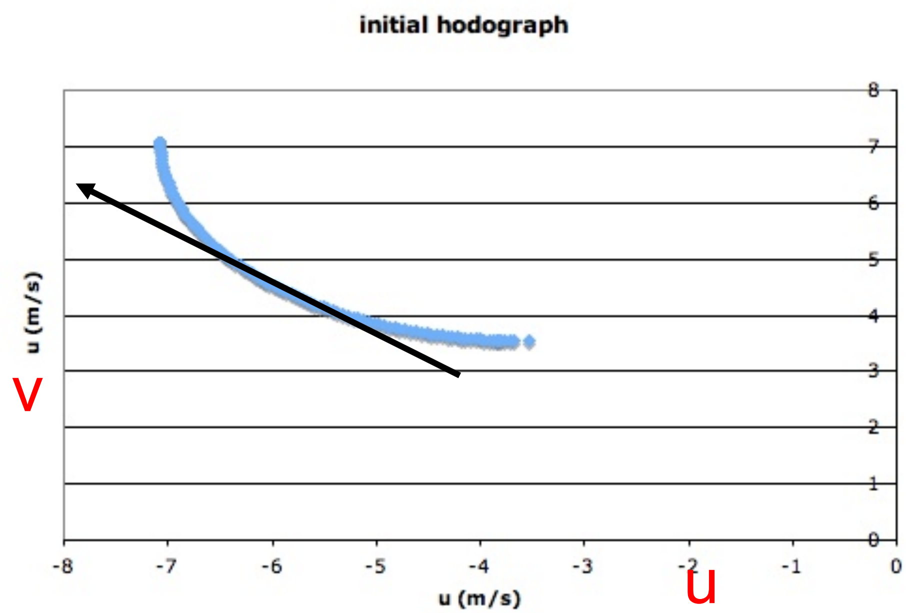
Fig. 7. Same as in Fig. 6 but $R_i = 10^{-2}$.

- Fig. 7 - when thermal instability removed, only dynamical instability (inflection point instability) remains

- This proves the other local maxima were due to thermal instability

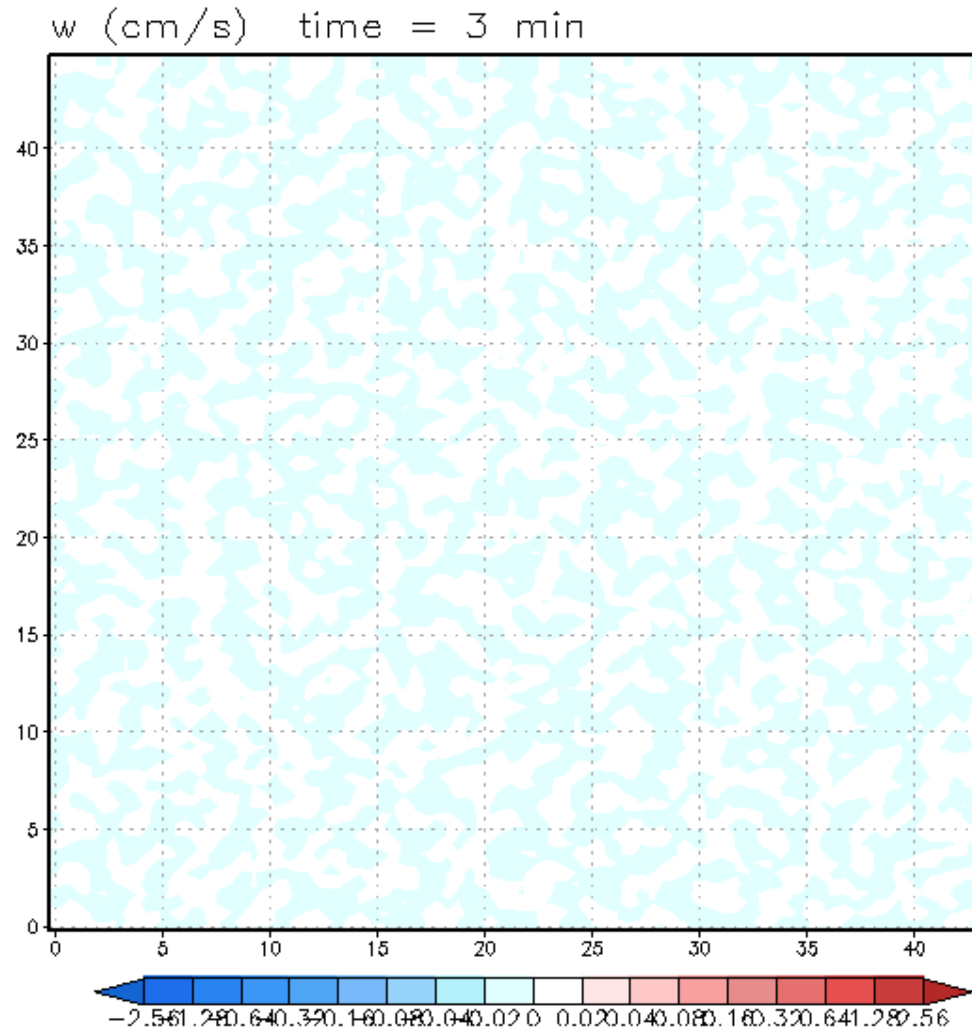
Revisit ARPS simulation

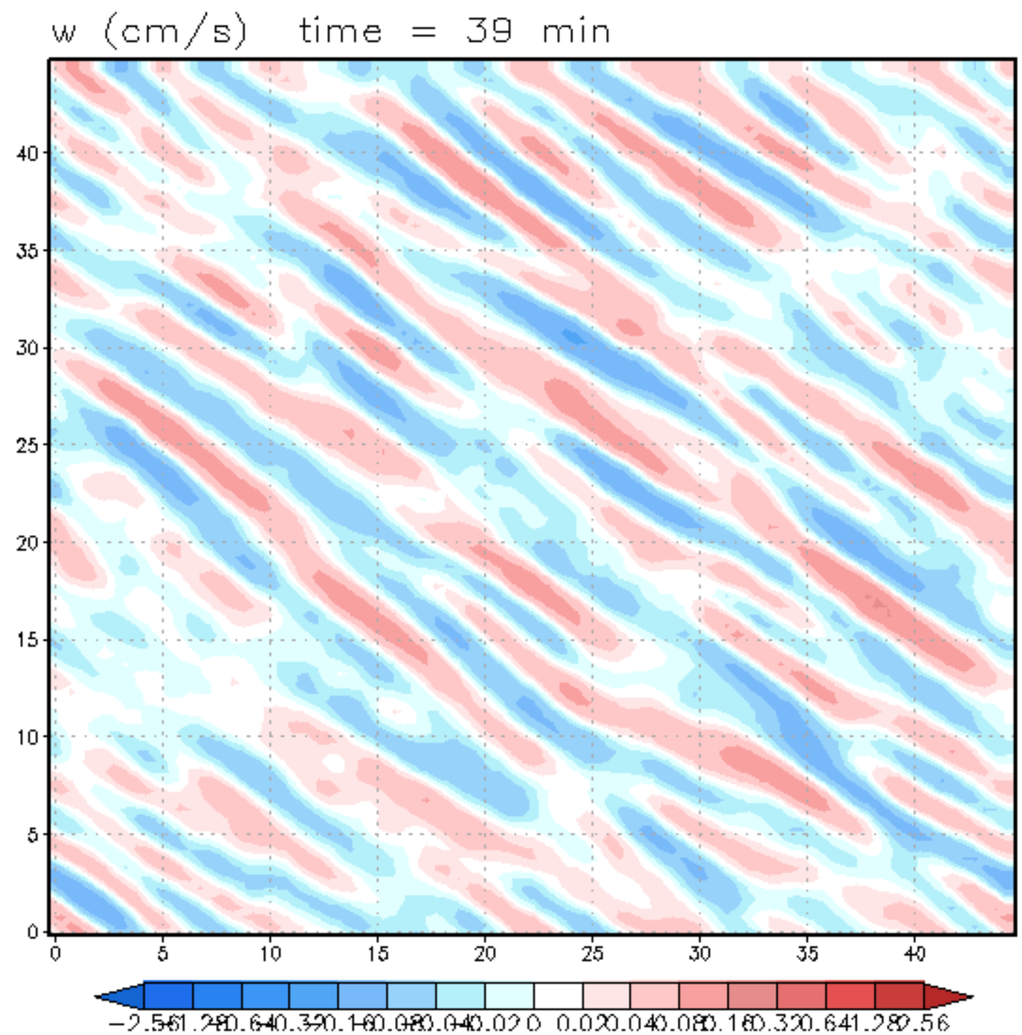




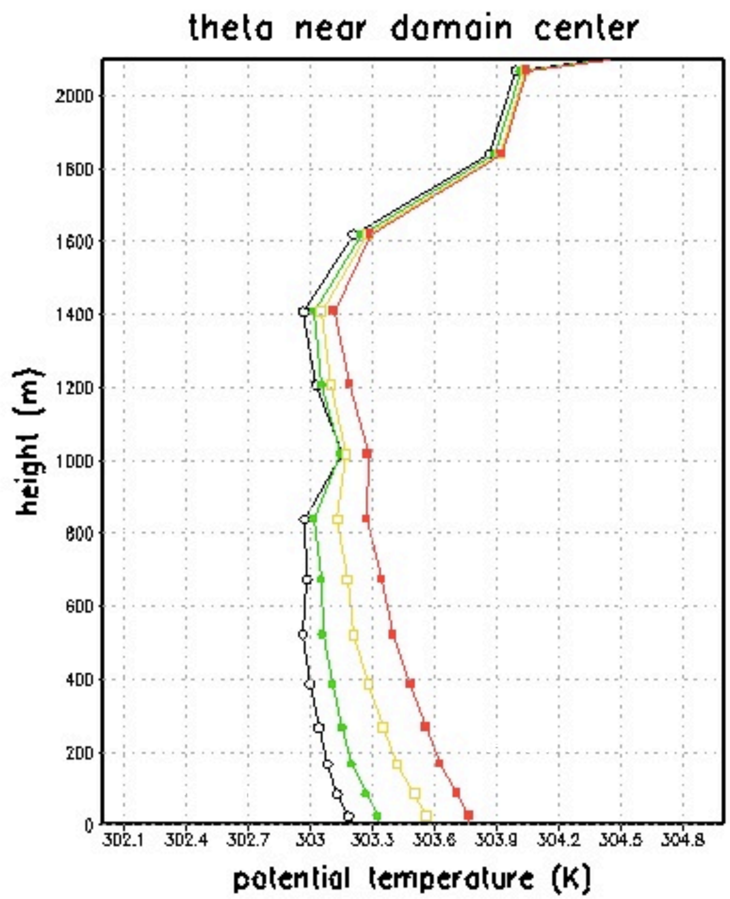
shear vector turns w/ z

Vertical velocity at 1.5 km AGL
(above the shear layer)



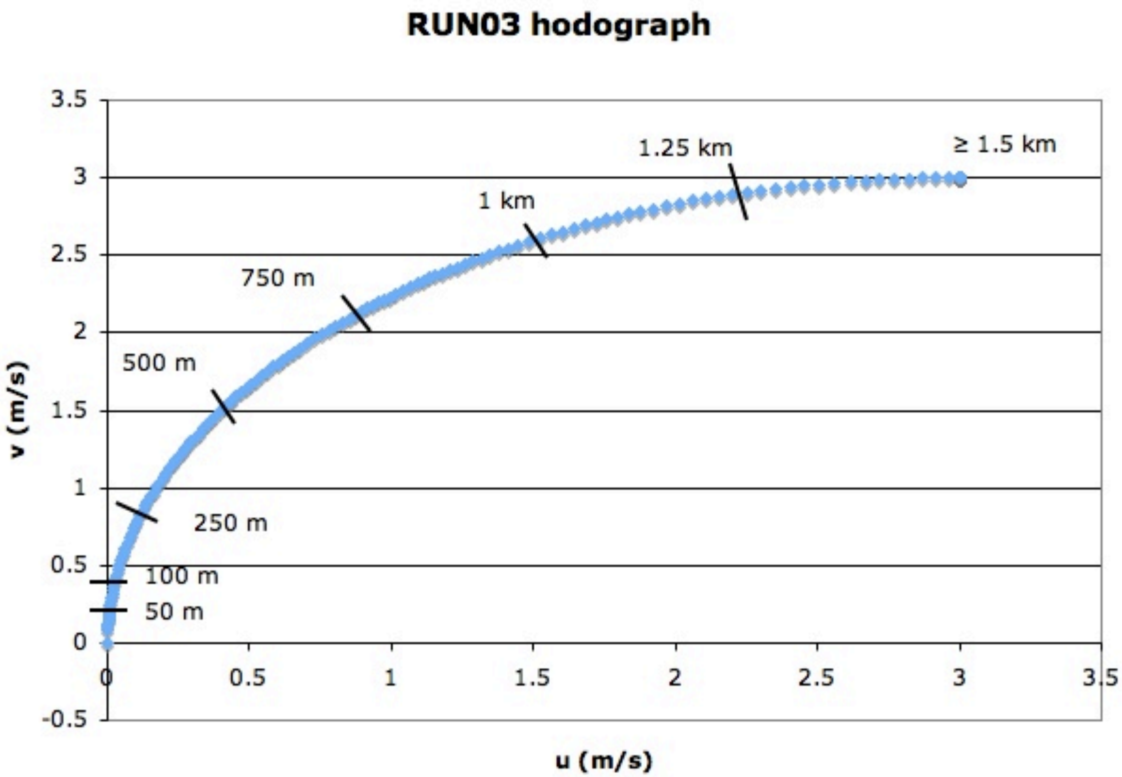

w (cm/s) time = 39 min
0
5
10
15
20
25
30
35
40

Vertical profiles of θ



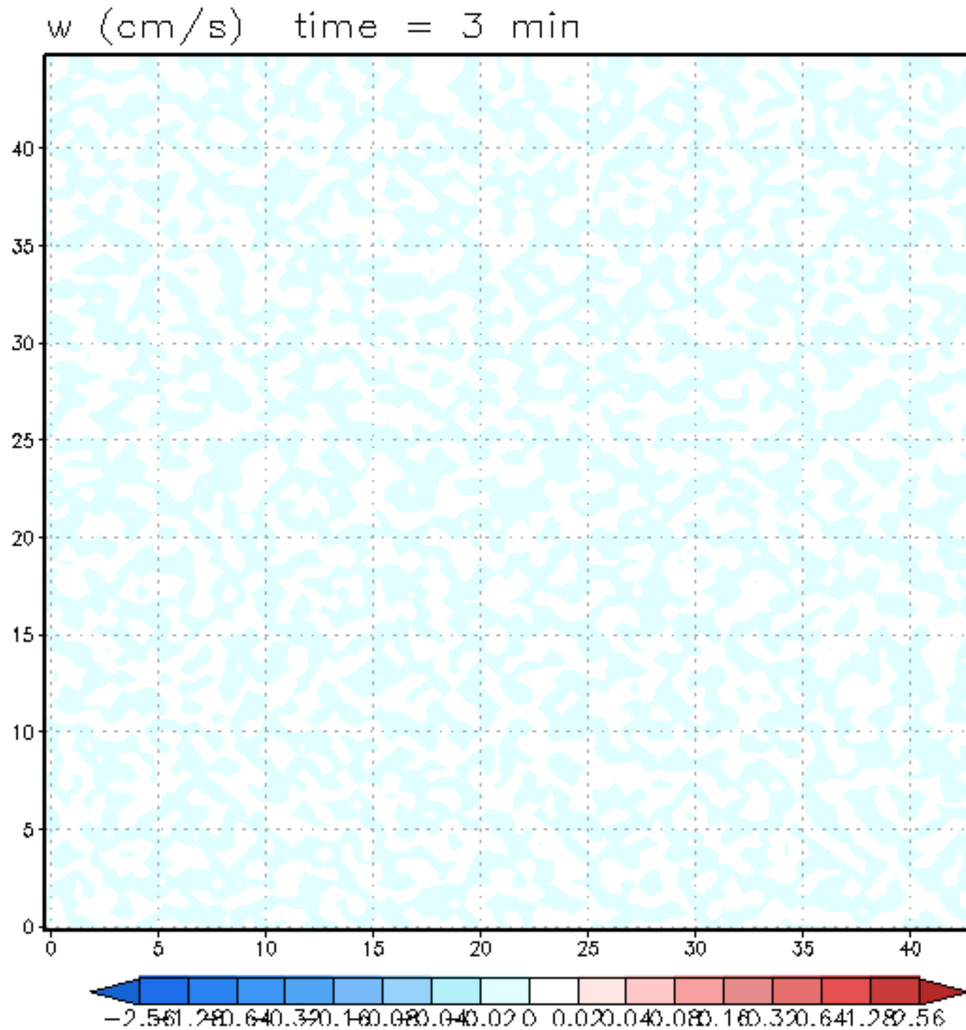
What happens if the shear vector varies with height?

RUN03



Shear vector veers with height
Little surface wind

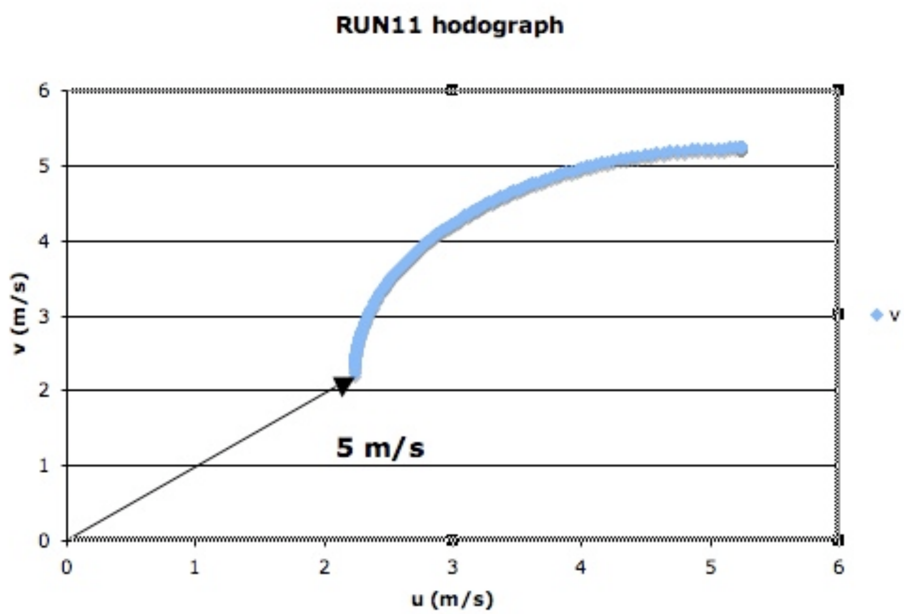
Animation



Lack of rolls in RUN03…

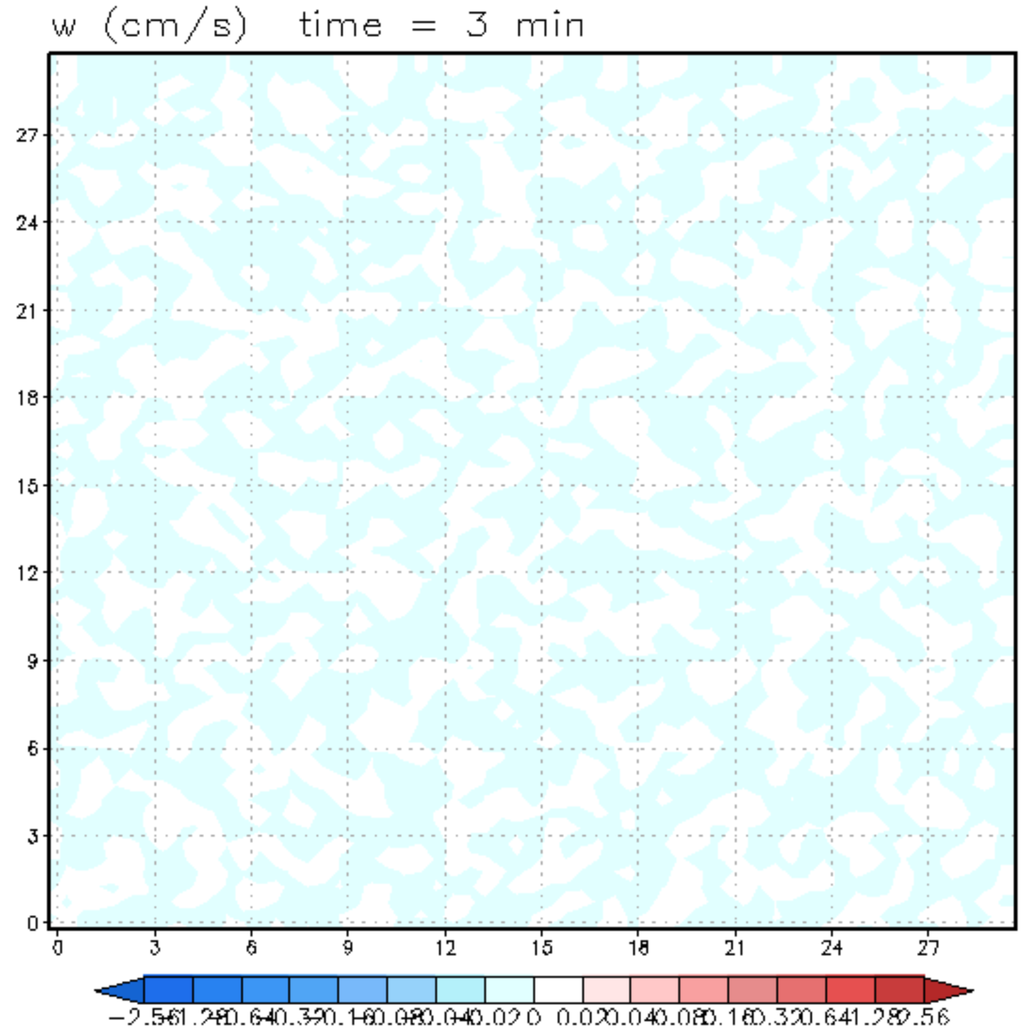
- Not enough shear?
- Too much directional shear?
- Not enough wind near surface? (Needed for surface heat flux)

RUN11
same shear, added mean wind



RUN11

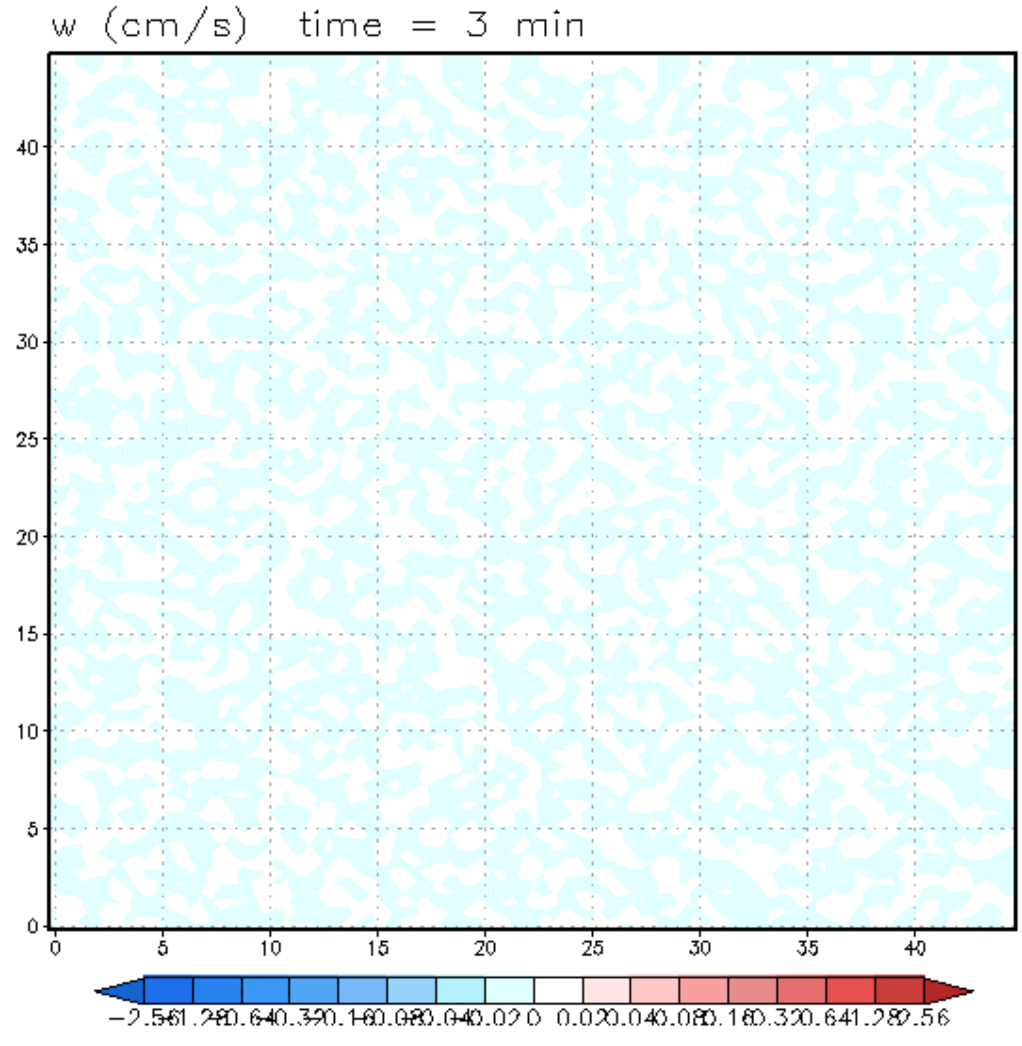
same shear, added mean wind



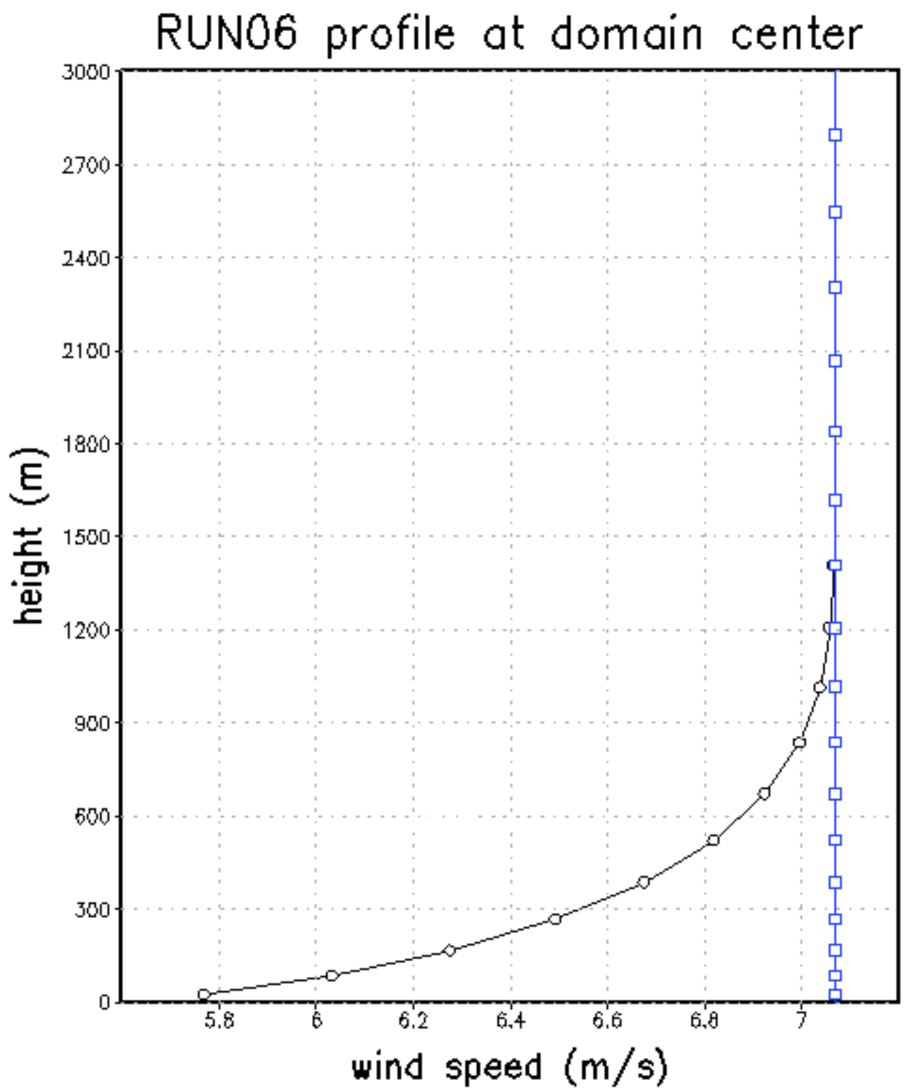
Smaller domain; same aspect ratio

What happens if we have no shear?

RUN06 - no (initial) shear



RUN06 - no (initial) shear

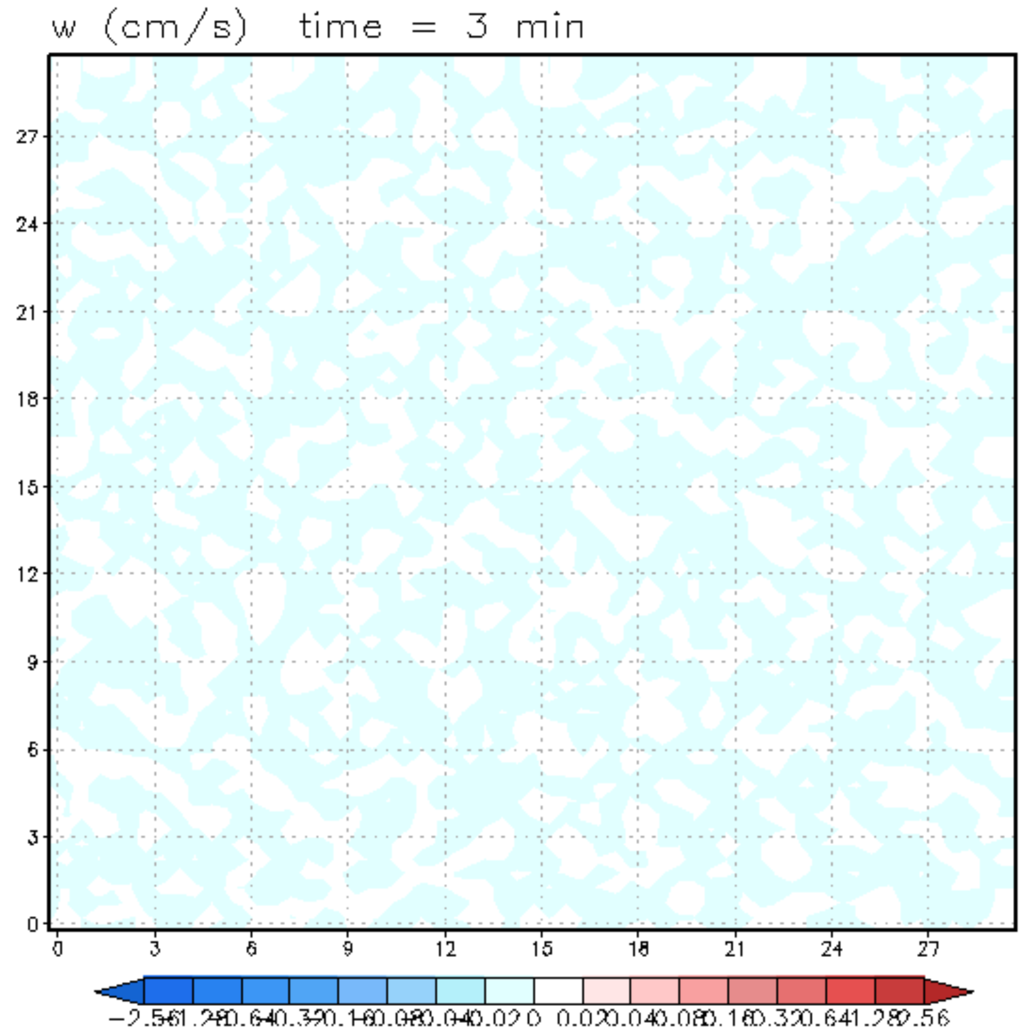


Shear created by surface friction

note small values

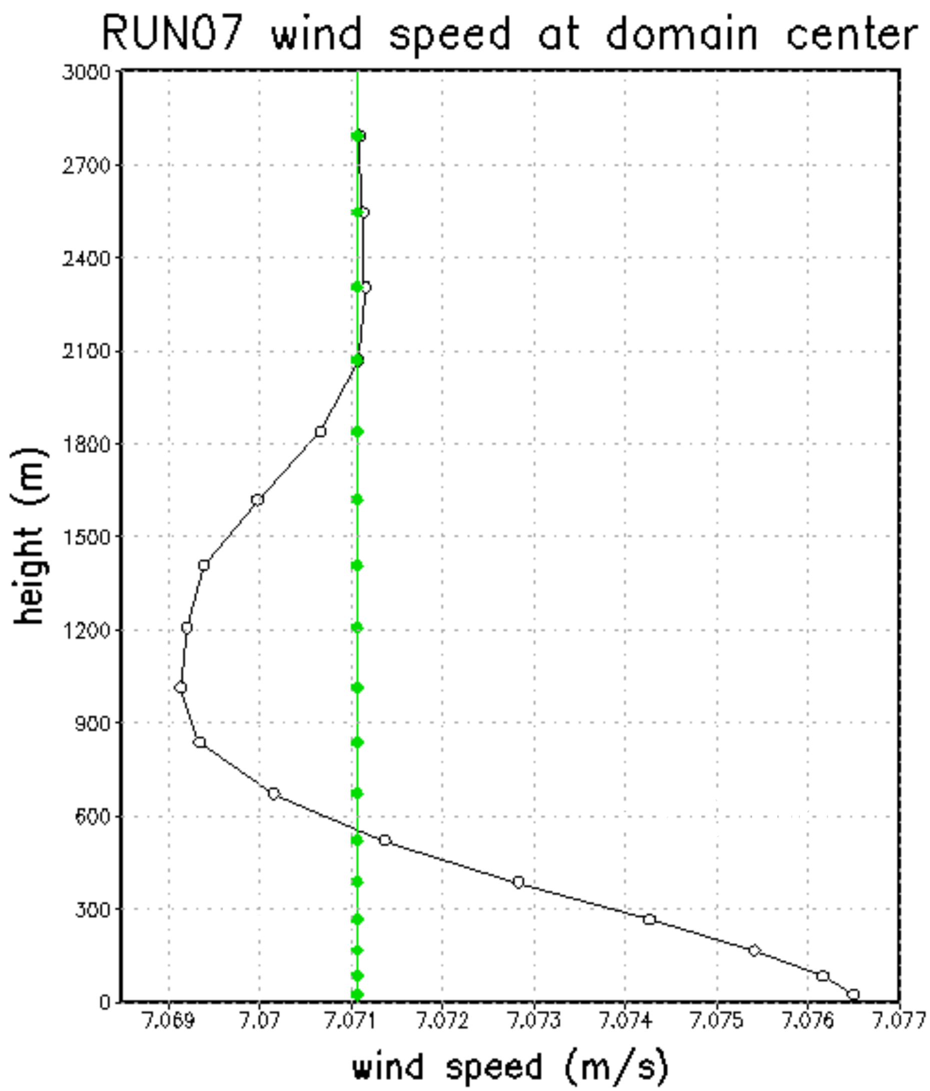
RUN07

no initial shear, no drag



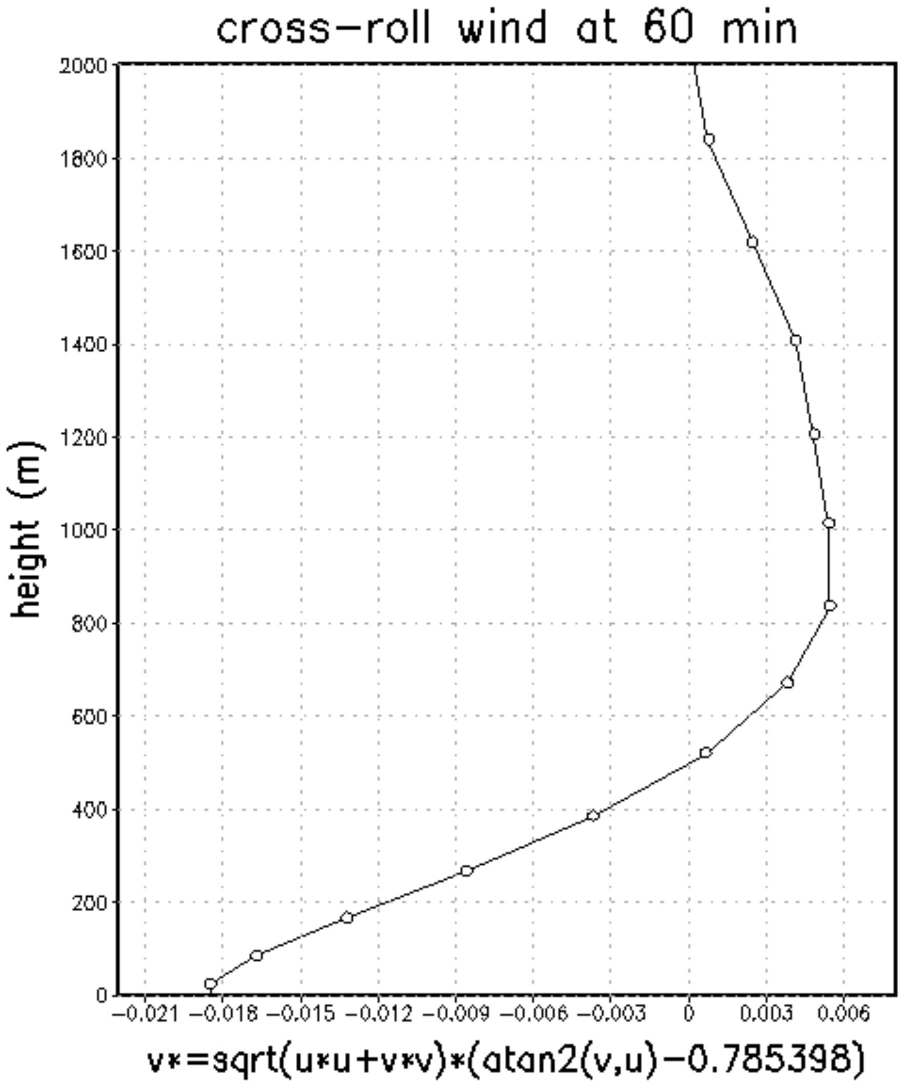
RUN07

no initial shear, no drag



Variation is very, very small

RUN07
no initial shear, no drag

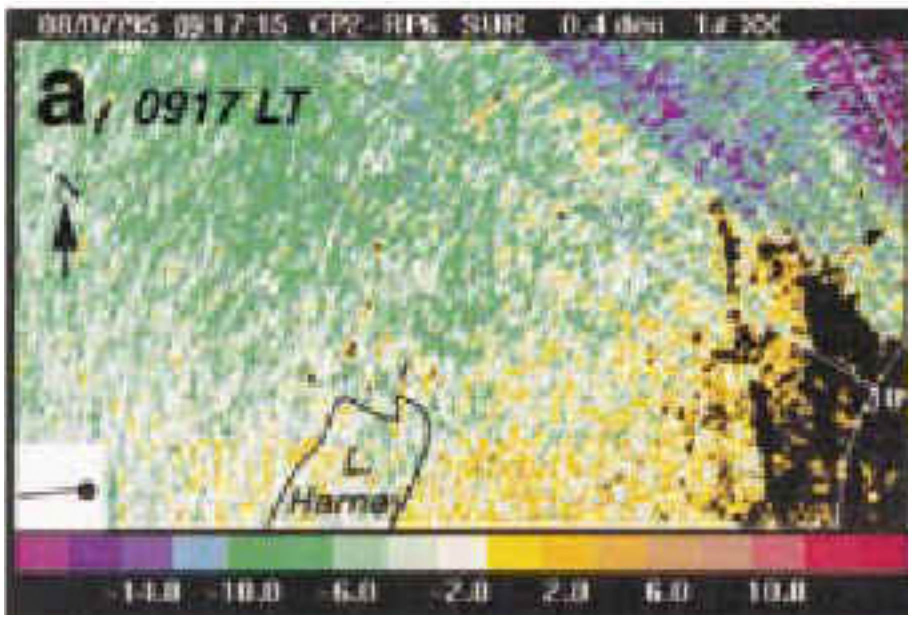


Cross-roll flow develops inflection point, but shear VERY small

Rolls vs. cells

- Monin-Obukhov length *L*
  - Ratio of vertical momentum flux to vertical heat flux (*negative* for strongly heated surface)
  - *L* magnitude large when heat flux small (i.e., early in day); decreases through afternoon
- Boundary layer depth z_i
- $-z_i/L$ is large when PBL is very unstable
- Deardorff (1972): rolls exist for $-z_i/L$ between 0 and 45
  - Other studies came up different ranges
  - Generally, with larger $-z_i/L$ rolls <u>less</u> likely
  - Therefore, rolls can change to cells as surface heats up

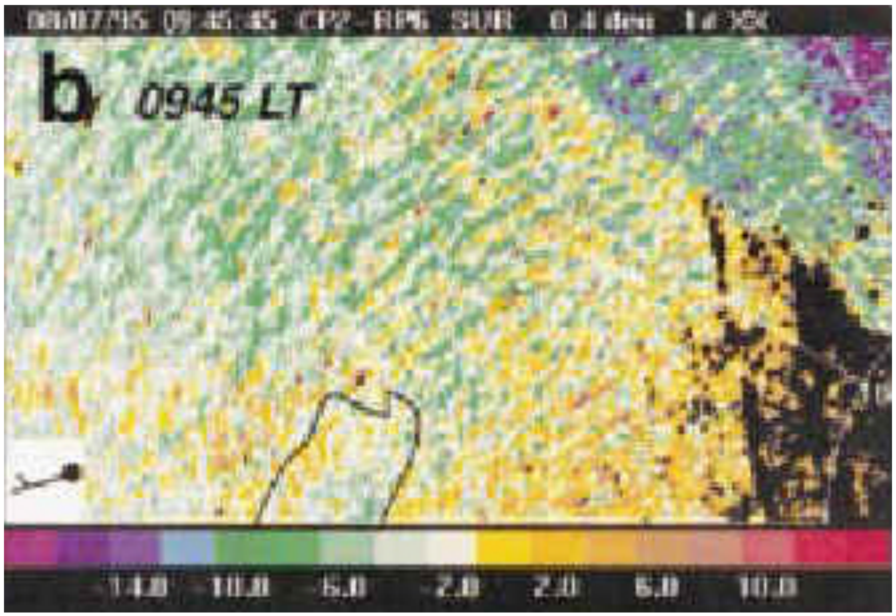
Rolls vs. cells



Early in day: no structure

Nolan Atkins

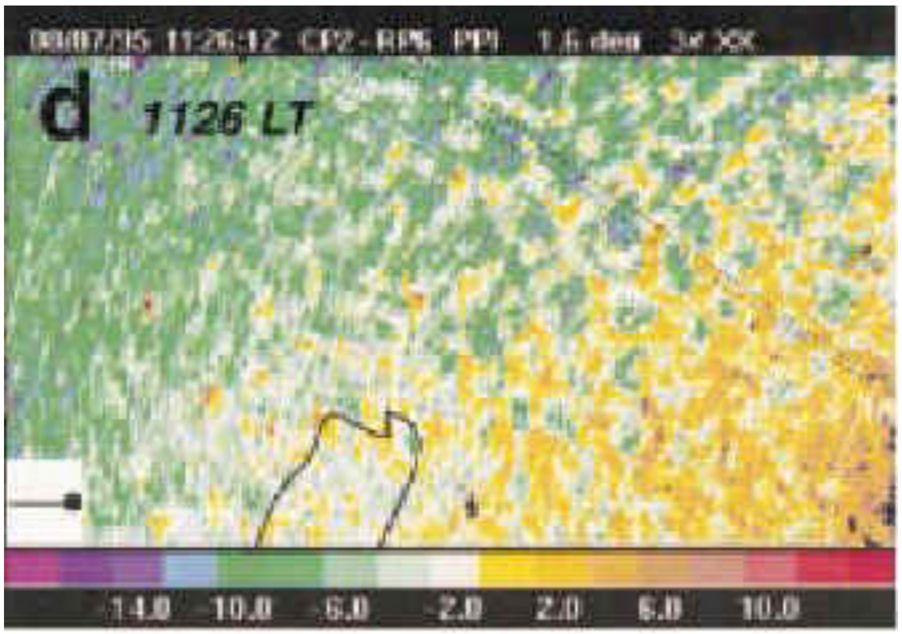
Rolls vs. cells



Surface heating increases; rolls appear

Nolan Atkins

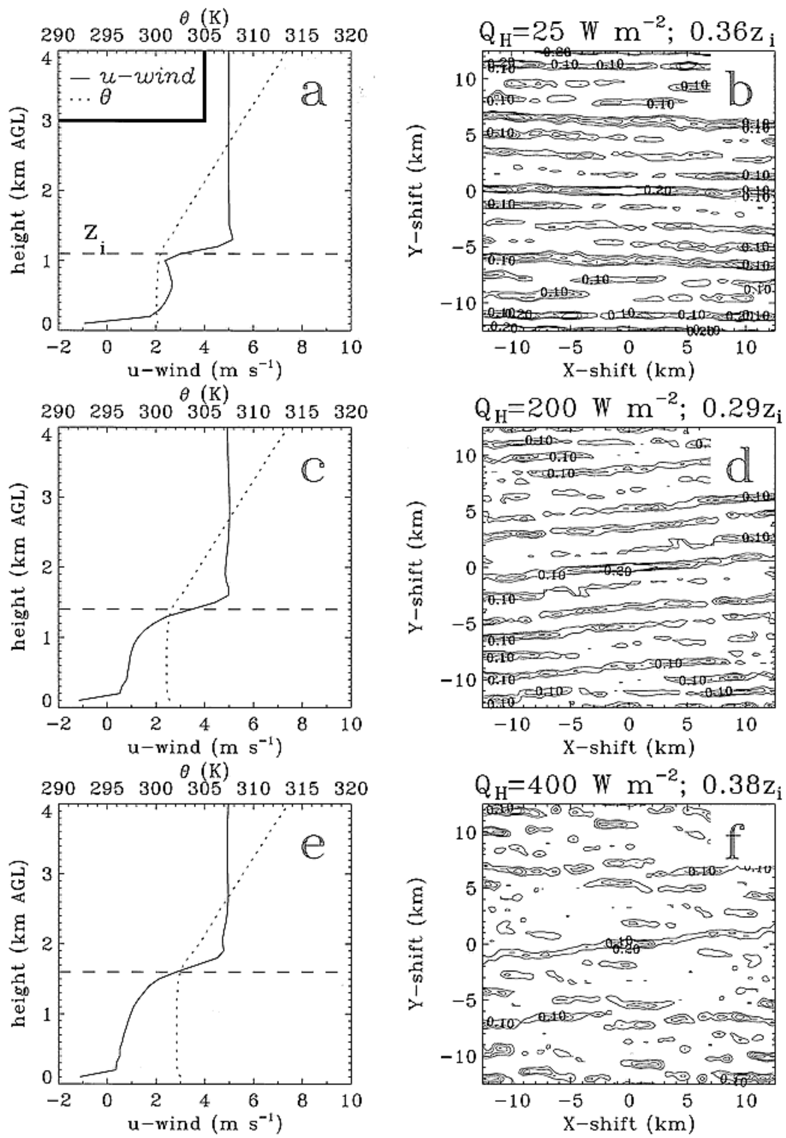
Rolls vs. cells



Stronger heating; cells replace rolls

Nolan Atkins

Weckwerth's experiments



Roll behavior as function of <u>surface heat flux</u> Q_H

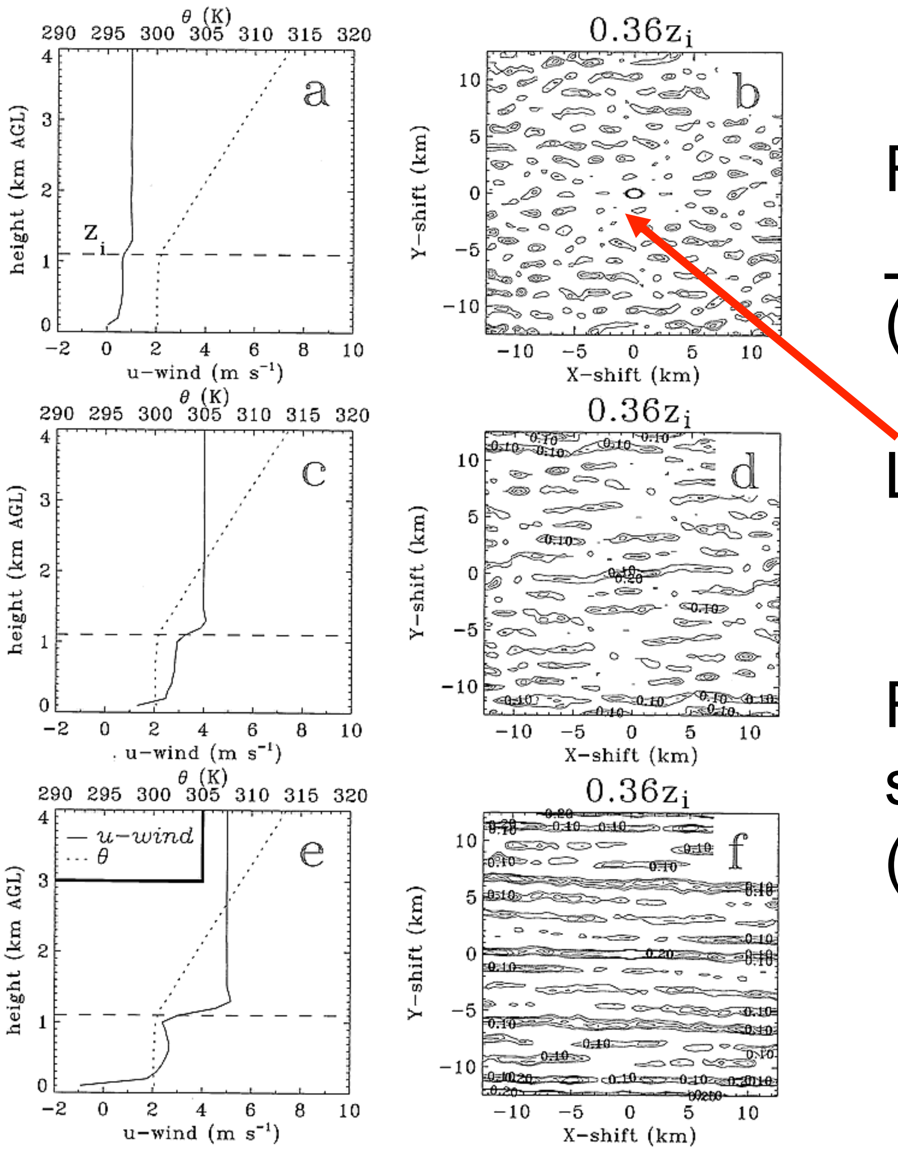
Plots at right show autocorrelation rather than vertical velocity

Small heat flux: rolls parallel to wind and wind shear

Rolls less coherent as surface heat flux increased; Turn CCW a bit first…

Weckwerth et al. (1997)

Weckwerth's experiments



Roll behavior as <u>surface wind speed</u> increased (fixed z_i)

Light surface winds -- rolls or cells?

Rolls more coherent as surface wind increased (shear has also increased)

Weckwerth et al. (1997)

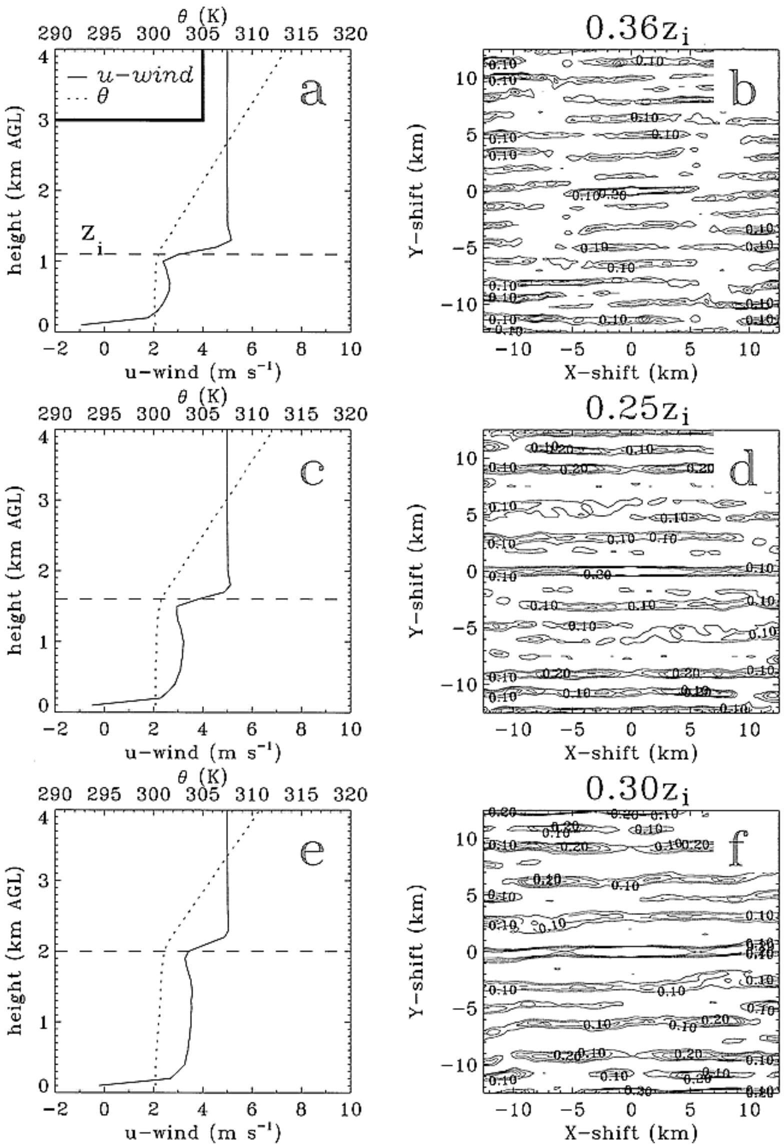
Roll wavelength

- Kuettner (1971) observations/theory

$$L_x = 2\sqrt{2}z_i$$

  - So as boundary layer depth z_i grows, horizontal roll spacing increases

Weckwerth's experiments



z_i

1.1 km

1.6 km

2.0 km

Varied PBL depth

Roll wavelength larger as PBL depth increases

Weckwerth et al. (1997)