Boundary Layer Rolls in the Plains

Nathaniel D. Reynolds

What are cloud streets and why do they form?

Clouds are observed to be arranged in “streets”, implying the presence of bands of rising motion.

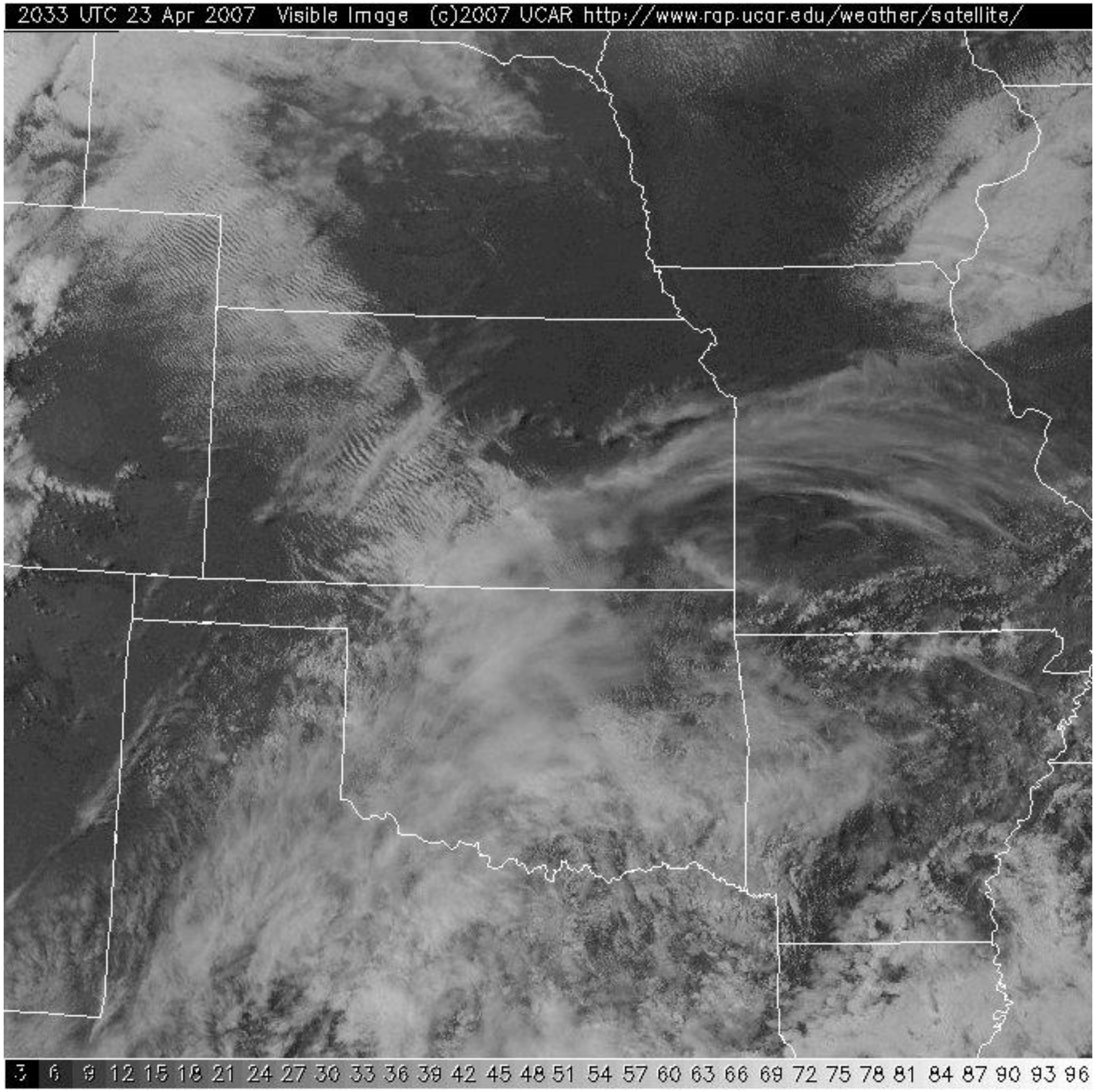
Observed by early astronauts from low earth orbit

Typical Parameters (Kuettner, 1971):

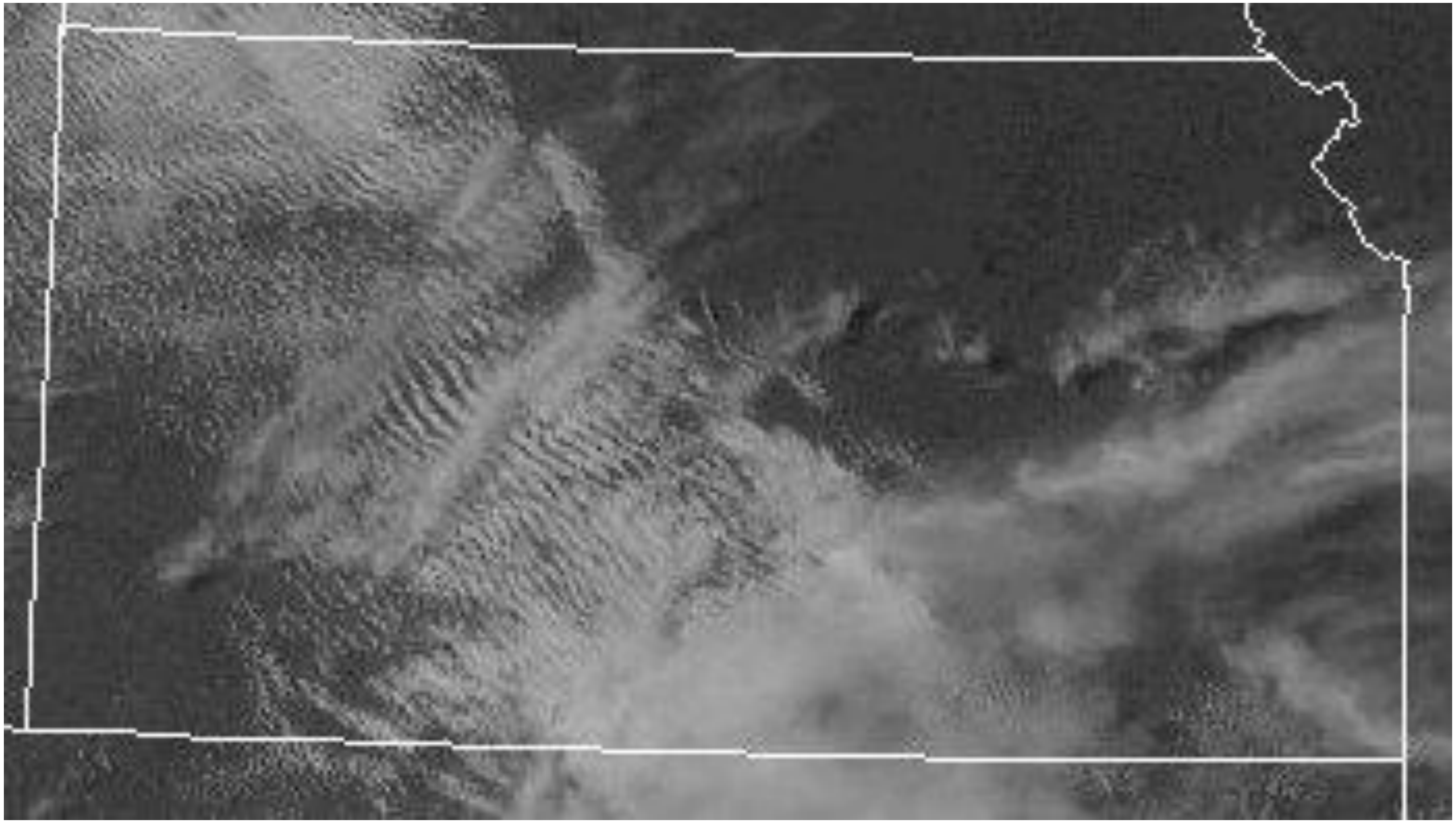
Length: 20 to 500 km
Spacing: 2 to 8 km
Layer Height: 0.8 to 2 km
Vertical Shear Gradient: 10^{-5} to 10^{-4} $m^{-1}s^{-1}$

Cloud Street Photograph

Satellite Image



Satellite picture, April 23, 2007

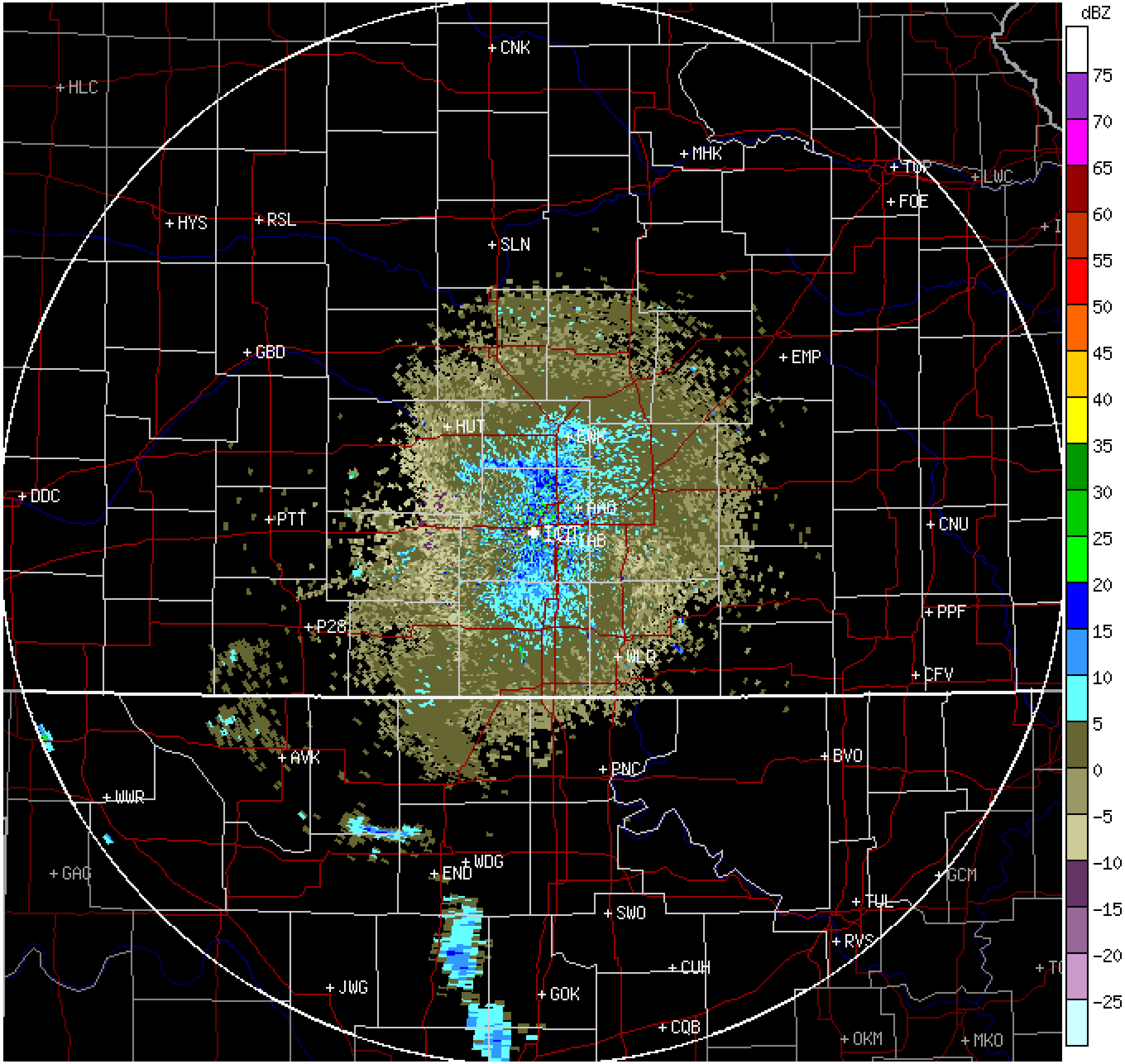


KICT -- Wichita, KS

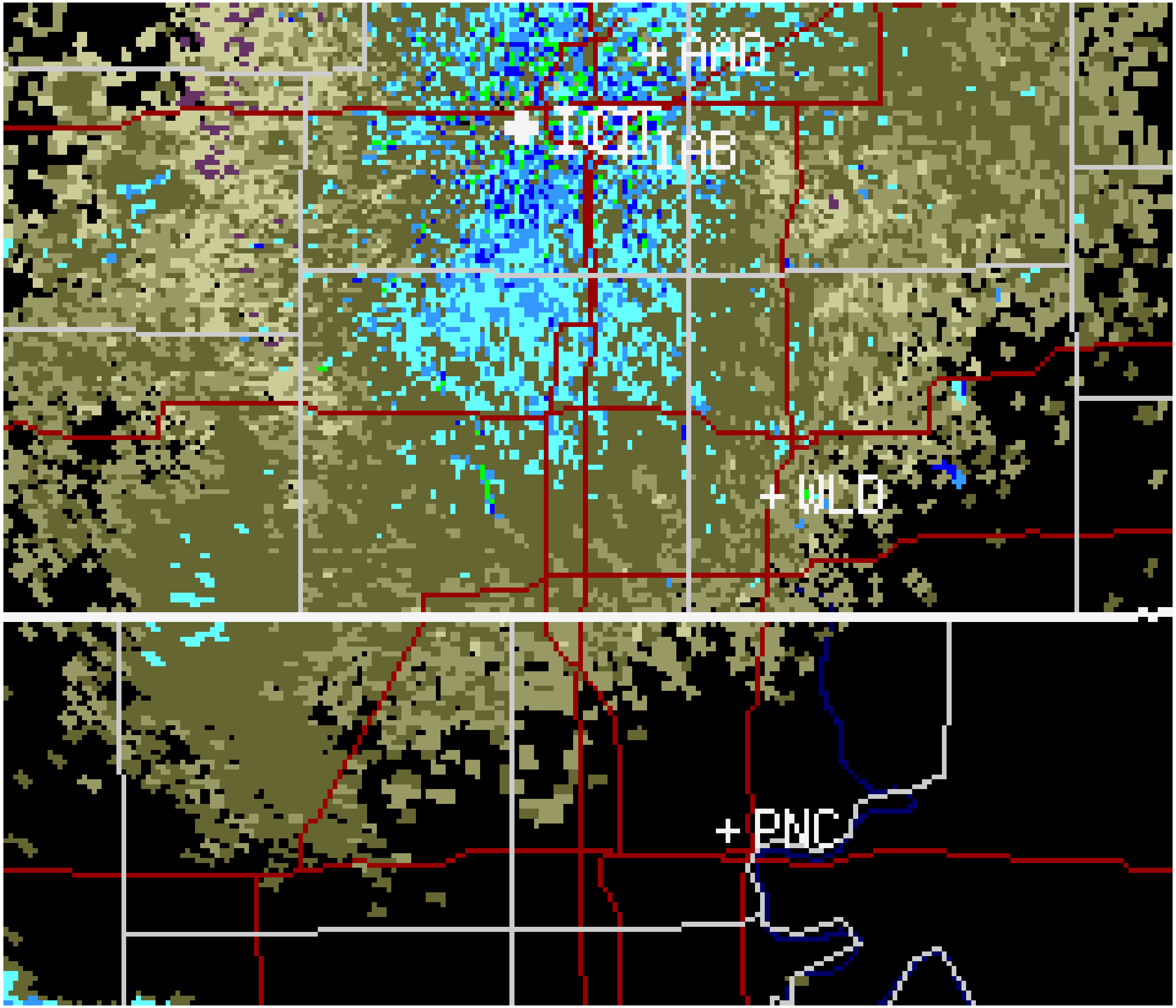
21:16:20 UTC Mon 23 April 2007

Base Reflectivity: 0.5 degrees, Clear-air Mode

(c) UCAR http://www.rap.ucar.edu/weather/radar/



Closer look at radar image



IMPORTANCE

Thunderstorm initiation (Weckwerth, *Mon.Wea.Rev*., 2000)

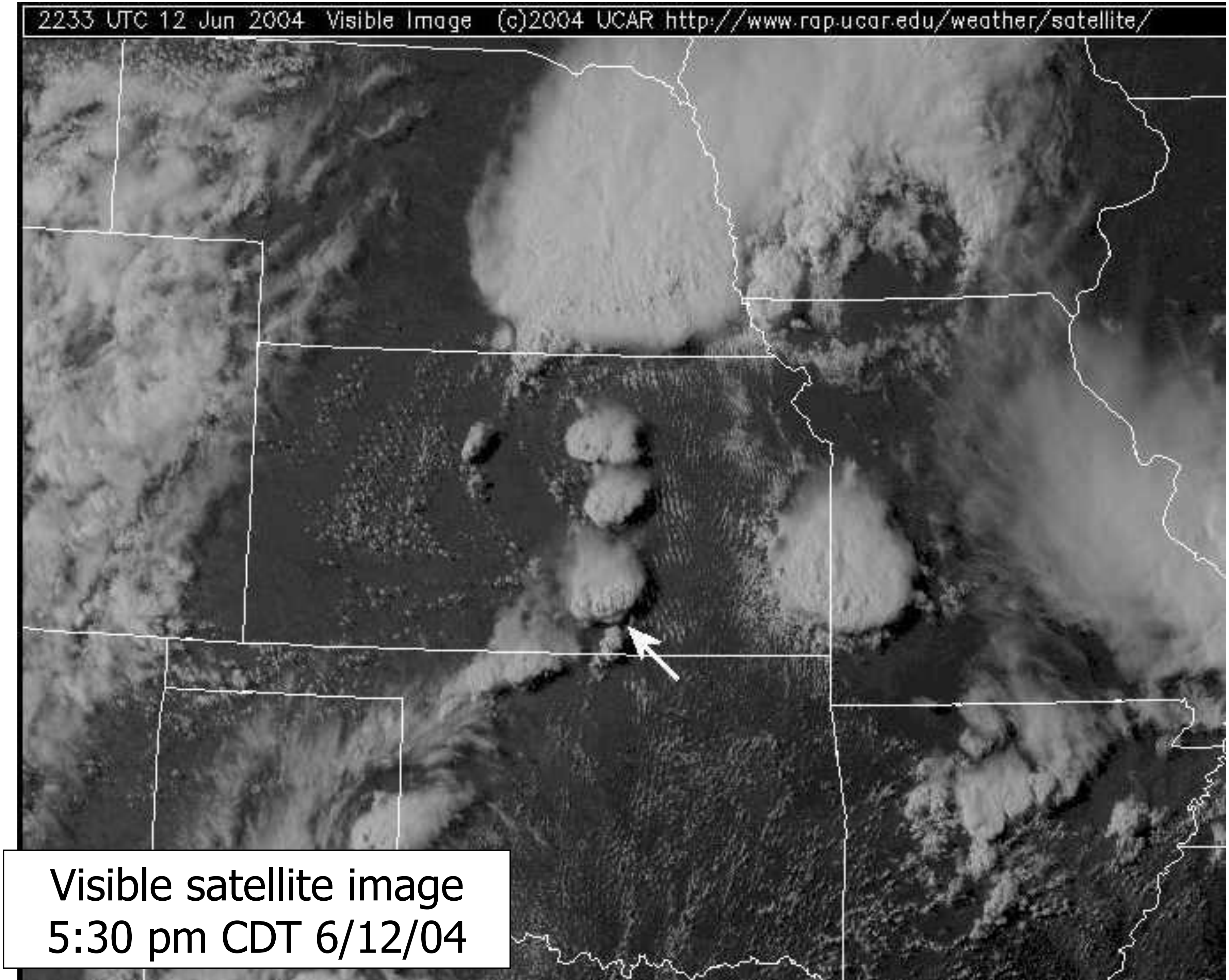
Convection and Precipitation Experiment, Florida, 1991

Rolls present about every day

Rolls often appear to initiate thunderstorms; at other times, rolls are present without thunderstorms

Goal of experiment: Improvement of thunderstorm prediction

Suggested that one needed better knowledge of static stability distribution



Visible satellite image
5:30 pm CDT 6/12/04

Long Distance Soaring:
(A. Woodcock, 1942, Etling and Brown, *Tellus*, 1993; Kuettner, *Tellus*, 1971)

J.P. Kuettner was a glider pilot, and was interviewed for the July 2006 BAMS.

Glide slope of glider:

Vertical velocity is of order 1 m/s

Question:

Will soaring only provide us with sport aviation, or is there a potential via new technology for serious, systematic use of atmospheric rising motion to keep aircraft aloft?

Theoretical Considerations:

Boundary layer circulations are an important part of atmospheric thermal balances involving heat exchange with the surface.

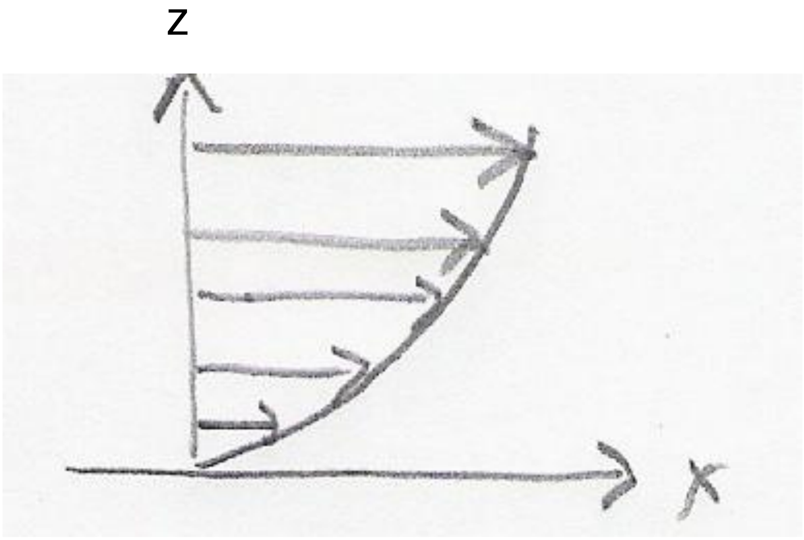
Atmospheric Environment:

Statically Stable, Neutrally Stable,
or Statically Unstable
Importance of the Coriolis Force
Orr-Sommerfeld equation
Ekman Layer equations

Neutrally Stable

Boundary Layer Profile:

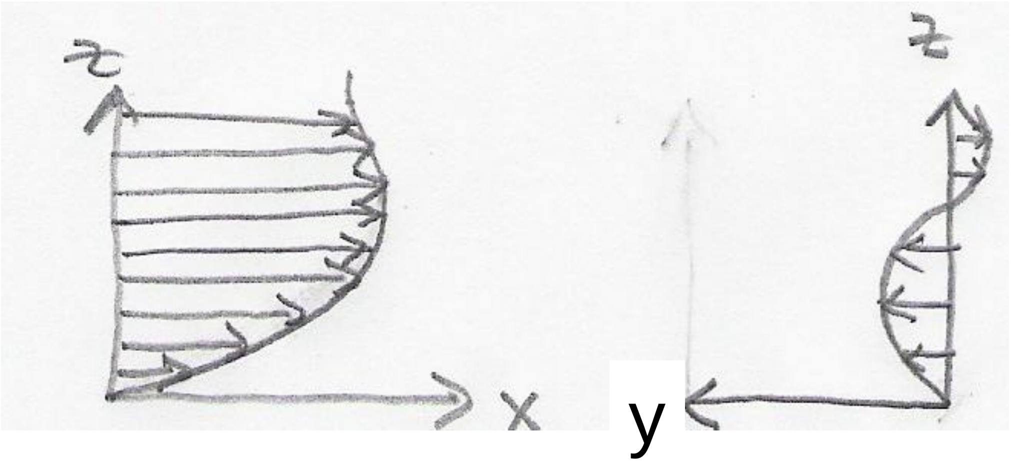
Tropics: (Non-rotating coordinates)



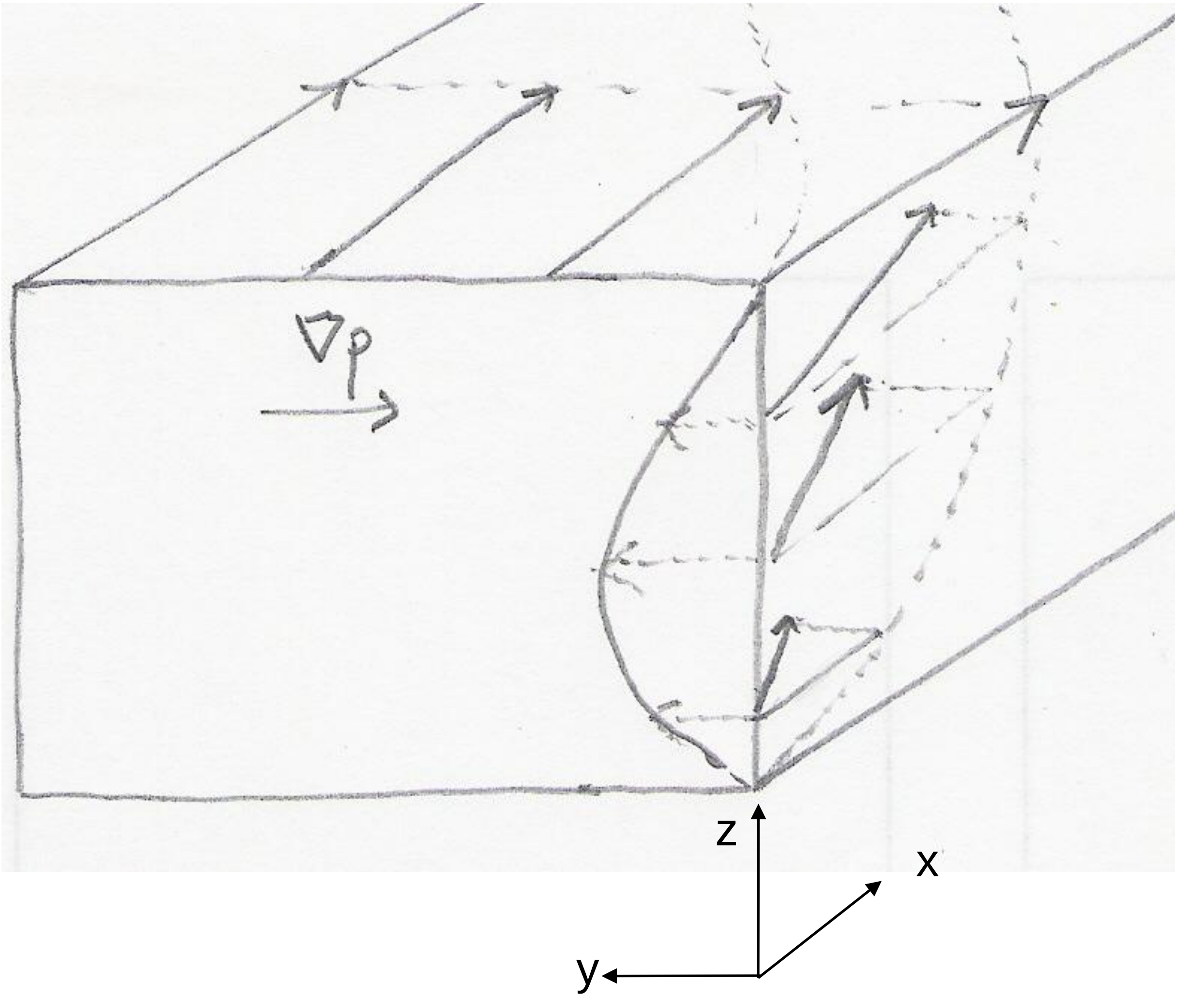
Boundary Layer Profile:

Mid or High Latitudes:
(Basic Flow dependent on the Coriolis force)

Ekman Spiral



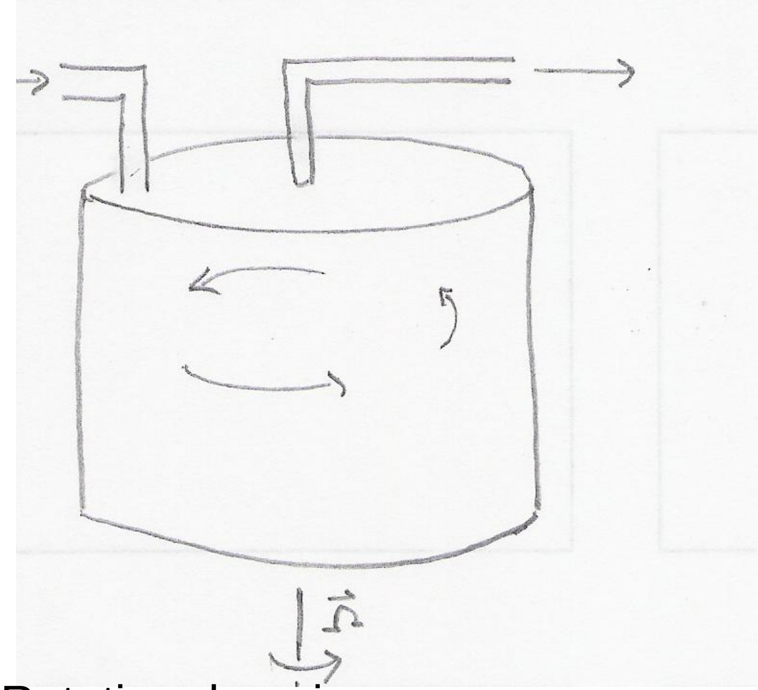
Mass Transport



M.E. Stern, 1960

Lab Experiment

Theory



Fluid Drawn

Fluid input

Rotating domain

Mean Ekman Flow and Perturbation

$$h_E = \left(\frac{\nu}{\Omega}\right)^{1/2}$$

$$E = \frac{\Omega H^2}{\nu}$$

Taylor number

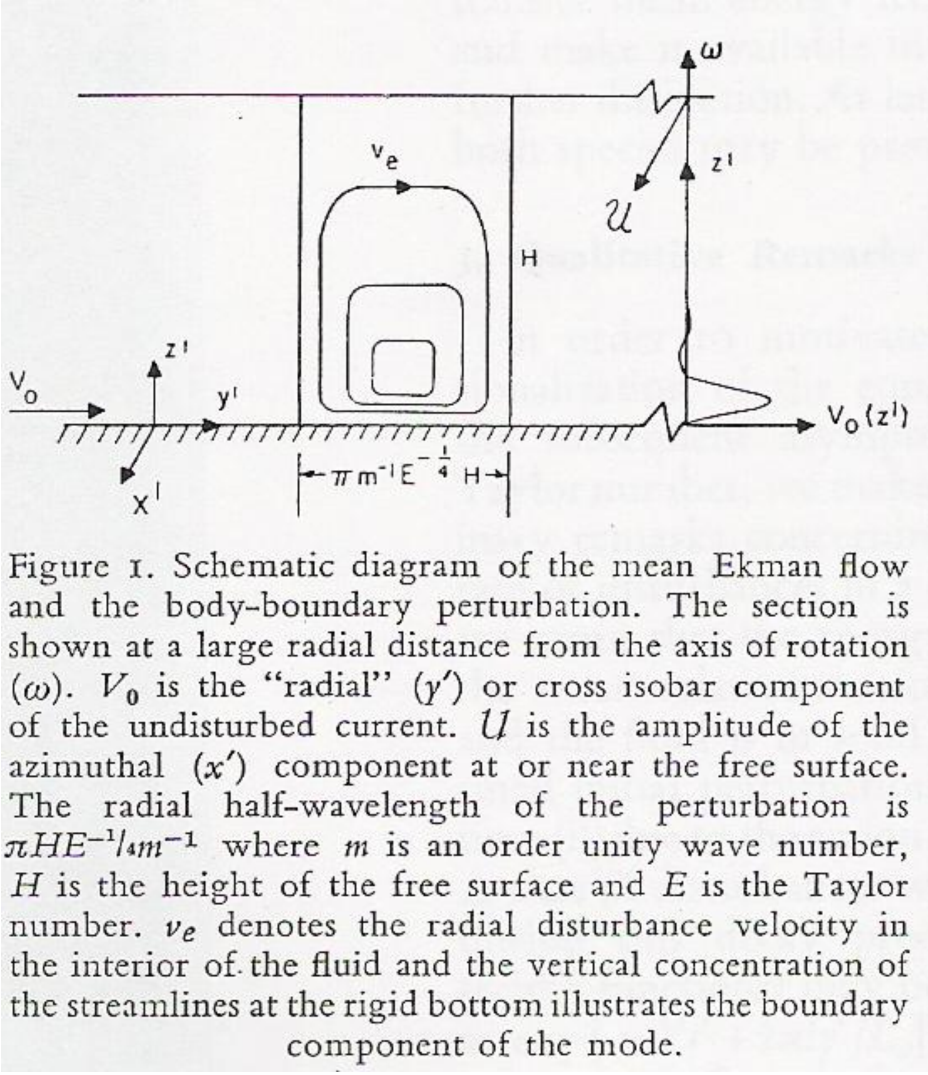
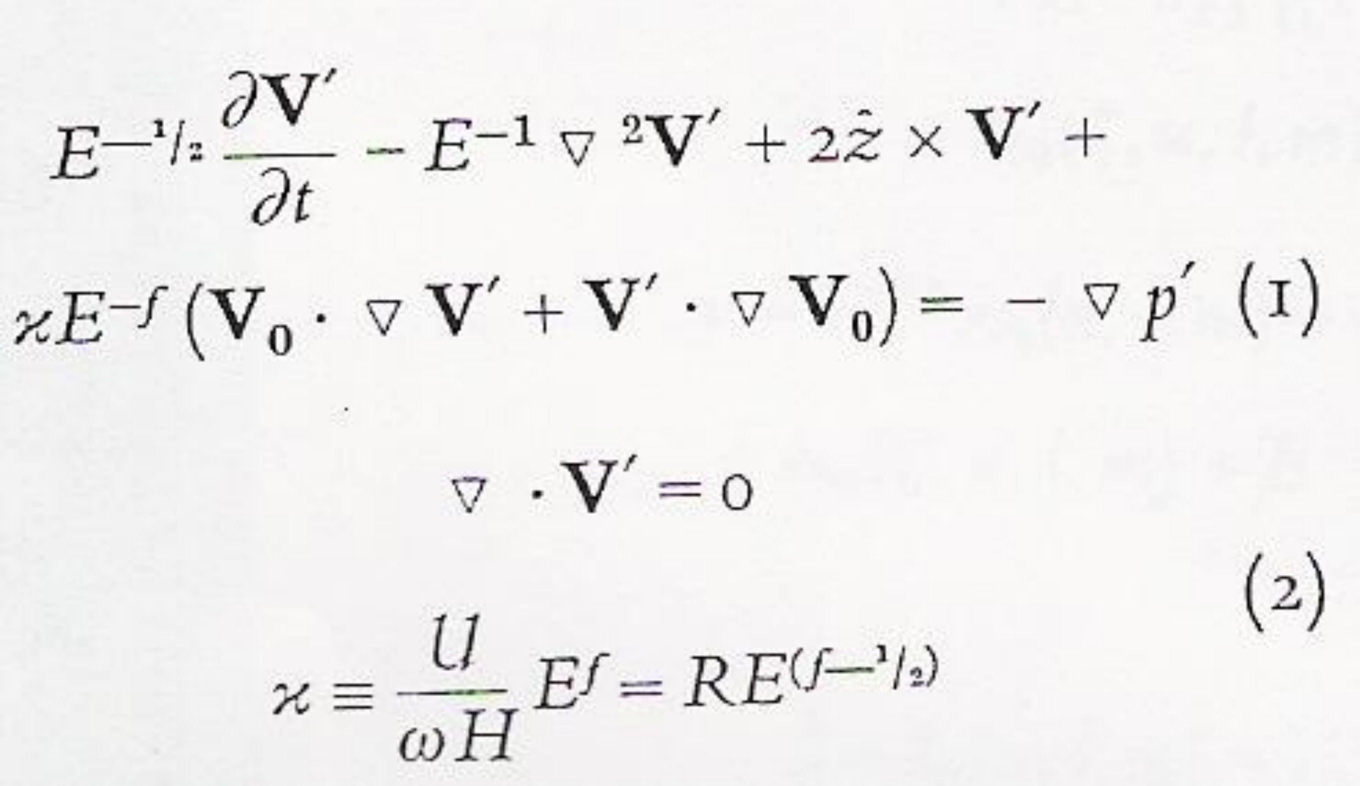


Figure 1. Schematic diagram of the mean Ekman flow and the body-boundary perturbation. The section is shown at a large radial distance from the axis of rotation (ω). V_0 is the "radial" (y') or cross isobar component of the undisturbed current. $\mathcal{U}$ is the amplitude of the azimuthal (x') component at or near the free surface. The radial half-wavelength of the perturbation is $\pi H E^{-1/4} m^{-1}$ where m is an order unity wave number, H is the height of the free surface and E is the Taylor number. ν_e denotes the radial disturbance velocity in the interior of the fluid and the vertical concentration of the streamlines at the rigid bottom illustrates the boundary component of the mode.

Governing Equations

(after performing asymptotic expansion in Taylor number)



momentum

$$E^{-1/2}\frac{\partial \mathbf{V}'}{\partial t} - E^{-1}\nabla^{2}\mathbf{V}' + 2\hat{z}\times\mathbf{V}' + \varkappa E^{-f}\left(\mathbf{V}_0\cdot\nabla\mathbf{V}' + \mathbf{V}'\cdot\nabla\mathbf{V}_0\right) = -\nabla p' \qquad (1)$$

continuity

$$\nabla\cdot\mathbf{V}' = 0 \qquad (2)$$

Scaling of the viscous effect

$$\varkappa \equiv \frac{U}{\omega H}E^{f} = RE^{(f-1/2)}$$

Linear stability analysis

Scale analysis: f = ¼

Assign wavenumbers in x and y and determine complex frequency λ

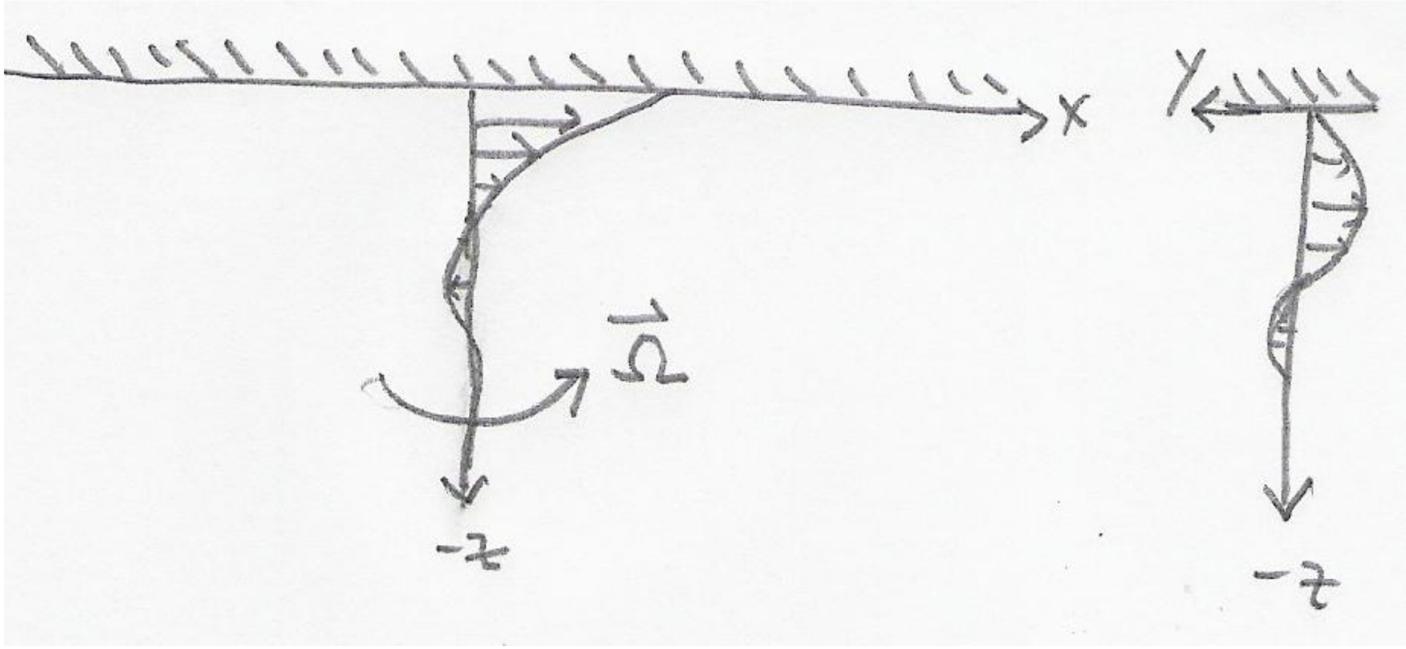
Obtain a marginal stability curve

Ekman suction, and magnitude related to Ekman layer depth and horizontal convergence.

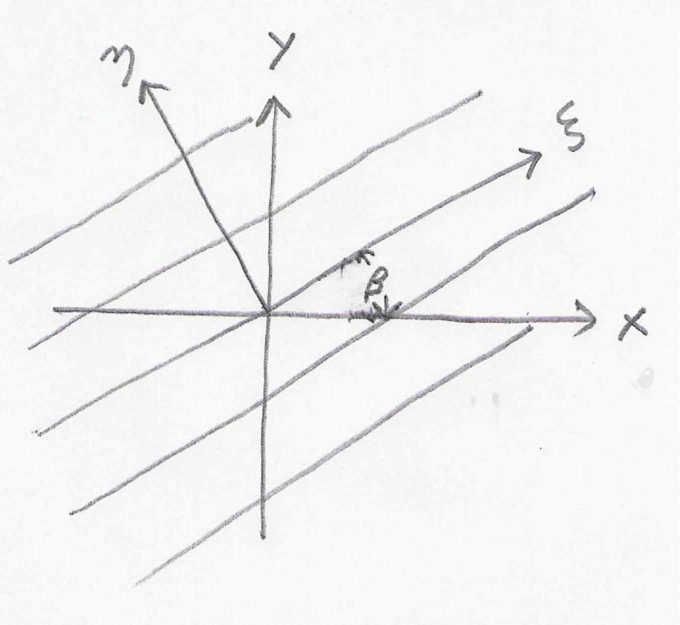
“Additional modes” Direct, stronger coupling between boundary layer and free atmosphere

V. Barcilon (1965):

Infinitely deep rotating fluid at rest, with a rigid lid moving at a constant velocity in the x direction



Instability of Non-Divergent Ekman Layer



- Plane wave solution
- Waves oriented at angle β to direction of translation of lid

Barcilon writes perturbations in the ξ, η system, and obtains a sixth order set of equations that have solutions which are reducible to the 4 solutions of the Orr-Sommerfeld equation obtained from plane-parallel flow.

Although the Coriolis parameter influences the velocity field, it does not affect the neutral stability curve.

Lilly (1966)

Neutrally Stratified Ekman flow is unstable for large enough Reynolds number.

R.A. Brown, *J Atmos Sci*, 1970:

Neutrally buoyant Ekman profile plus a finite amplitude helical rolls.

The full solution alters the ***dynamically*** unstable Ekman profile to become stable in combination with the secondary flow.

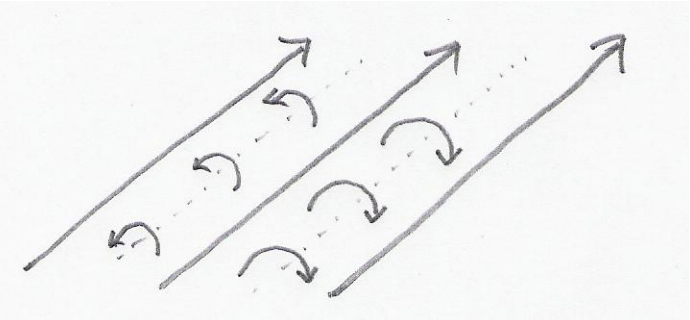
Statically Unstable

Measure of the ratio of the stratification effect to the shear: Richardson number Ri

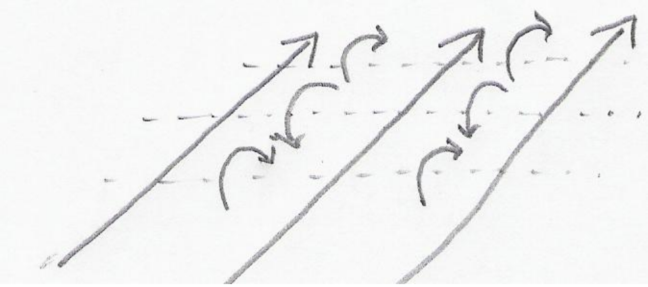
Kuo, 1963

Negative Ri: Convectively unstable. Rayleigh convection problem

Small negative Ri: Longitudinal rolls



Large negative Ri: Transverse rolls

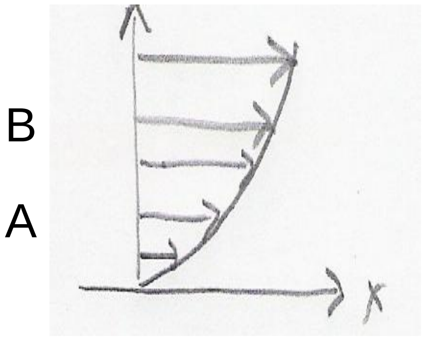


Physical description of longitudinal roll instability mechanism: (Lin, 1955, Kuettner, 1971):

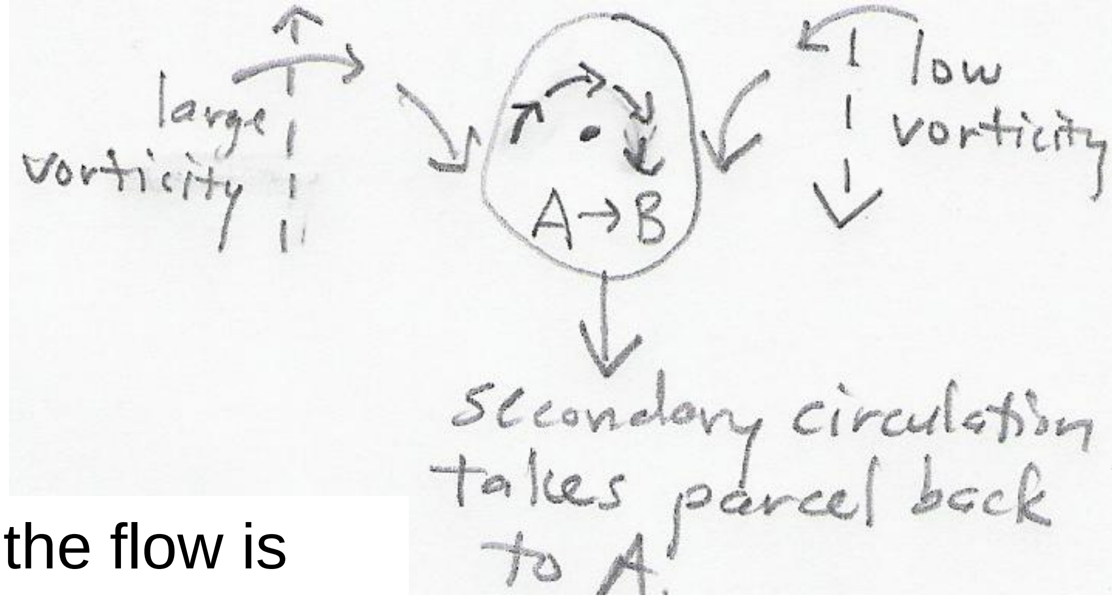
Mechanism of instability is based on conservation of vorticity

For parallel flow, the vorticity is the vertical
shear of the horizontal wind.

Suppose the vorticity decreases upward; i.e. the second partial of u with respect to z is less than zero. (No infllection point.)



Displace a parcel from point A to B. It will carry its vorticity with it, and will have a vorticity excess over its neighbors.



Therefore the flow is dynamically stable.

If an inflection point exists, then a displaced parcel may "camp out" at a place on the other side of the inflection point where there is the same vorticity. This would result in instability.

- If buoyancy displaces a parcel, it has to overcome the restoring force due to vorticity.

Lines of parcels

Suppose buoyancy displaces a line of parcels that is oriented parallel to the flow.

Then, in the x-z plane, there is no excess of vorticity at any point relative to others.

Therefore there is no “vortex restoring” force to overcome.

The flow is completed in the y-direction.

In the y-direction, there is no vortex restoring force since there is no basic state shear in the y-direction.

Rayleigh theory of convection

- Critical Rayleigh number for onset of convection in a fluid at rest is the same as that for 2-D longitudinal rolls.
- The Rayleigh number for 3-D cells and for 2-D transverse rolls is higher.
- Hence, as heating of a flow occurs, the 2-D longitudinal rolls may be unstable while the others are stable.

Etling and Brown, *Boundary Layer Meteorology*, 1993

(Review)

Examine a number of observations and numerical experiments (LES)

Various parallel, inflection point, and convective instability mechanisms have been proposed

Capping inversion usually suppresses the inflection point instability

Etling and Brown conclusions:

Both dynamic (inflection-point) and convective instabilities play their roles in these large eddies in certain situations

Sometimes wave-wave interactions are important

No single instability mode can explain the observed structure of large roll-type eddies

Observed cloud streets are probably flow visualizations of a multi-scale boundary-layer process containing dynamic instabilities, thermal instabilities, and nonlinear interactions between various scales of motion

Dubos, Barthlott and Drobinski (2008, JAS)

Quote numerous studies in which 2-D flows generated equilibrated rolls, but 3-D DNS and LES simulations featured instabilities feeding on these rolls and wiping them out

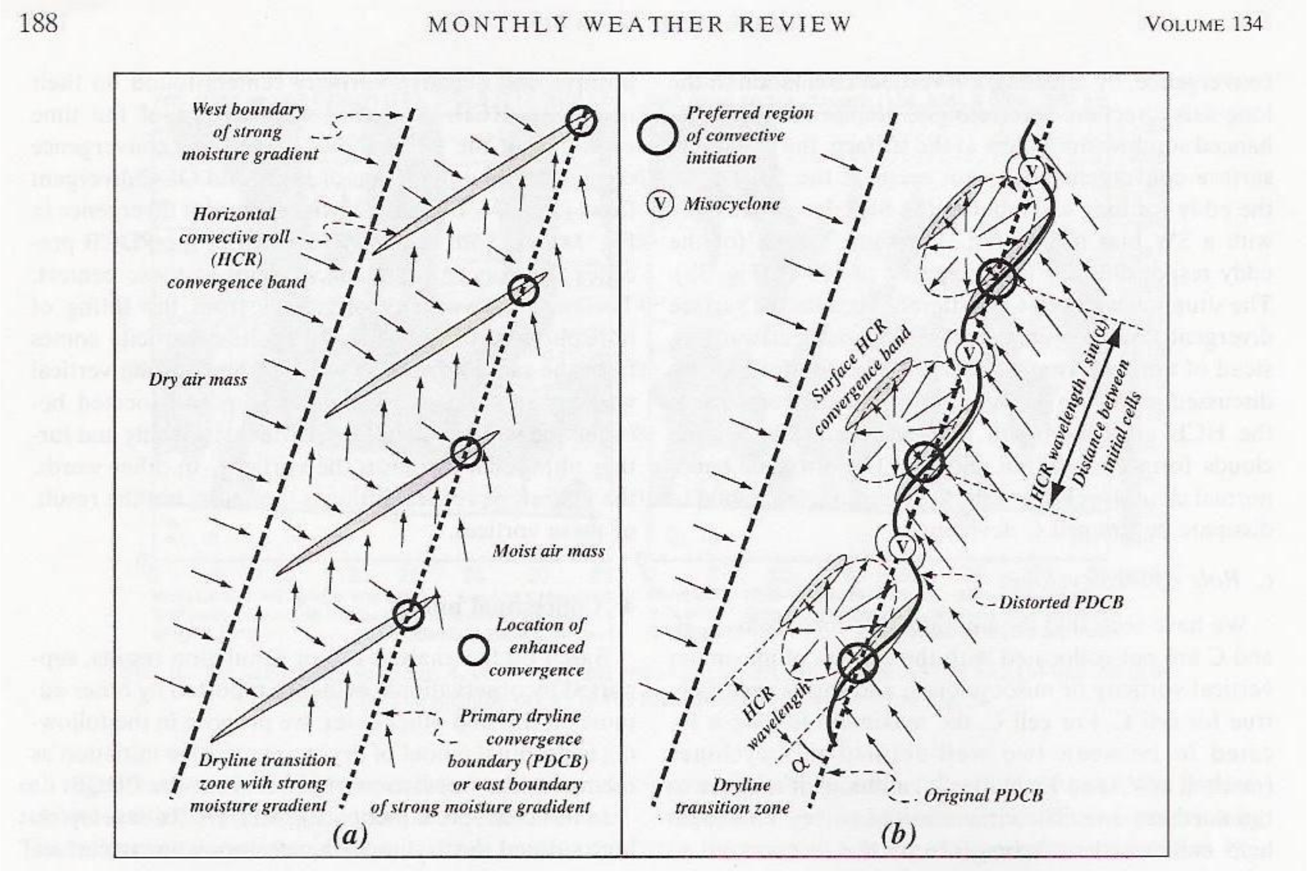
Demonstrate that 3-D instabilities act on rolls, but find it difficult to identify the nature of these in terms of known “pure” or idealized mechanisms.

Numerical Modelling

Xue and Martin, MWR, 2006

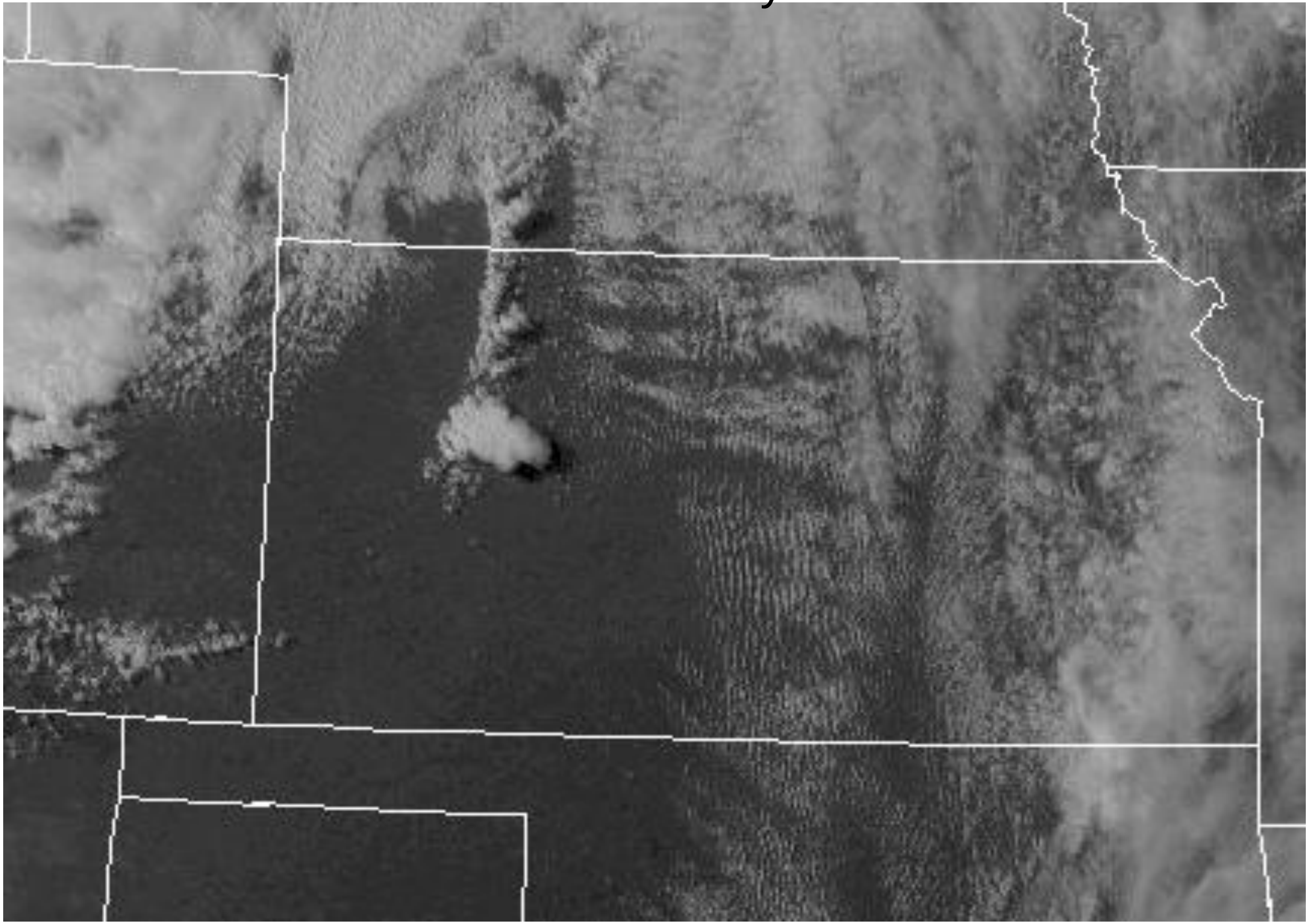
Produced rolls on both sides of dryline in numerical model, with stronger rolls to the west. Interaction of rolls and dryline yield convergence maxima which are favorable sites for convection.

Convective Initiation (Xue and Martin)



188 MONTHLY WEATHER REVIEW VOLUME 134

Example:
Roll Vortices in Kansas on Both Sides of the Dryline
2133 UTC 23 May 2007



20 minutes later severe storm reports started coming in in Gove County, KS

Measurements

Millimeter-scale wavelength Doppler radar

(Geers and Mian, JAOT, 2005): Int. $H_2 0$ Project (IHOP)

Echo plumes and “fine lines” provided by hordes of small insects transported by boundary layer circulations

Recent measurement of mountain lee waves:

Profilers

Sailplanes (Millane et al, JAOT 2010): A scheme to calculate velocity using flight data