Mesoscale Meteorological Features : Introduction

Recall from WAF I we largely emphasized synoptic-scale processes associated with vertical motion and precipitation.

Examples:
- QG Theory: QG-ω equation, Q-vectors
- Frontal circulations: QG + SG theory
- Jet streak dynamics
- Isentropic lifting

But we also talked about some cool season weather phenomena that were more on the mesoscale, in association with extreme weather.

Examples:
- Cold air damming & barrier jets
- Atmospheric rivers
- Mountain wave dynamics, downslope windstorms
- Lake-effect snow.

In this part of the course want to focus on important mesoscale features that are pre-requisite conditions for convective development (in CONUS)

Such features may be identified in mesoscale analyses (i.e. spatial scale of 1 to 10s of km) and may require the use of remote sensing data (i.e. satellite and radar) to effectively detect them.

Particular foci for warm season convection:

- Low-level jets
- Dry lines
- Density currents (e.g. due to storm outflows)
- Diurnally-forced circulations
  - Sea breezes
  - Mountain valley circulations.

How are these phenomena different than what we studied previously on the synoptic scale?

=> Comes down to basic idea of convective triggering.

1) They tend to have a strong tie to diurnal cycle of solar heating, which controls heating, moisture, and depth of PBL

2) Presence of orography, coastlines, or more basically a surface gradient that causes differential heating creates mesoscale circulations.

3) Density and moisture gradients tend to be focal points for convective initiation

Low-level jets

- Say "low-level" because they tend to occur in the lower troposphere (e.g. below 700-mb)

- Tend to transport warm, humid air (mT) from large bodies of water (e.g. Gulf of Mexico), providing "fuel" for convection.

- Important conveyors of atmospheric moisture deep into continental interior.

- Tend to occur more nocturnally, because of PBL decoupling and sloping terrain. Coincides with timing of maximum convective rainfall where they happen (e.g. MCSs in central US)

⇒ The two LLJ we'll talk about are
  - Great Plains LLJ
  - Gulf of California LLJ
  (during monsoon lectures later..)

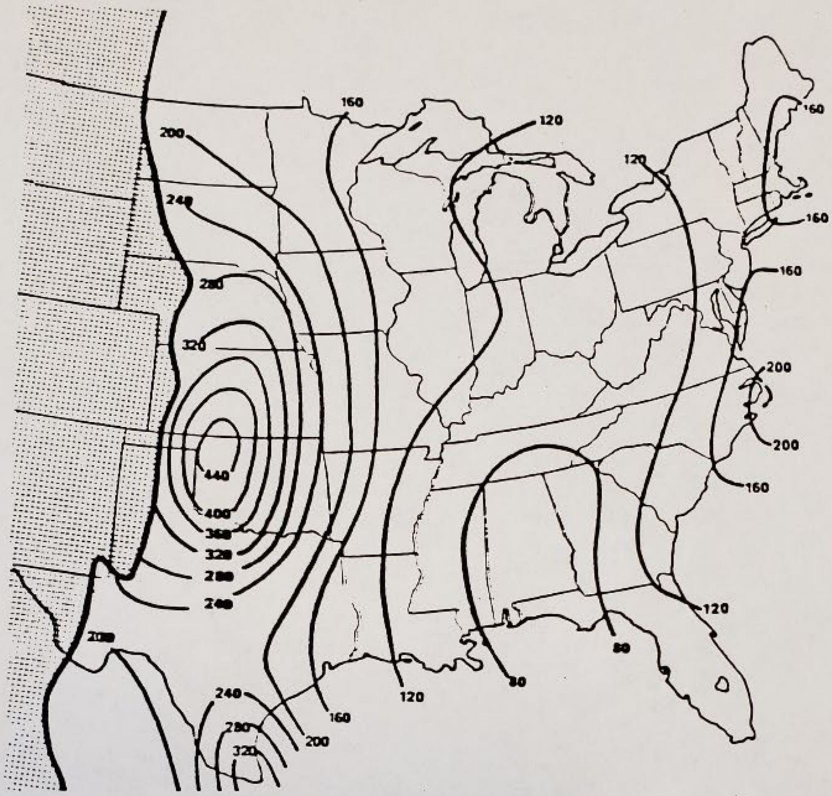


Fig. 3 Number of low-level jet observations from January 1959 – December 1960 at 1200 and 0000 GMT (From Bonner, 1968)

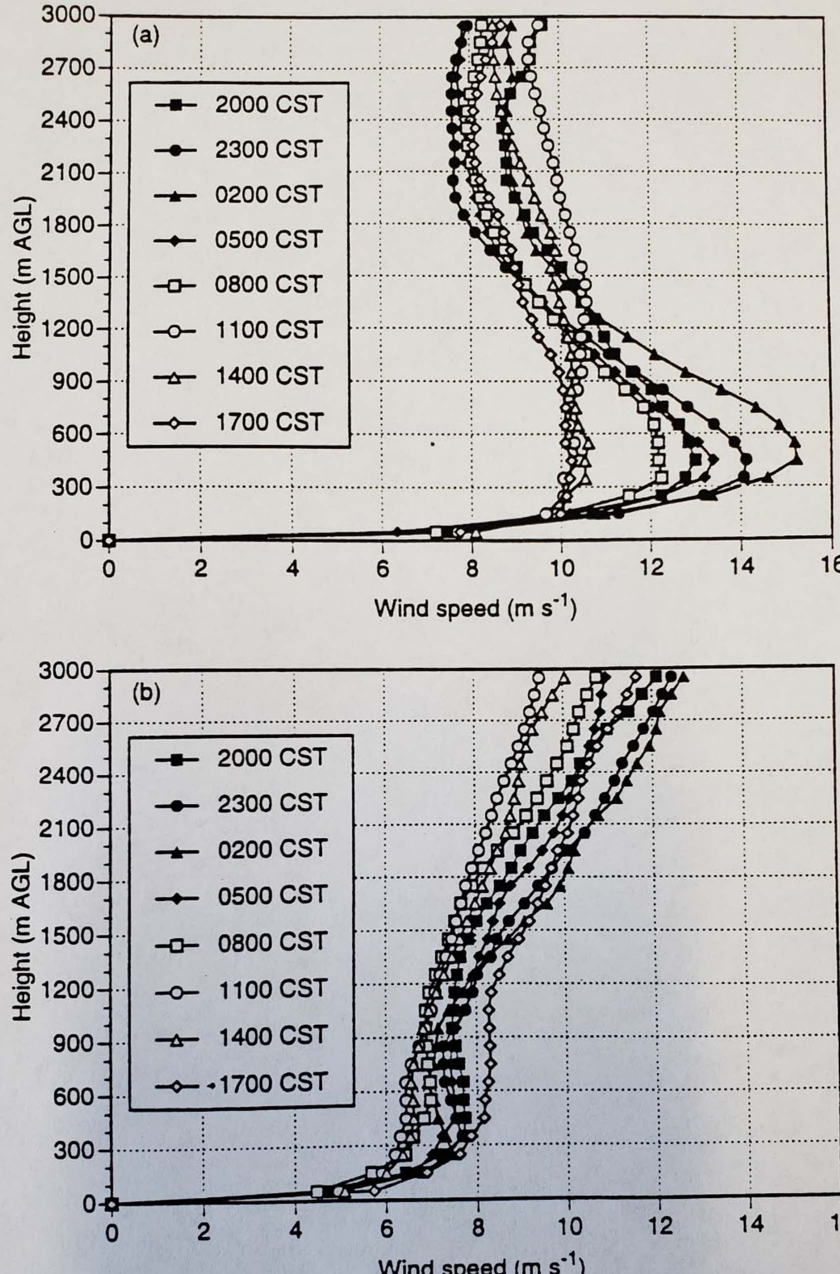
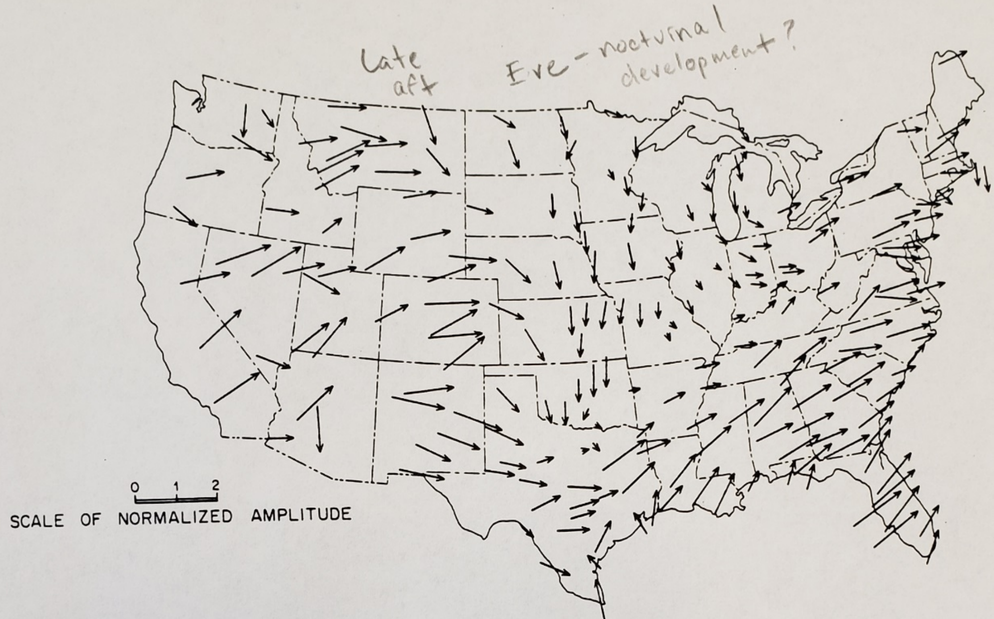


Fig. 5 Diurnal variation of the mean warm season wind profiles as determined from (a) LLJ soundings and (b) non-LLJ soundings.

Longer the vector - more amplified the diurnal cycle.



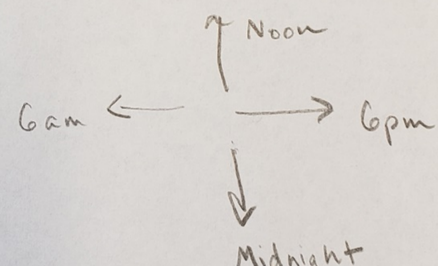


Fig. 4 Diurnal variation of hourly thunderstorm frequency over the United States. Normalized amplitude of the diurnal cycle is given by the length of the arrows in relation to the scale at bottom left. (Amplitudes are normalized by dividing by the mean hourly thunderstorm frequency averaged over the 24 hr of the day at each station.) Phase (time of maximum thunderstorm frequency) is indicated by the orientation of the arrows. Arrows directed from north to south denote a midnight maximum, arrows directed from east to west denote a 6 a.m. maximum, those from south to north denote a midday maximum, etc. (Based on data in *Mon. Wea. Rev.*, **103**, 409 (1975))

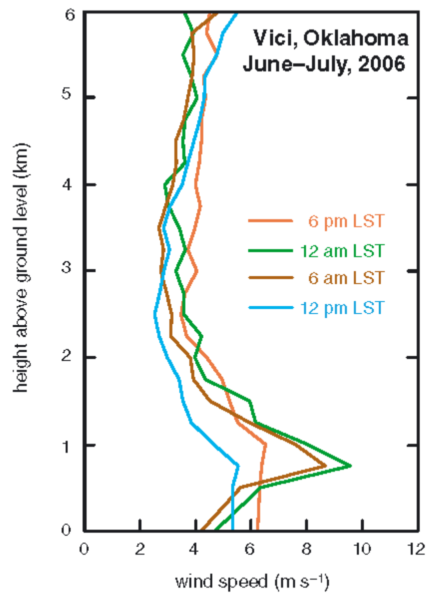


Figure 4.31 Vertical profiles of the mean horizontal wind speed at the Vici, OK, wind profiler at 6 pm, 12 am, 6 am, and 12 pm local standard time in June and July, 2006.

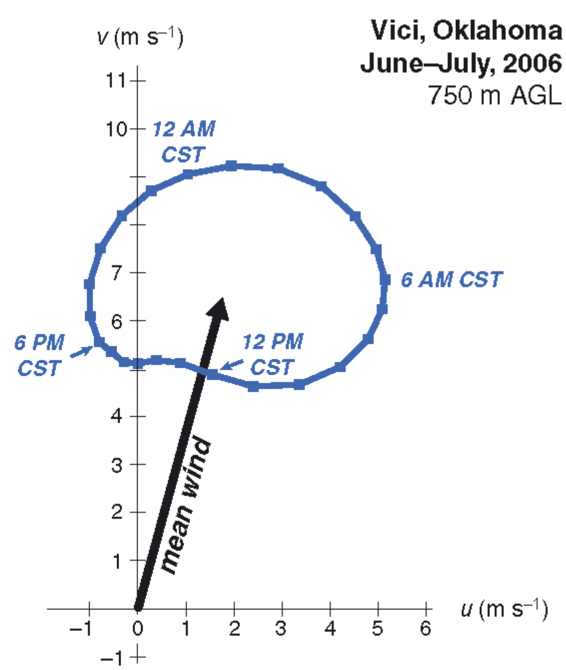


Figure 4.32 Mean diurnal cycle of the horizontal wind velocity components at 750 m above ground level observed by the Vici, OK, wind profiler in June and July, 2006.

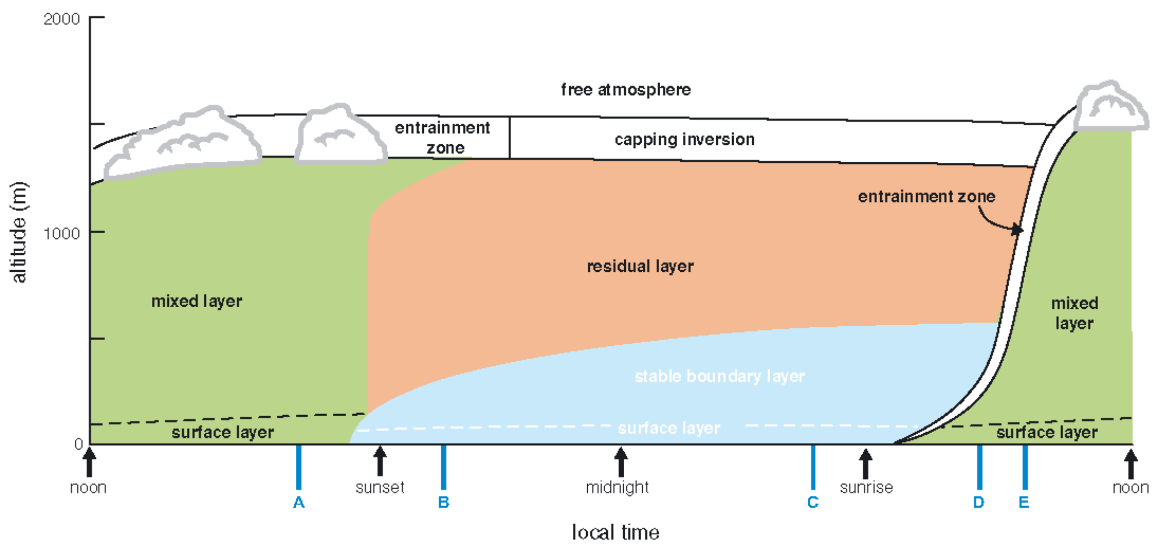


Figure 4.9 The boundary layer in relatively tranquil conditions over land consists of three major parts: a very turbulent mixed layer, a less turbulent residual layer consisting of former mixed-layer air, and a nocturnal stable boundary layer of sporadic turbulence. The letters A–E identify the times of the soundings shown in Figure 4.10. (Adapted from Stull [1988].)

PBL decoupling idea for LLJ (Blackadar, 1957)

Consider ageostrophic motions on a base state where horizontal PGF is constant in time and x, y and $w = 0$

Above the (nocturnal) inversion of PBL:

$$\frac{du}{dt} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + fv$$

PGF_x COR_x

★ No friction!! here.

$$\frac{dv}{dt} = -\frac{1}{\rho}\frac{\partial p}{\partial y} - fu$$

PGF_y COR_y

Note: Important idea here is that we are neglecting friction. The idea is that taking away the friction at night with PBL decoupling will cause ageostrophic wind to oscillate

Define geostrophic and ageostrophic components to wind.

$$\frac{du_a}{dt} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + f(v_g + v_a)$$

$$\frac{dv_a}{dt} = -\frac{1}{\rho}\frac{\partial p}{\partial y} - f(u_g + u_a)$$

Assume that $\frac{d\vec{V}_g}{dt} = 0$

By definition

$$u_g = -\frac{1}{\rho f}\frac{\partial p}{\partial y} \qquad v_g = \frac{1}{\rho f}\frac{\partial p}{\partial x}$$

Then:

$$\frac{du_a}{dt} = f v_a \qquad \frac{dv_a}{dt} = -f u_a$$

Can express this as:

$W = u_a - i v_a$ → complex number.

$W = u_a - i v_a$

$$\frac{\partial W}{dt} = -ifW$$ → 1st order differential equation with oscilatory solution.

Solution:

$$W = W_0 e^{-ift}$$

W_0 = amplitude of ageostrophic wind at sunset, when the heat fluxes in PBL would go to zero.

Describes an oscillation with a period of $2\pi/f$ or ½ pendulum day.

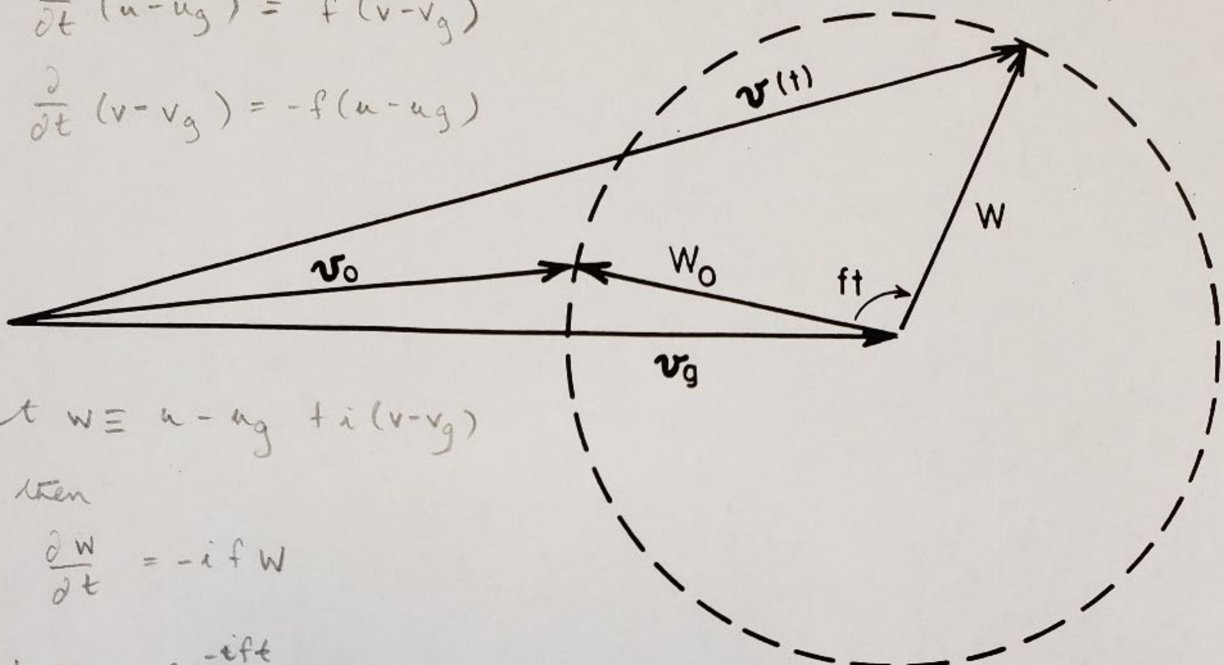
Ageostrophic wind rotates clockwise (in NH) in a circle, with maxima and minima 12 hours apart, starting with cessation of PBL mixing at sunset.

Eventually the total wind becomes supergeostrophic at night, approximately 2 to 7 hours after sunset

Base state: Homog. p-gradient in t, x, y ; w = 0

$$\frac{\partial}{\partial t}(u-u_g) = f(v-v_g)$$

$$\frac{\partial}{\partial t}(v-v_g) = -f(u-u_g)$$



Let $W \equiv u - u_g + i(v-v_g)$

then

$$\frac{\partial W}{\partial t} = -ifW$$

$$W = W_o e^{-ift}$$

Period $\frac{2\pi}{f}$ or $\frac{1}{2}$ pendulum day

Fig. 6 Relation of the complex number W and the wind vector $\mathbf{v}_t$ to the initial values W_o, $\mathbf{v}_o$ and the geostrophic wind vector $\mathbf{v}_g$ during a frictionally initiated inertial oscillation. From Blackadar (1959)

Surface friction and PBL decoupling create inertial oscillation

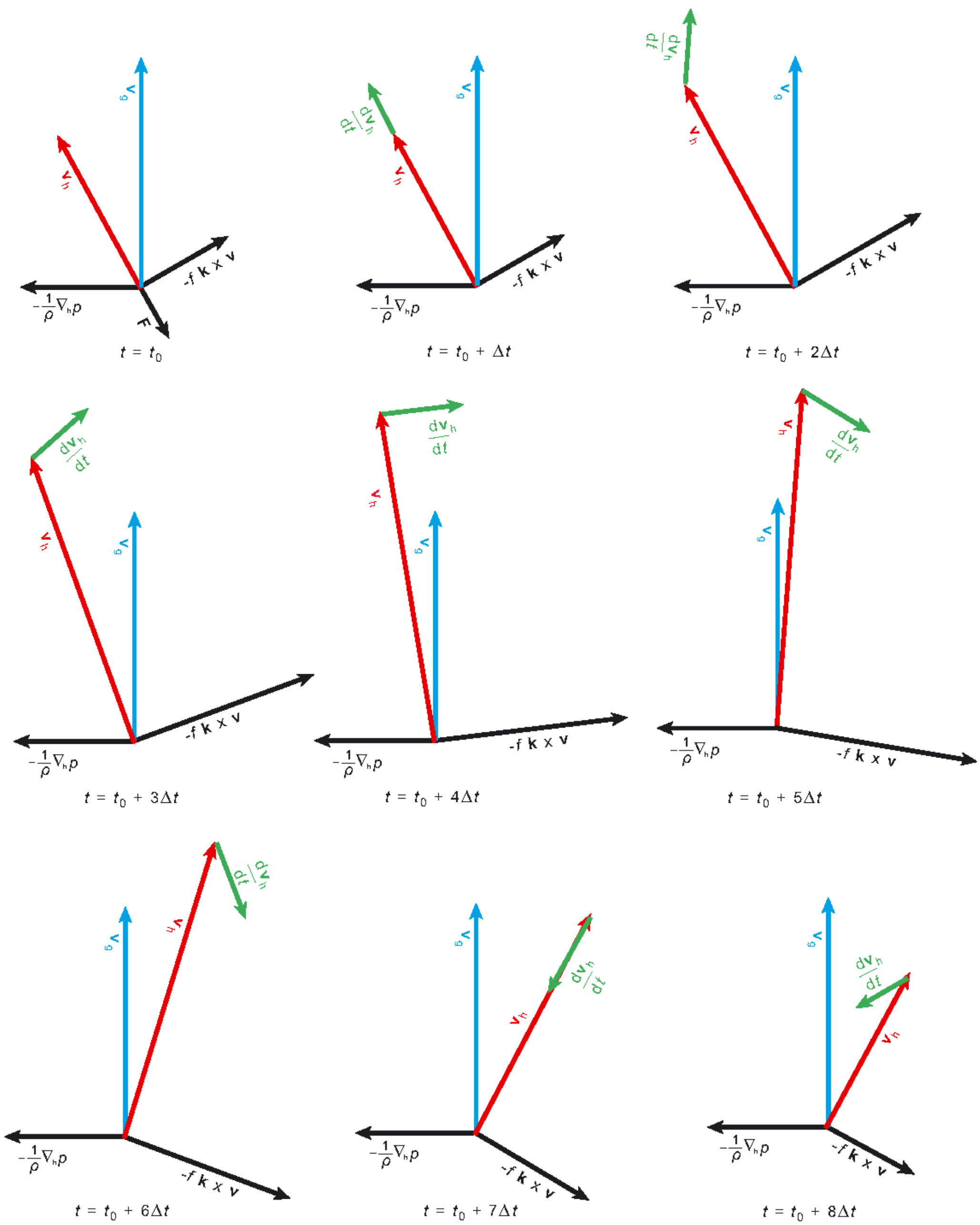


Figure 4.33 Schematic illustrating how the nocturnal low-level wind maximum develops, for the case of a southerly geostrophic wind, without loss of generality. At $t = t_0$ (during the late afternoon), the friction, Coriolis, and pressure gradient forces are in balance; thus, $d\mathbf{v}_h/dt = 0$, where $\mathbf{v}_h$ is the horizontal wind velocity. The removal of the friction force at $t = t_0 + \Delta t$ creates a force imbalance (where $d\mathbf{v}_h/dt = -\frac{1}{\rho}\nabla_h p - f\mathbf{k} \times \mathbf{v} \neq 0$), which results in net acceleration of the wind vector $t = t_0 + \Delta t$ and $t = t_0 + 8\Delta t$. An inertial oscillation results, with winds becoming supergeostrophic from approximately $t = t_0 + 2\Delta t$ to $t = t_0 + 7\Delta t$.

Synoptic factors influencing LLJ development in Central US.

- warm sectors of extra tropical cyclones
- Exit region of upper-level jet

Also, sloping terrain can induce a mesoscale enhancement of wind due to differential heating of the terrain, which creates a stronger LLJ than that would occur due to frictional decoupling alone.

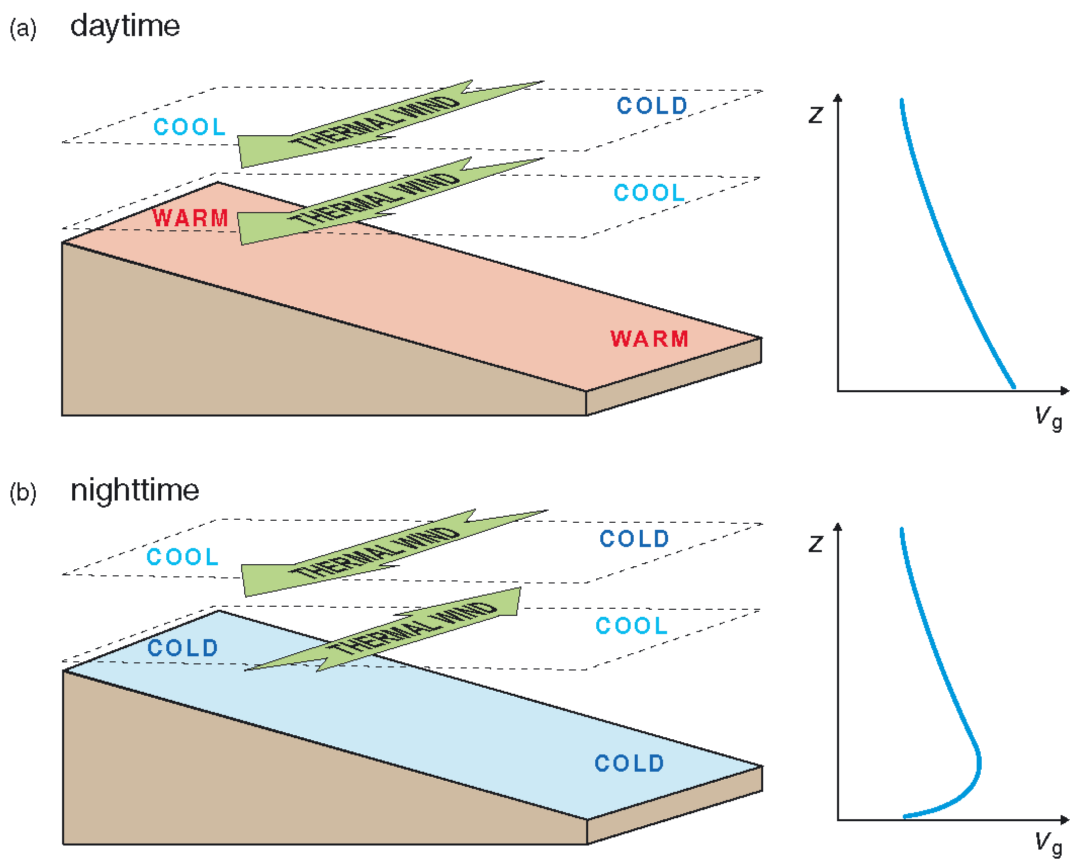


Figure 4.36 Diurnal oscillation of the low-level thermal wind owing to the diurnal heating and cooling of sloped terrain. The northern hemisphere case is shown, such that $|v_g| = v_g$. (a) Daytime conditions. (b) Nighttime conditions. (Adapted from Stull [1988].)

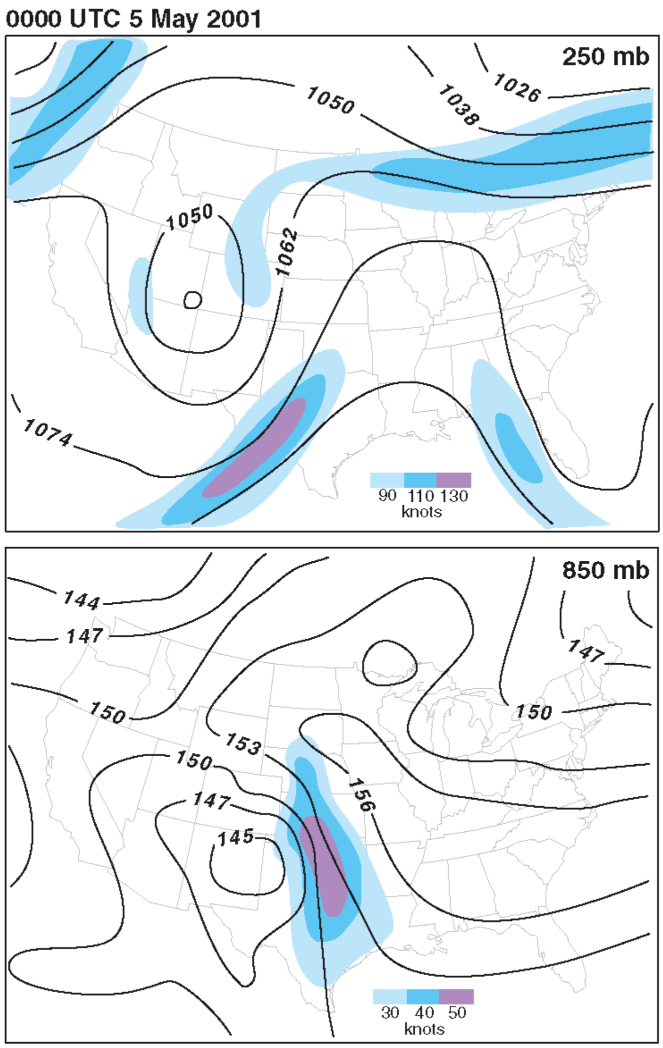


Figure 4.37 Eta model forecast of 250 mb and 850 mb geopotential heights (dam, contoured) and wind speeds (shaded) for 0000 UTC 5 May 2001. The 850 mb low-level jet stream in the southern Great Plains region is coupled with the exit region associated with the 250 mb jet stream.

Drylines (or dry fronts, dewpoint fronts)

- Air mass boundary seperating moist, maritime tropical air from dry continental tropical air (mT vs. cT)

- Dewpoint gradient in the range of 10K/1Km to 10 K/100 Km

- The confluence of air from different source regions cause basically the same dynamics as lifting at frontal boundaries (i.e. advective effects of ageostrophic wind lead to vertical motion)

- Wind shift may be present near moisture gradient

- Larger diurnal temperature cycle in dry air, and that's different than a cold front.

- In US, most commonly encountered in central US, mT air from Gulf of Mexico, cT from Southwest US, Mexico

- Soil moisture, vegetation gradients also contribute

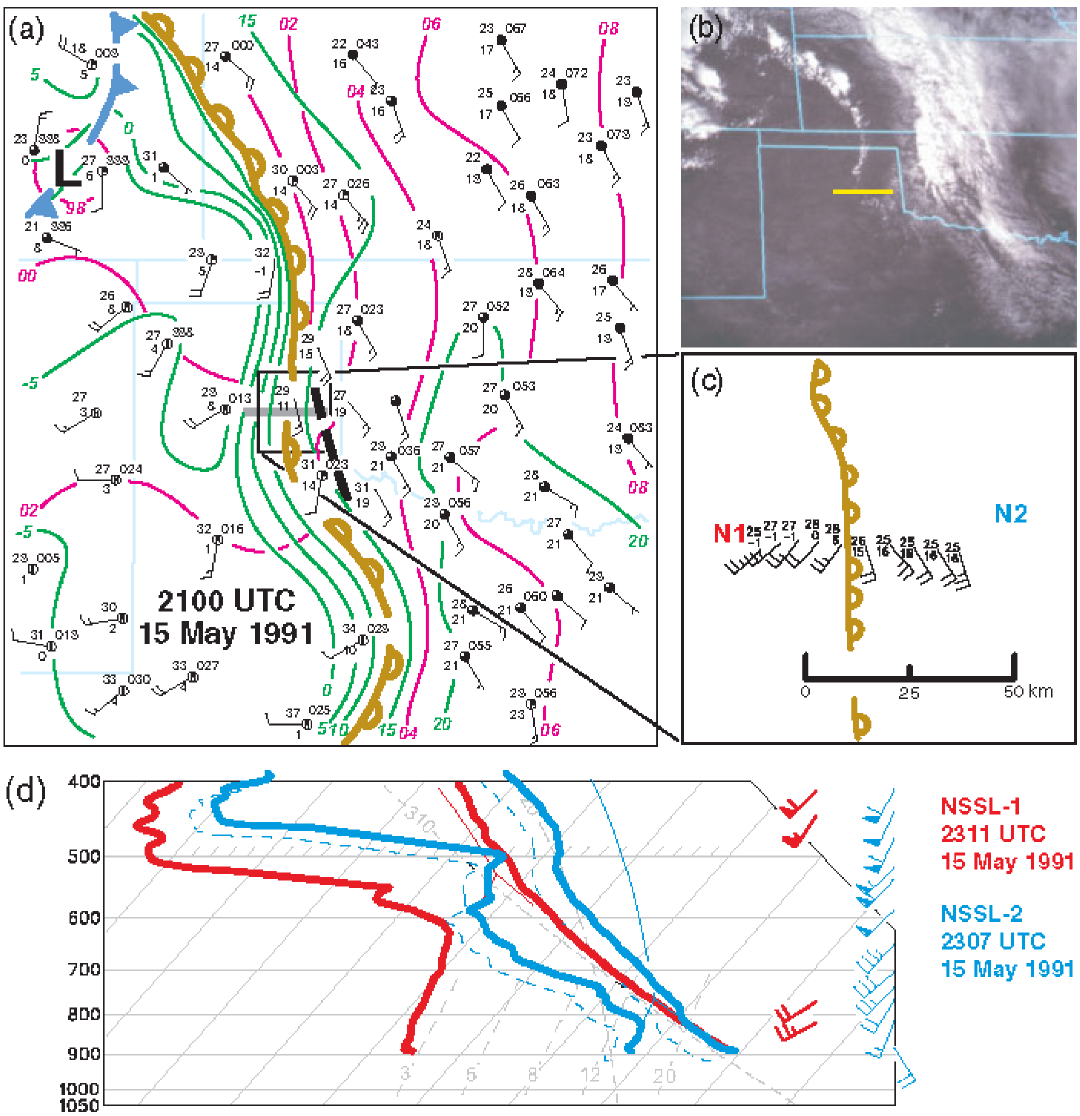


Figure 5.14 Surface, visible satellite, and sounding observations on 15 May 1991. (a) Manual analysis at 2100 UTC of mean sea level pressure (magenta contours every 2 mb; the leading '9' or '10' is dropped) and surface dewpoint (green contours every 5°C). The dryline is indicated with the brown, open-scalloped line. A low-pressure trough is indicated with a dashed black contour. A cold front is indicated with a heavy blue barbed line. Station models display temperature (°C), dewpoint (°C), mean sea level pressure (tenths of mb with the leading '9' or '10' dropped), sky conditions, and wind barbs (kt). The heavy gray line indicates the approximate location of aircraft transects used to construct the vertical cross-sections shown in Figure 5.18. (b) Visible satellite image at 2100 UTC. The yellow line indicates the approximate location of the aforementioned aircraft transects. (c) Close-up of surface observations in the immediate vicinity of the dryline obtained by mobile instrumentation (the enlarged region is shown in (a)). The station models display temperature (°C), dewpoint (°C), and wind (kt). The locations of two mobile sounding units (NSSL-1 and NSSL-2) positioned on opposite sides of the dryline are also indicated (N1 and N2, respectively). (d) Soundings obtained west and east of the dryline by NSSL-1 (red) and NSSL-2 (blue), respectively. The thin contours show the paths of a lifted surface parcel for each of the two soundings on the thermodynamic diagram. Winds are also shown for each sounding. (Adapted from Ziegler and Rasmussen [1998].)

Dryline formation (typically spring, early summer)

- Confluence is typically related to lee troughing downstream of Rockies. Recall lee troughing occurs due to vertical expansion of isentropes downstream of a mountain range, causing vertical stretching of air columns and spin-up of low-level circulation due to PV conservation (WAF I...)

- Stronger lee troughing in association with short-wave troughs that would trigger strong cyclogenesis.

- Drylines represent intersection of warm moist layer with ground, so they are oriented with terrain gradient.

Mechanisms for dryline strengthening

- Frontogenetic-like circulations that tighten moisture gradient, in confluence zone of mT and cT air masses

- Differential vertical mixing. Deeper mixing on west side of line increases westerly momentum transport to ground, enhancing convergence.

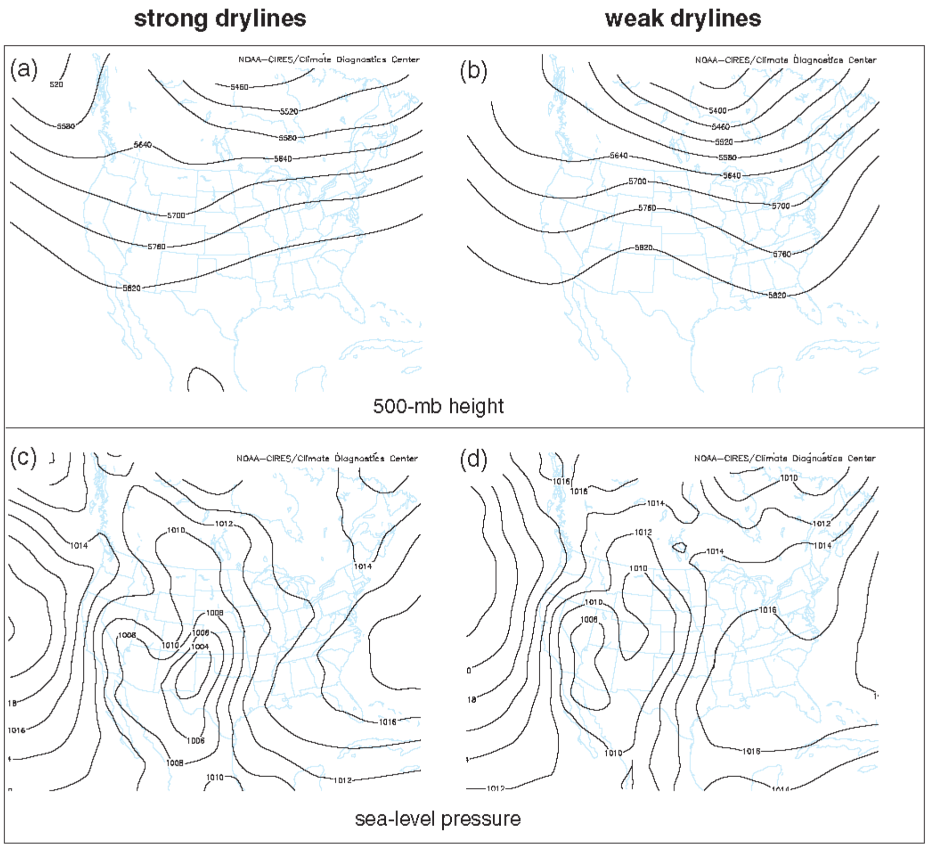


Figure 5.15 Composites of synoptic-scale conditions in cases of (left) strong drylines and (right) weak drylines: (a), (b) 500 mb geopotential height (contoured every 60 m); (c), (d) sea level pressure (contoured every 2 mb). (Adapted from Schultz *et al.* [2007].)

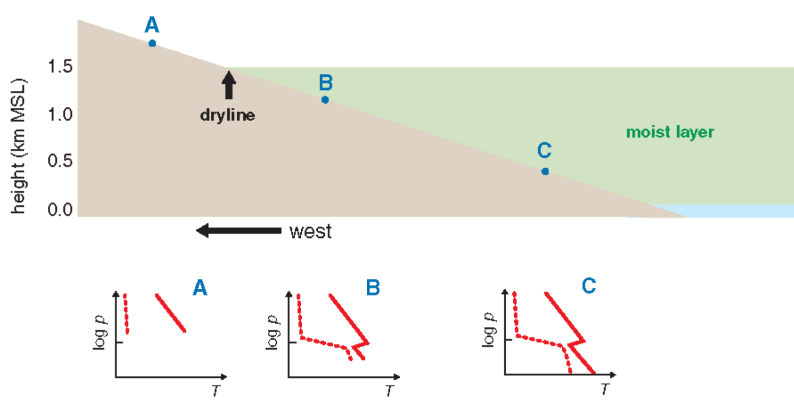


Figure 5.16 Schematic vertical cross-section of the dryline and its relation to topography. Idealized soundings at points A, B, and C represent the conditions west, just east, and far east of the dryline. (Adapted from Bluestein [1993].)

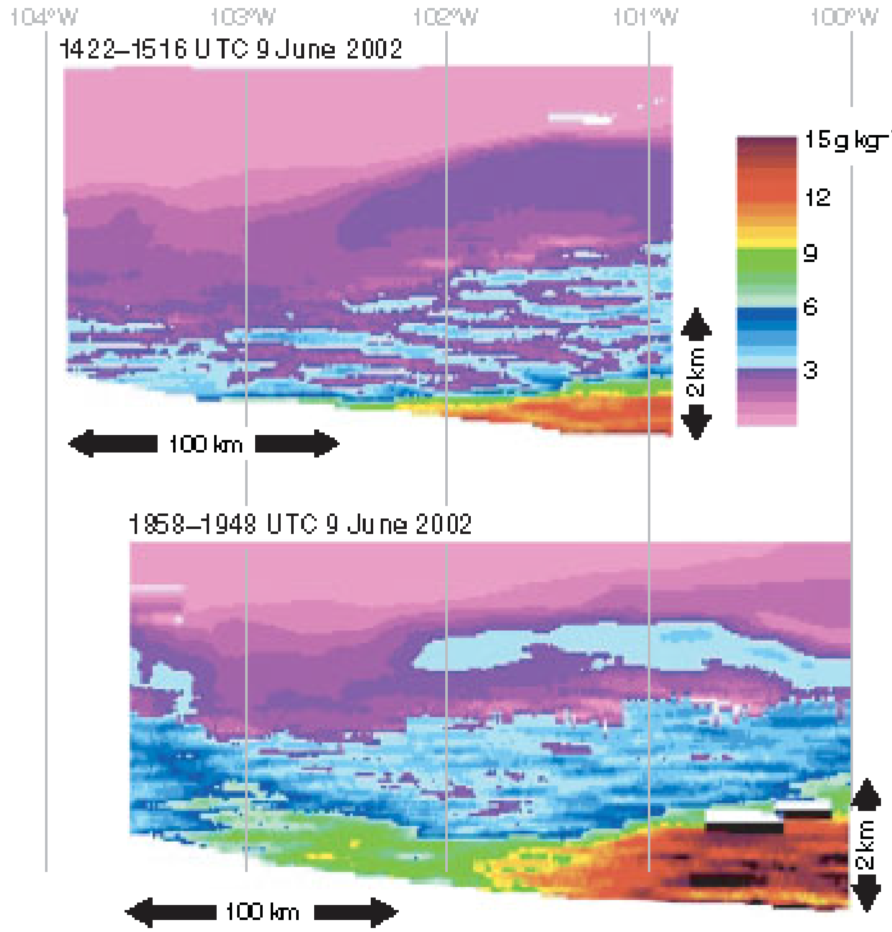


Figure 5.17 Cross-sections of mixing ratio obtained from west–east traverses of a downward-pointing airborne water vapor lidar over the southern United States Great Plains during the International H_2O Project (the aircraft was flying at approximately 37°N latitude). The top cross-section was obtained during the mid-morning, and the bottom cross-section was obtained during the early afternoon. Note how the moist layer intersects the sloping terrain at the location of the surface dryline. Also note the differences in the moisture distribution between the morning and afternoon traverses. (Imagery courtesy of the National Center for Atmospheric Research Earth Observing Laboratory.)

Dryline motion

- Absent presence of fronts, drylines move east during day and west at night, due to vertical PBL mixing and radiational cooling, respectively.

- Drylines can "jump" if the PBL mixing breaks through a capping inversion

- If strong synoptic-scale forcing, the dryline moves eastward, typically ahead of a cold front.

Importance of drylines for convective initiation

- Storms often form in dry air mass just west of dryline in ascending, thermally direct circulation, then move east into favorable high θ_e environment.

- If storms form east of dryline, typically some other synoptic-scale mechanism involved (e.g. cold front, gravity waves)

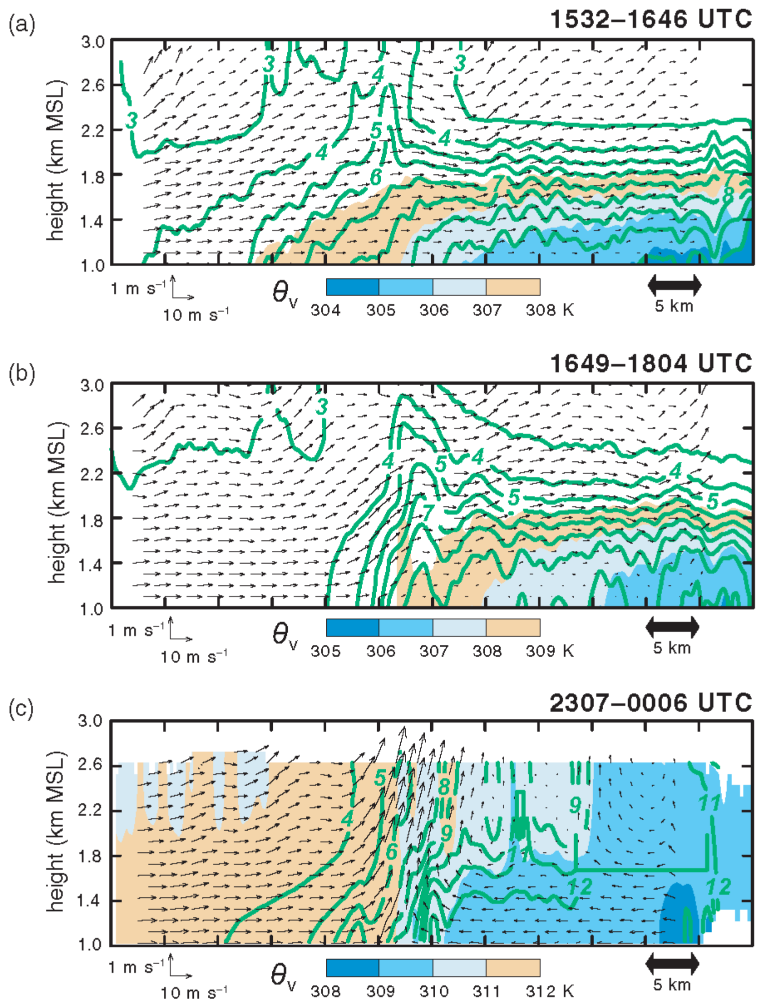


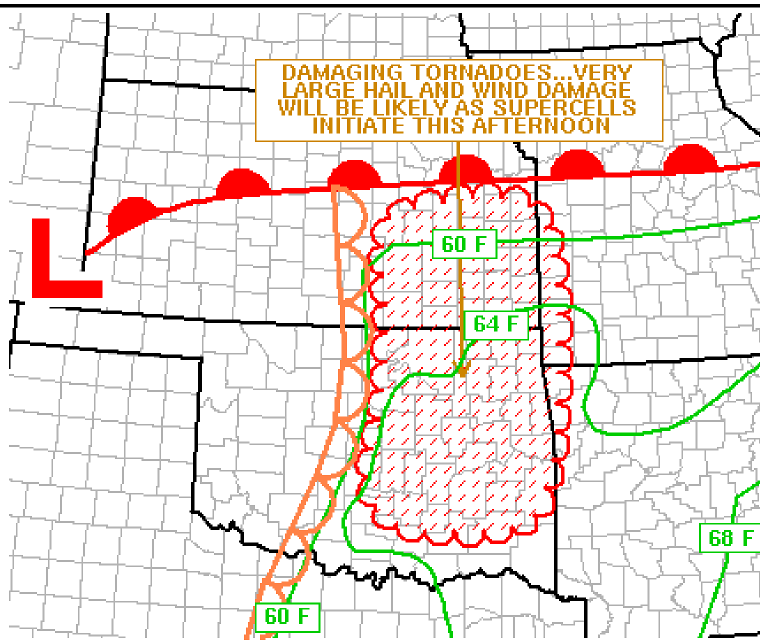
Figure 5.18 Vertical cross-sections of virtual potential temperature (θ_v; shaded), water vapor mixing ratio (g kg^{-1}; green contours), and wind (see scale) obtained from stepped aircraft traverses across a dryline between (a) 1532 and 1646 UTC, (b) 1649 and 1804 UTC, and (c) 2307 and 0006 UTC 15–16 May 1991. The location of the traverses is indicated in Figure 5.14a, 5.14b. (Adapted from Ziegler and Rasmussen [1998].)

- Dry line thunderstorms tend to be more isolated with greater propensity to be supercellular and tornadic
  - favorable wind shear profiles (i.e. high helicity, streamwise vort.)
  - Presence of capping inversions from cT airmass.

More on this point later . . .

SUPERCELLS WILL LIKELY INITIATE THIS AFTERNOON ALONG A DRYLINE FROM ERN KS TO CNTRL OK. DAMAGING TORNADOES...VERY LARGE HAIL AND WIND DAMAGE WILL BE LIKELY AS STORMS INITIATE AND TRACK ENEWD ACROSS THE REGION THIS AFTERNOON. A TORNADO WATCH WILL BE ISSUED SHORTLY.

SFC ANALYSIS CURRENTLY SHOWS A DRYLINE ORIENTED FROM NORTH TO SOUTH FROM SCNTRL KS TO SOUTHWEST OK. SFC DEWPOINTS EAST OF THE DRYLINE ARE IN THE LOWER TO MID 60S F WHERE MODERATE INSTABILITY IS PRESENT. THE CAPPING INVERSION IS VERY WEAK AND STORMS SHOULD INITIATE AS LARGE-SCALE ASCENT INCREASES AS A 100 KT MID-LEVEL JET MAX NOSES INTO THE REGION THIS AFTERNOON.



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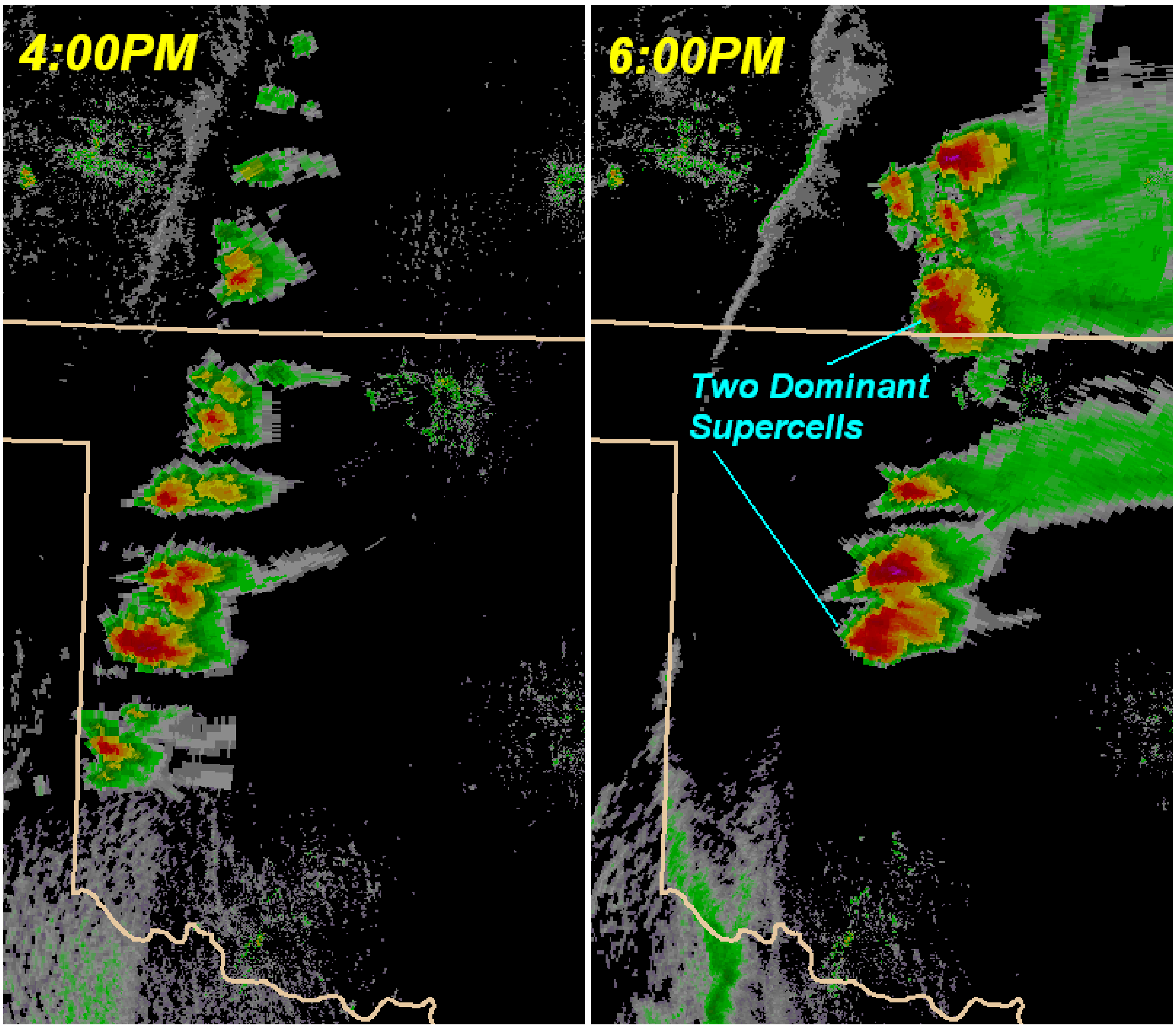
4:00PM
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Two Dominant
Supercells