

Material by Rich Thompson, Ariel Cohen,  
Andrew Moore, Tom Galarneau

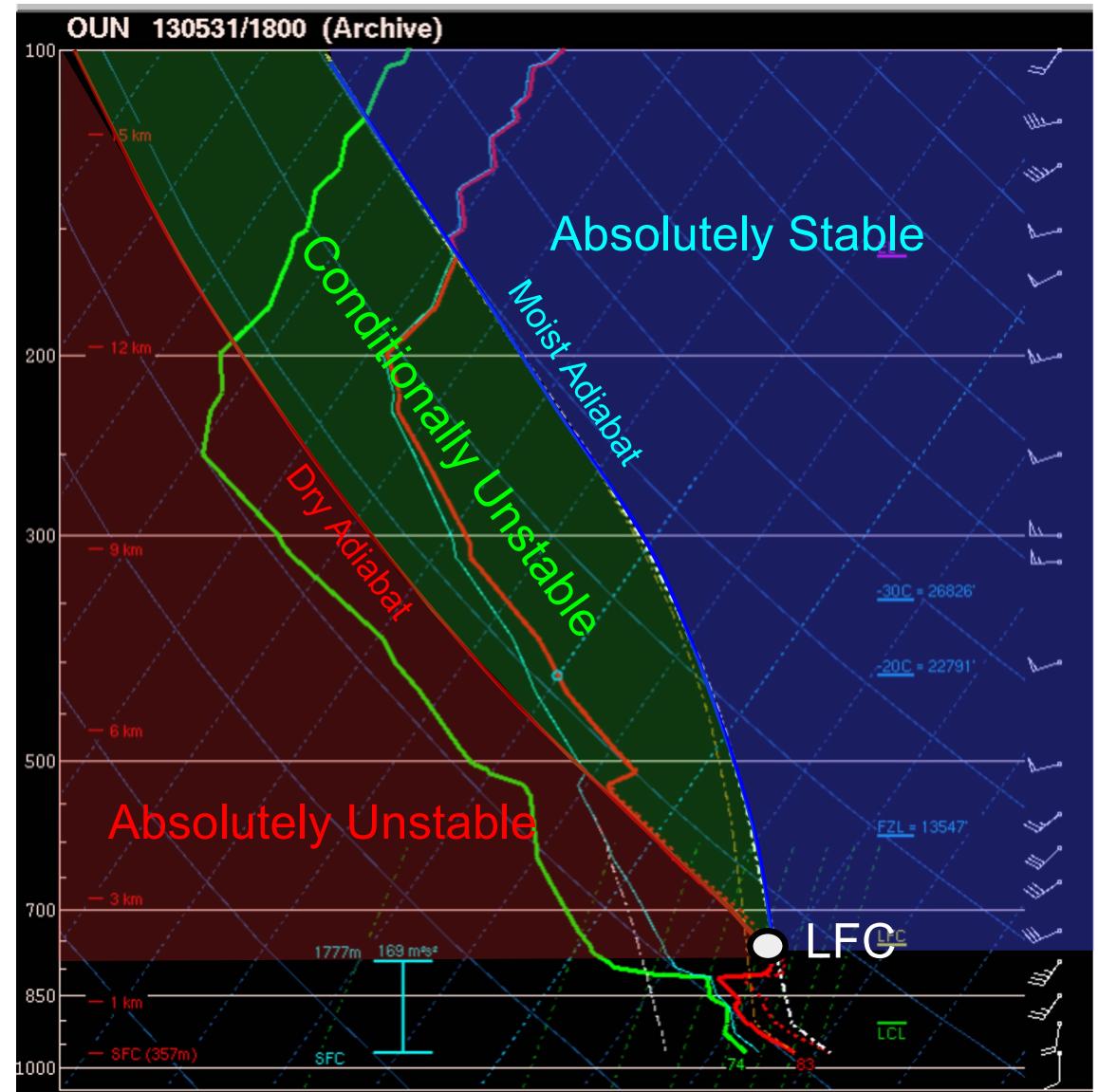
Photo by Andrew Moore

## Why do we care about lapse rates?

- Helps generate buoyancy (influences T-storm intensity)
- Influences convective initiation (Houston and Niyogi 2007)
- Influence precipitation intensity (Takemi 2009)

Lapse rates in most T-storm environments will be conditionally unstable...

In other words, between the dry adiabatic lapse rate (9.8 C/km) and the moist adiabatic lapse rate.

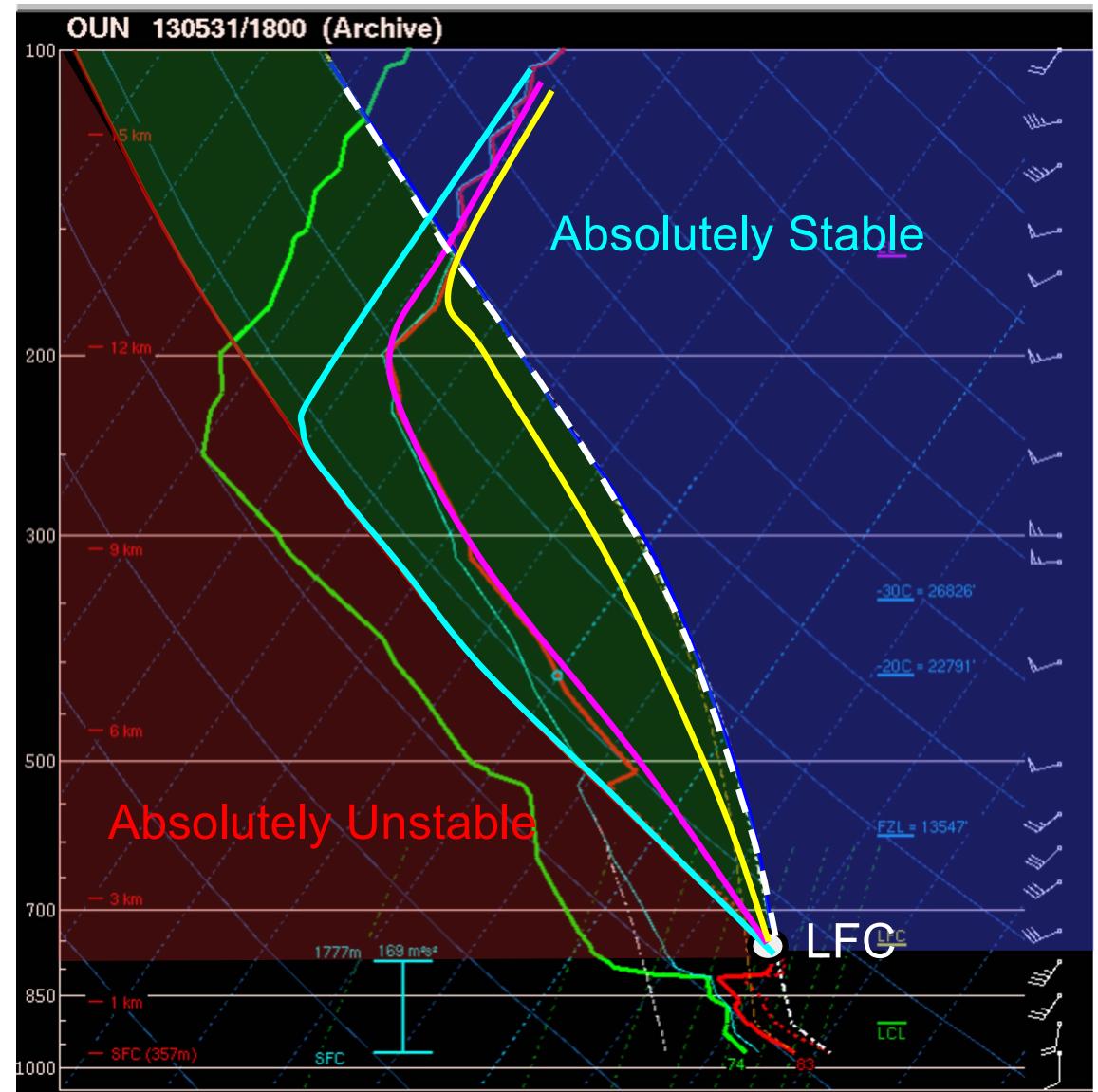


Lapse rates in most T-storm environments will be conditionally unstable...

In other words, between the dry adiabatic lapse rate (9.8 C/km) and the moist adiabatic lapse rate.

Compare the CAPE profiles for these three environmental lapse rates. What are the implications for updraft acceleration?

(Recall:  $W_{max} = \sqrt{2 \cdot CAPE}$ )



# How do lapse rates change?

**Local change in lapse rate =**

- Horizontal lapse rate advection**
- Influence of lift/stretching**
- Differential Thermal Advection**
- Diabatic Heating**

# Lapse Rate Tendency

- What physical processes alter the environment lapse rate?

Start with 1<sup>st</sup> Law of Thermodynamics

$$q = C_p \frac{dT}{dt} - \alpha \frac{dp}{dt}$$

heating rate

specific heat

temperature

specific volume ( $\frac{1}{\rho}$ )

pressure

time

This is an important point!  
Our ability to anticipate changes in lapse rate  
derives directly from the first law of  
thermodynamics!

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temperature  
pressure  
time  
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specific heat  
specific volume ( $\frac{1}{\rho}$ )

Expand full derivatives and assume hydrostatic conditions (OK for synoptic and mesoscale)

$$q = C_p \left( \frac{\partial T}{\partial t} + \mathbf{v}_h \cdot \nabla_h T + w \frac{\partial T}{\partial z} \right) - \frac{1}{\rho} \left( \frac{\partial p}{\partial t} + \mathbf{v}_h \cdot \nabla_h p + w \frac{\partial p}{\partial z} \right)$$

Local change in temperature with time    Horizontal temperature advection    Vertical temperature advection    Local change in pressure    Horizontal pressure advection    Vertical pressure advection

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Relatively small

$$= -\rho g$$

Assume that the  
hydrostatic approx  
applies

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Relatively small,  
assume  
hydrostatic  
 $= -\rho g$

Differentiate with respect to  $-z$

$$-\frac{\partial q}{\partial z} = C_p \left[ \frac{\partial}{\partial t} \left( -\frac{\partial T}{\partial z} \right) + \mathbf{v}_h \cdot \nabla_h \left( -\frac{\partial T}{\partial z} \right) + w \frac{\partial}{\partial z} \left( -\frac{\partial T}{\partial z} \right) - \frac{\partial \mathbf{v}_h}{\partial z} \cdot \nabla_h T - \frac{\partial w}{\partial z} \frac{\partial T}{\partial z} \right] - g \frac{\partial w}{\partial z}$$

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Relatively small,  
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Substitute in definition for environment lapse rate  $\gamma = -\frac{\partial T}{\partial z}$  and dry adiabatic lapse rate  $\Gamma_d = \frac{g}{C_p}$

$$\frac{\partial \gamma}{\partial t} = -\mathbf{v}_h \cdot \nabla_h \gamma - w \frac{\partial \gamma}{\partial z} + \frac{\partial \mathbf{v}_h}{\partial z} \cdot \nabla_h T + \frac{\partial w}{\partial z} (\Gamma_d - \gamma) - \frac{1}{C_p} \frac{\partial q}{\partial z}$$

We neglected  
 $\frac{\partial^2 T}{\partial z^2}$  terms

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Relatively small,  
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$= -\rho g$

Differentiate with respect to  $-z$

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**Lapse rate tendency equation**

# Lapse Rate Tendency Equation

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A            B            C            D            E            F

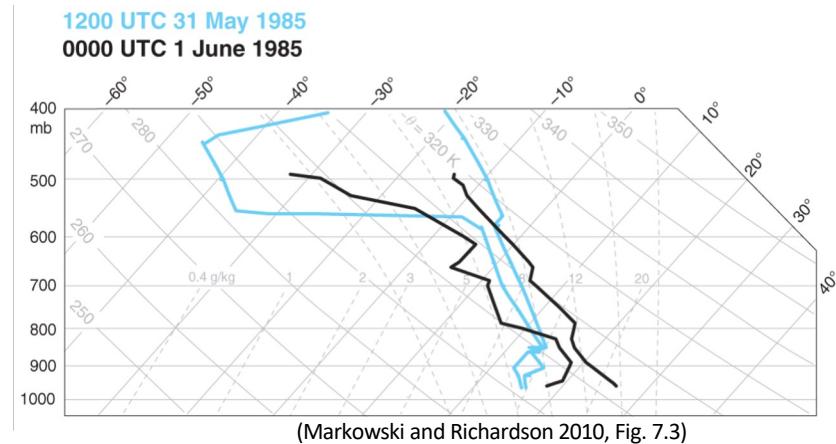
**We'll work through each term to understand  
the physical mechanisms**

# Lapse Rate Tendency Equation

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A      B      C      D      E      F

Term A: local time rate of change of environment lapse rate



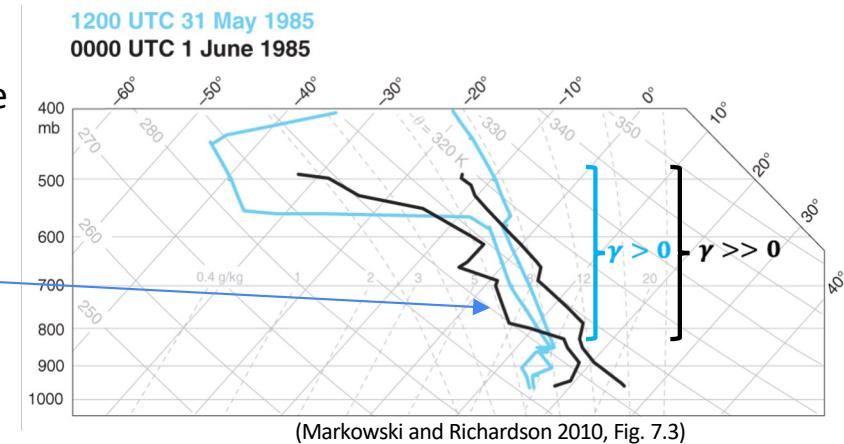
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A      B      C      D      E      F

Term A: local time rate of change of environment lapse rate

$\frac{\partial \gamma}{\partial t} > 0$  lapse rate increasing at PIT  
due to warming below 600 mb



# Lapse Rate Tendency Equation

$$\frac{\partial \gamma}{\partial t} = \boxed{-\mathbf{v}_h \cdot \nabla_h \gamma} - w \frac{\partial \gamma}{\partial z} + \frac{\partial \mathbf{v}_h}{\partial z} \cdot \nabla_h T + \frac{\partial w}{\partial z} (\Gamma_d - \gamma) - \frac{1}{C_p} \frac{\partial q}{\partial z}$$

A      B      C      D      E      F

Term B: horizontal lapse rate advection - this one is very important! Let's take a closer look!

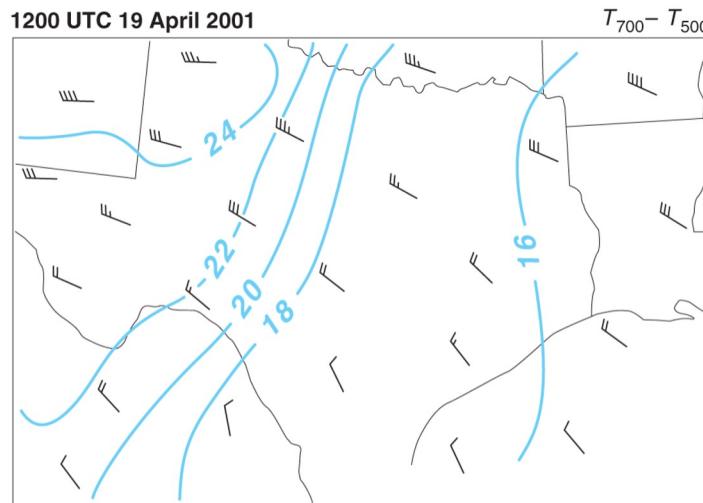


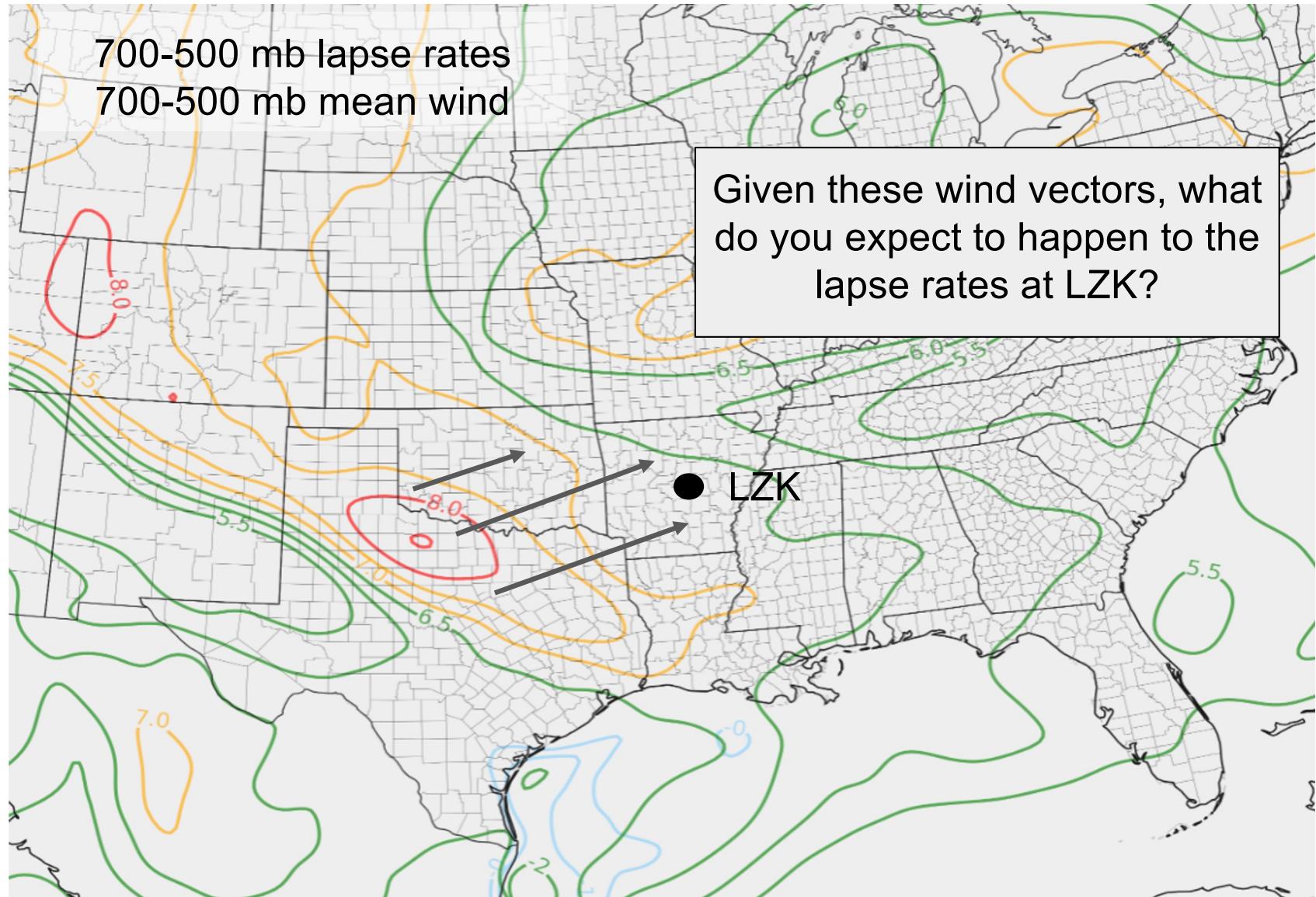
Figure 7.4

Analysis of the environmental temperature difference between 500 and 700 mb (K), which is a bulk measure of the midlevel lapse rate (a temperature difference of 27 K between 500 and 700 mb corresponds to an approximately dry adiabatic environmental temperature profile), revealing the presence of horizontal lapse rate advection. Wind barbs depict the mean wind in the 500–700 mb layer. Large lapse rates from the high terrain of northern Mexico and eastern New Mexico are being advected toward the southern Great Plains of the United States. This common warm season phenomenon leads to the formation of the elevated mixed layer that caps soundings in the Great Plains region.

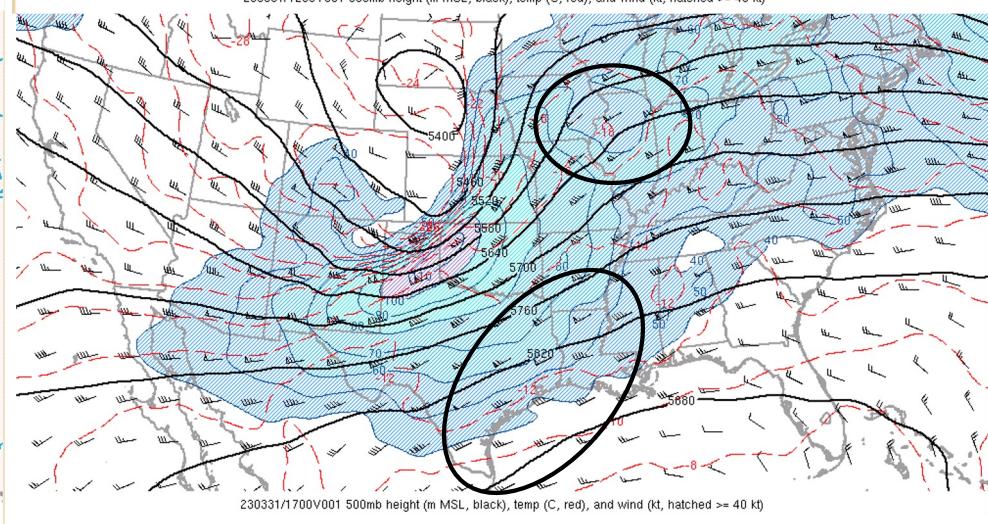
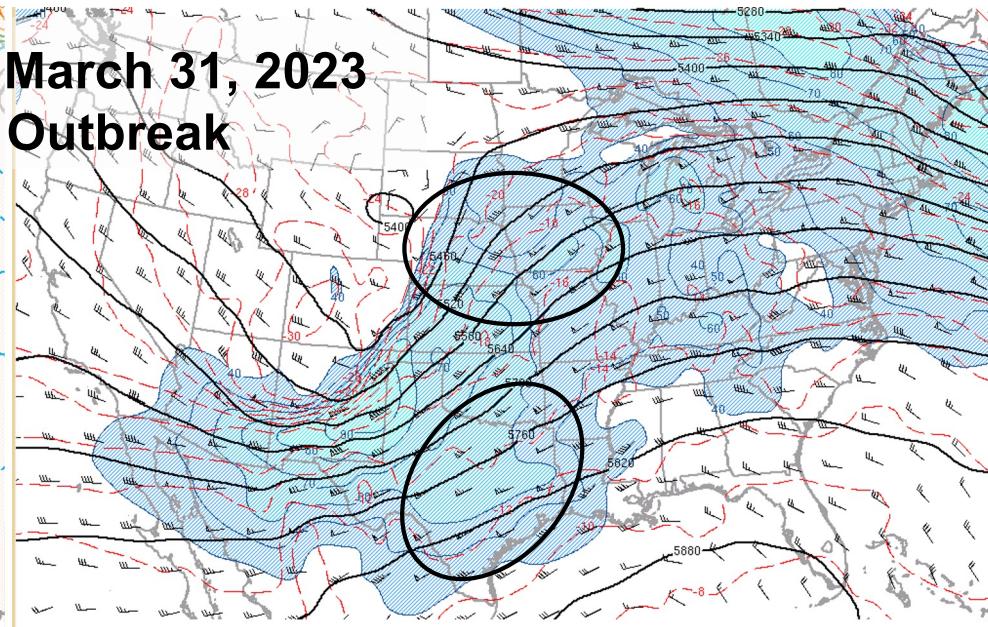
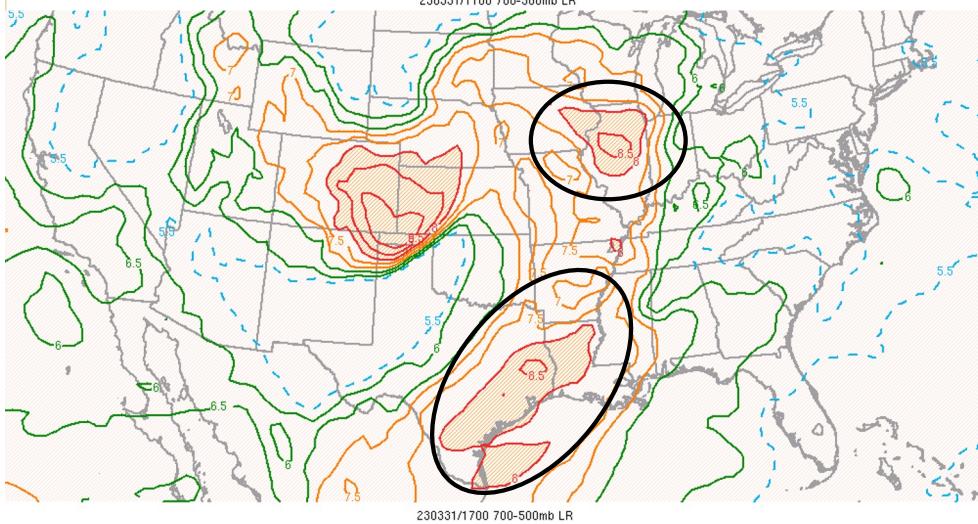
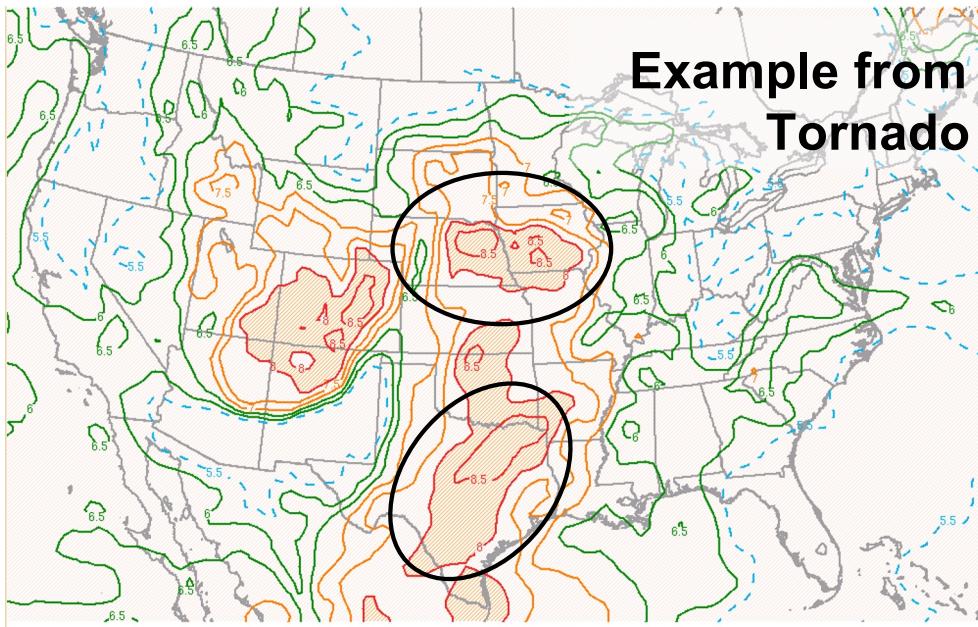
(Markowski and Richardson 2010, Fig.

700-500 mb lapse rates  
700-500 mb mean wind

Given these wind vectors, what  
do you expect to happen to the  
lapse rates at LZK?

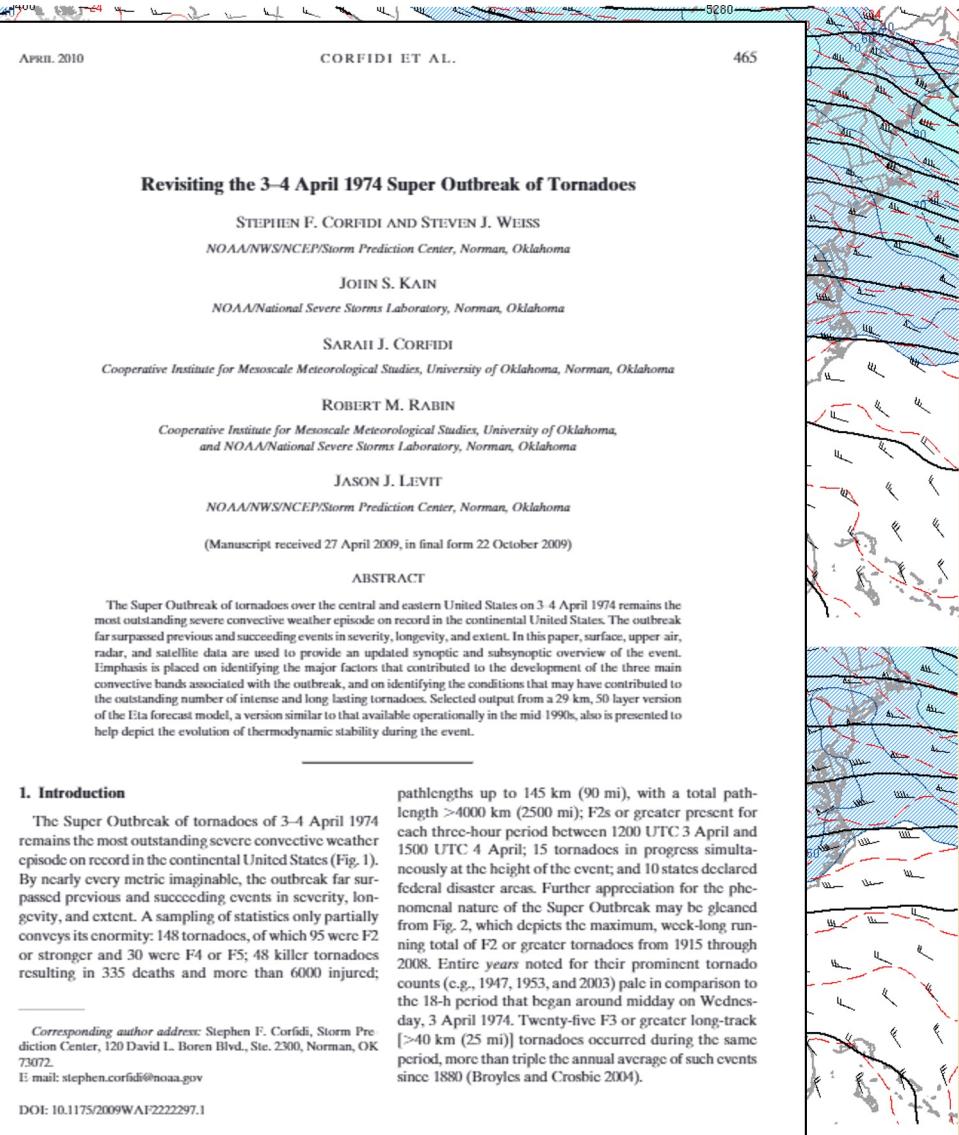
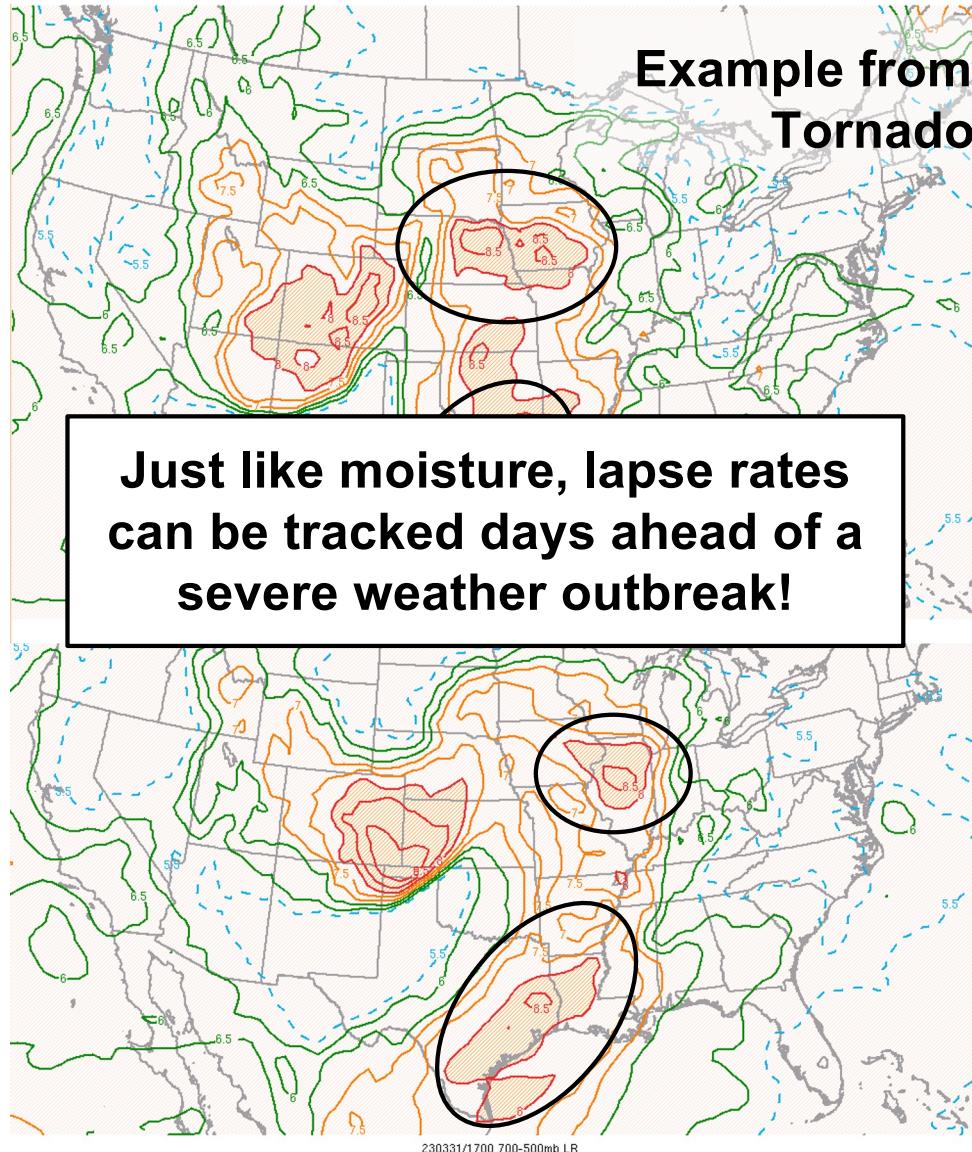


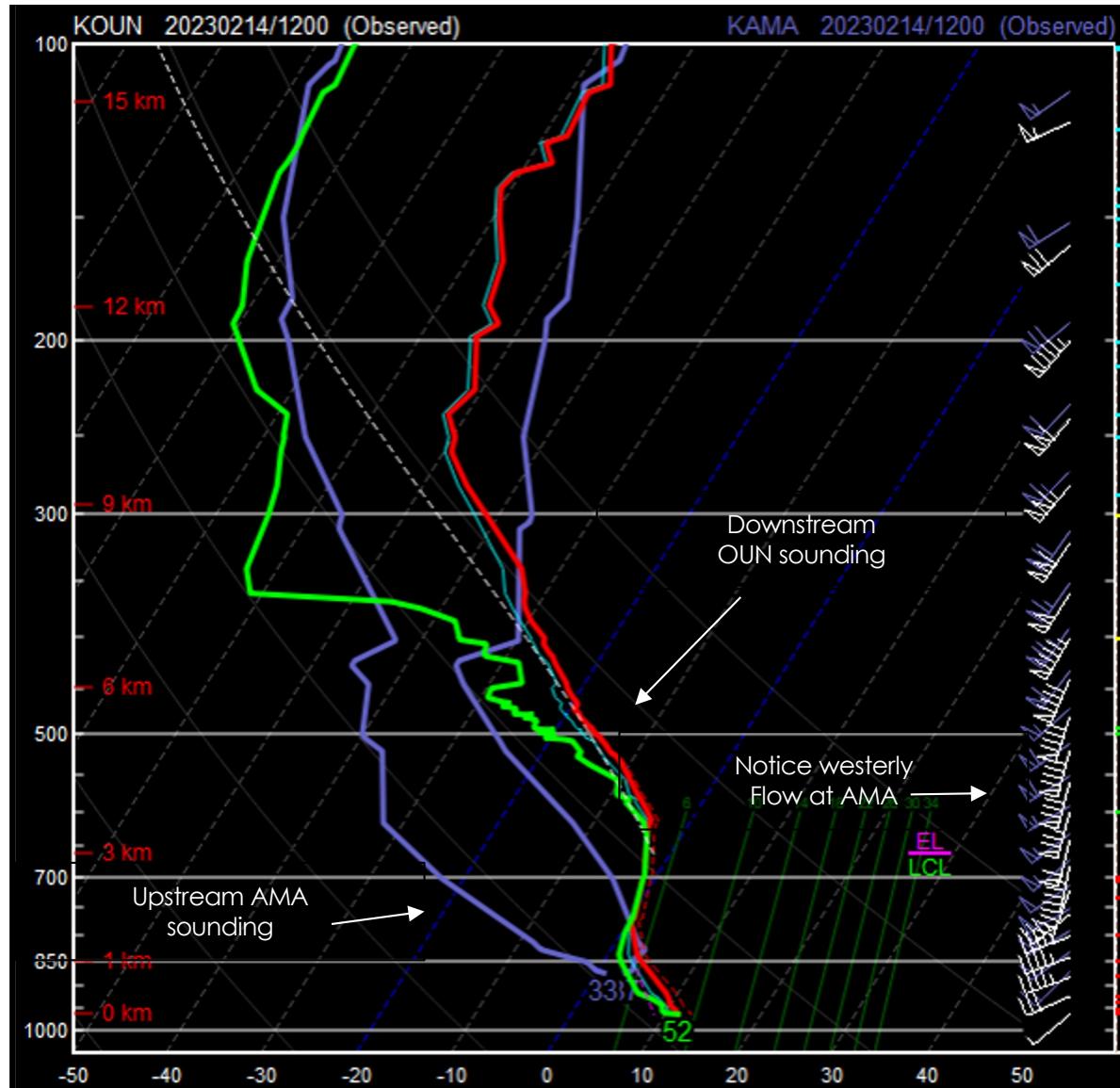
## Example from March 31, 2023 Tornado Outbreak



## Example from Tornado

Just like moisture, lapse rates  
can be tracked days ahead of a  
severe weather outbreak!





Here's another example.

Notice the steeper lapse rates upstream at AMA.

Given westerly winds, what do you think will happen to the lapse rates at OUN?

# Consider the terrain!

Elevation generally increases as you go west towards the mountains. What would happen if we advected a surface parcel from ABQ to OUN?



4,172 m
3,796 m
3,435 m
3,089 m
2,758 m
2,443 m
2,143 m
1,859 m
1,592 m
1,341 m
1,108 m
892 m
695 m
517 m
359 m
223 m
108 m
18 m
-44 m
-71 m

# Consider the terrain!

Elevation generally increases as you go west towards the mountains. What would happen if we advected a surface parcel from ABQ to OUN?

ABQ  
5309 ft MSL

OUN  
1238 ft MSL

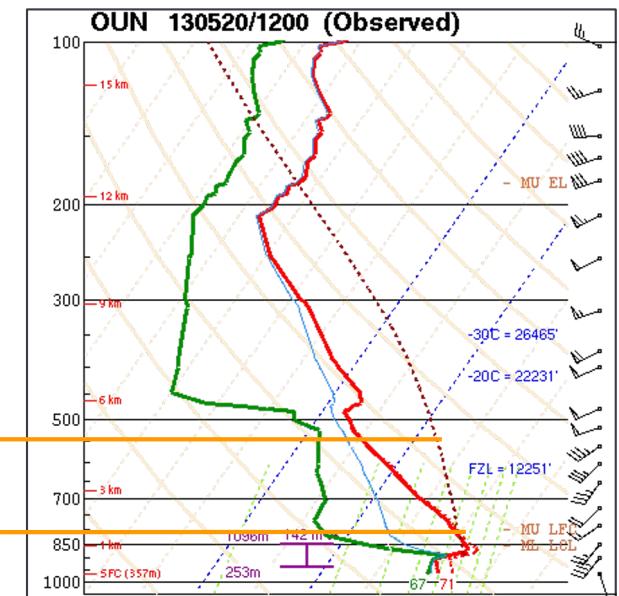
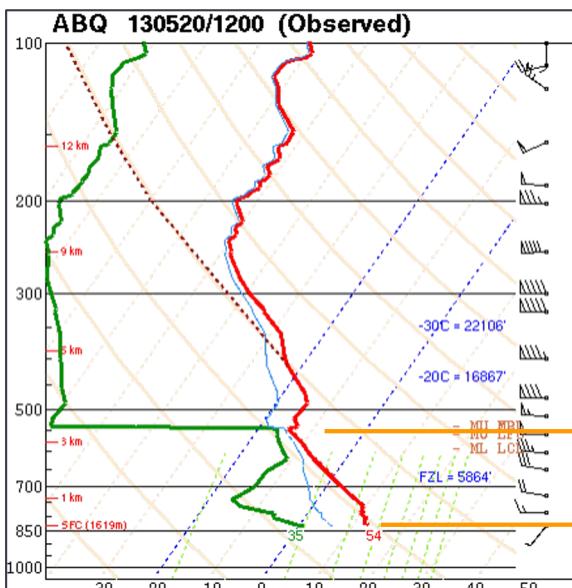
Parcel is now at a higher altitude AGL!

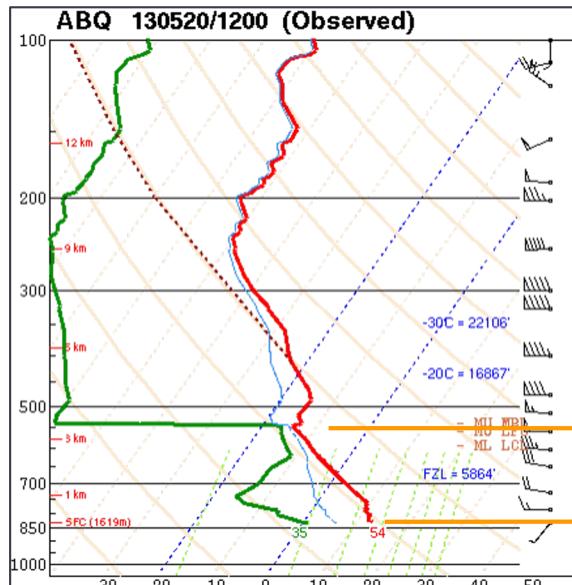
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The last slide was a slight exaggeration of what occurs (parcels can descend in altitude), but illustrates an important point.

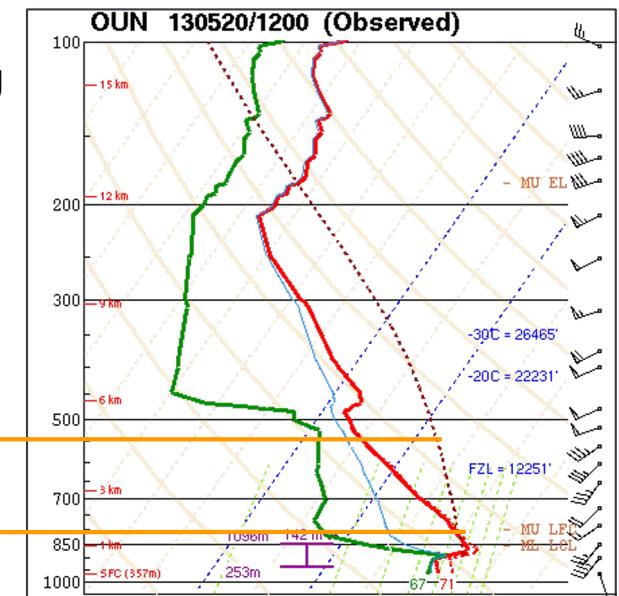
The deep, well-mixed boundary layer over the southern Rockies can be advected east over the plains...

And becomes an **Elevated Mixed Layer!**

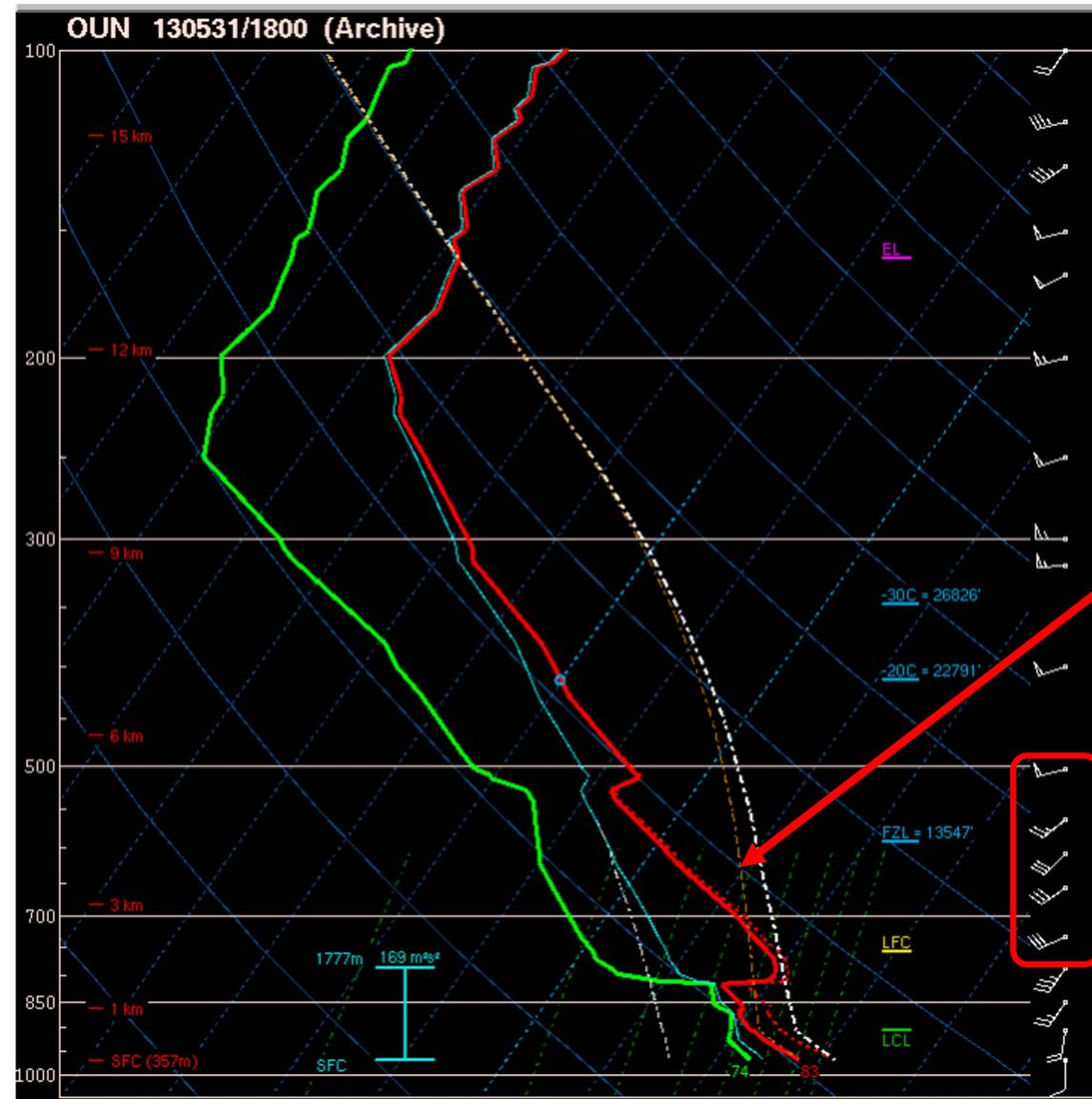




This is an important process for generating steep lapse rates over the Plains, which in turn support large CAPE values.



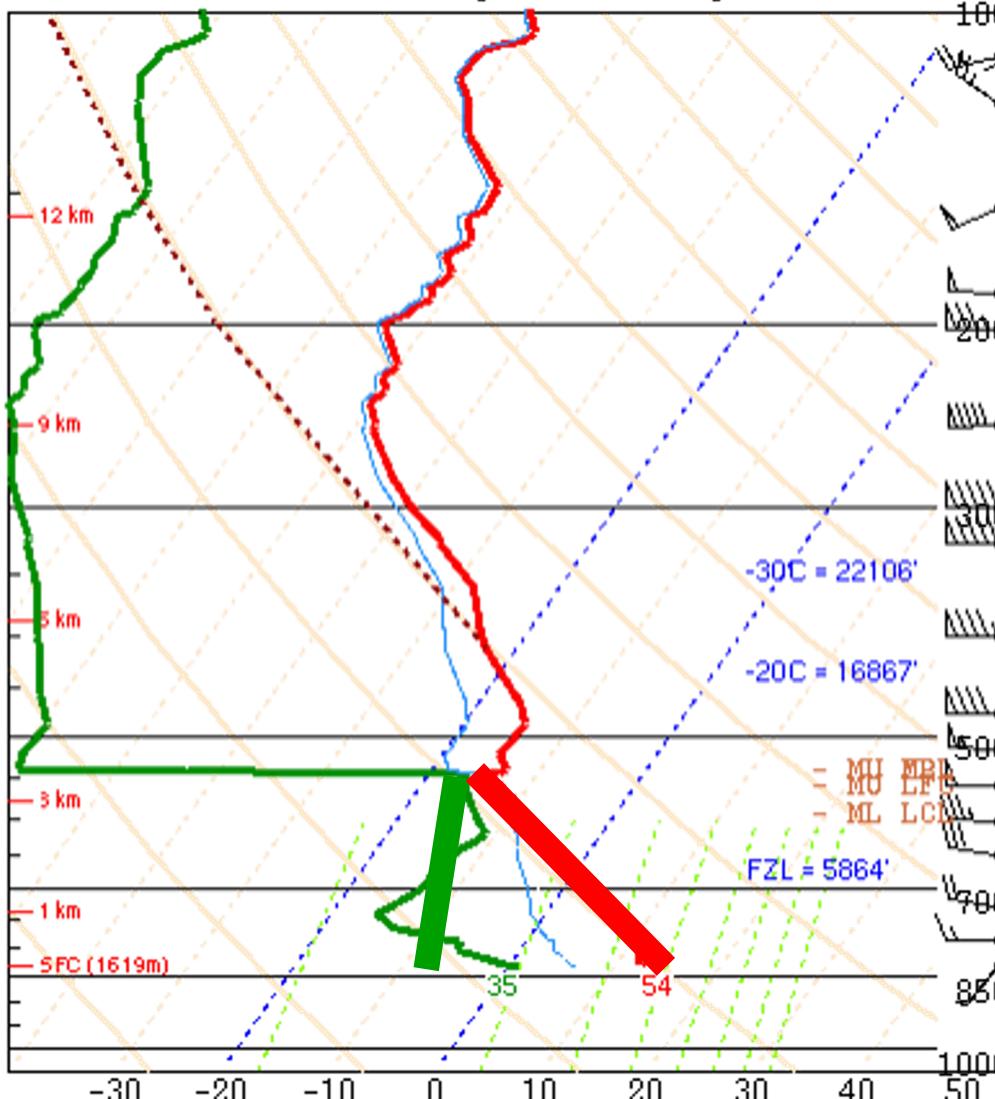
## OUN-ABQ Terrain Profile



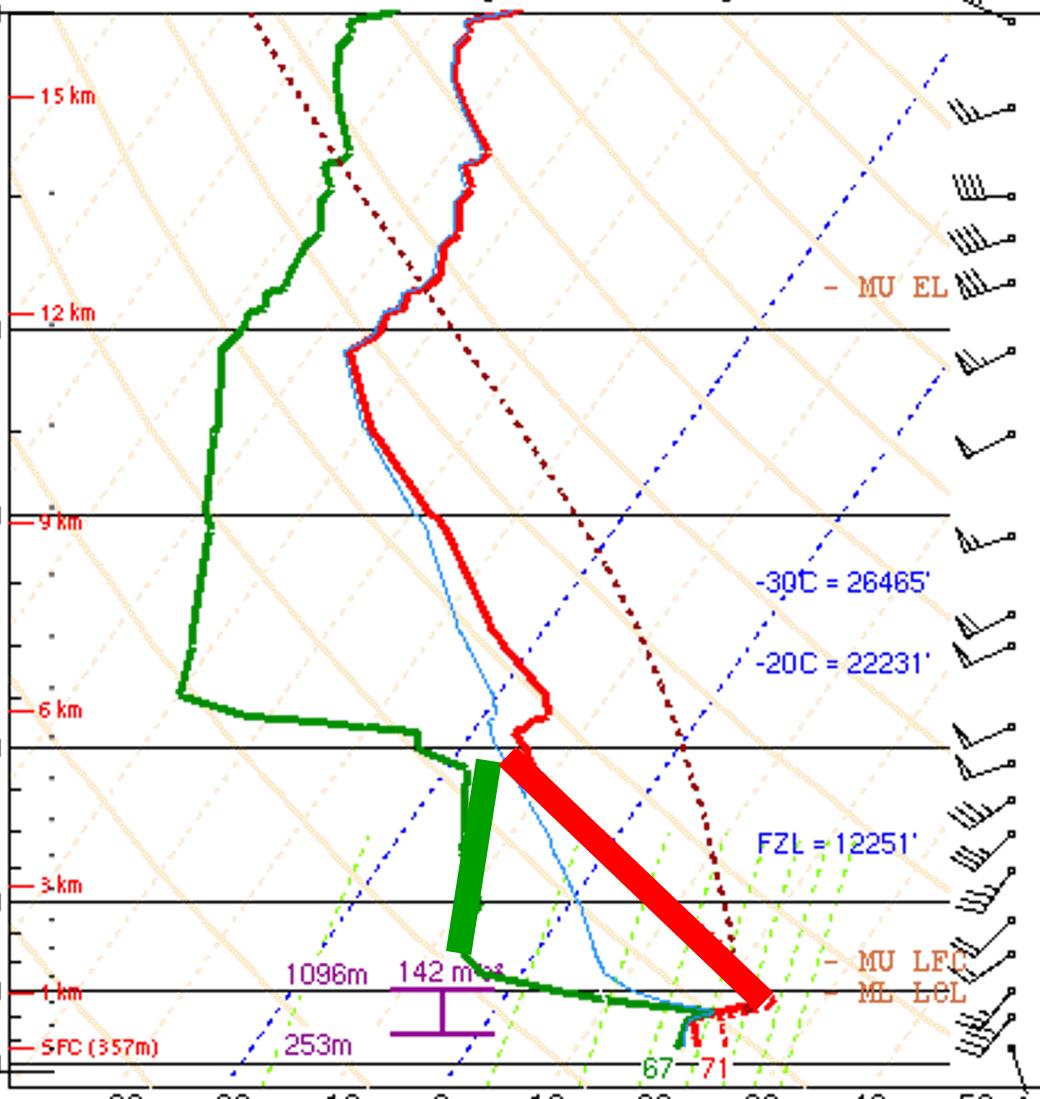
Nearly neutral layer  
above boundary layer in  
Norman noon sounding.

Notice the southwesterly flow in  
this layer - it likely originated from  
New Mexico plateau!

ABQ 130520/1200 (Observed)



OUN 130520/1200 (Observed)



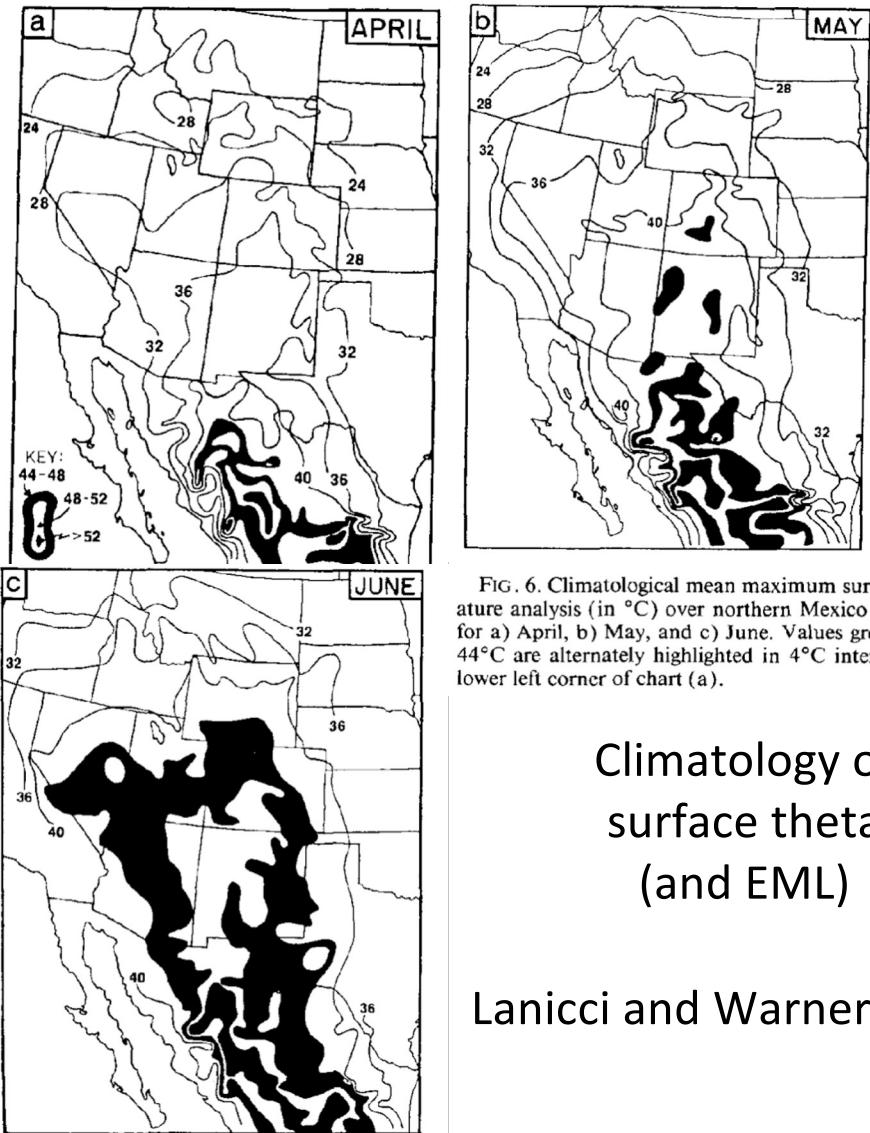
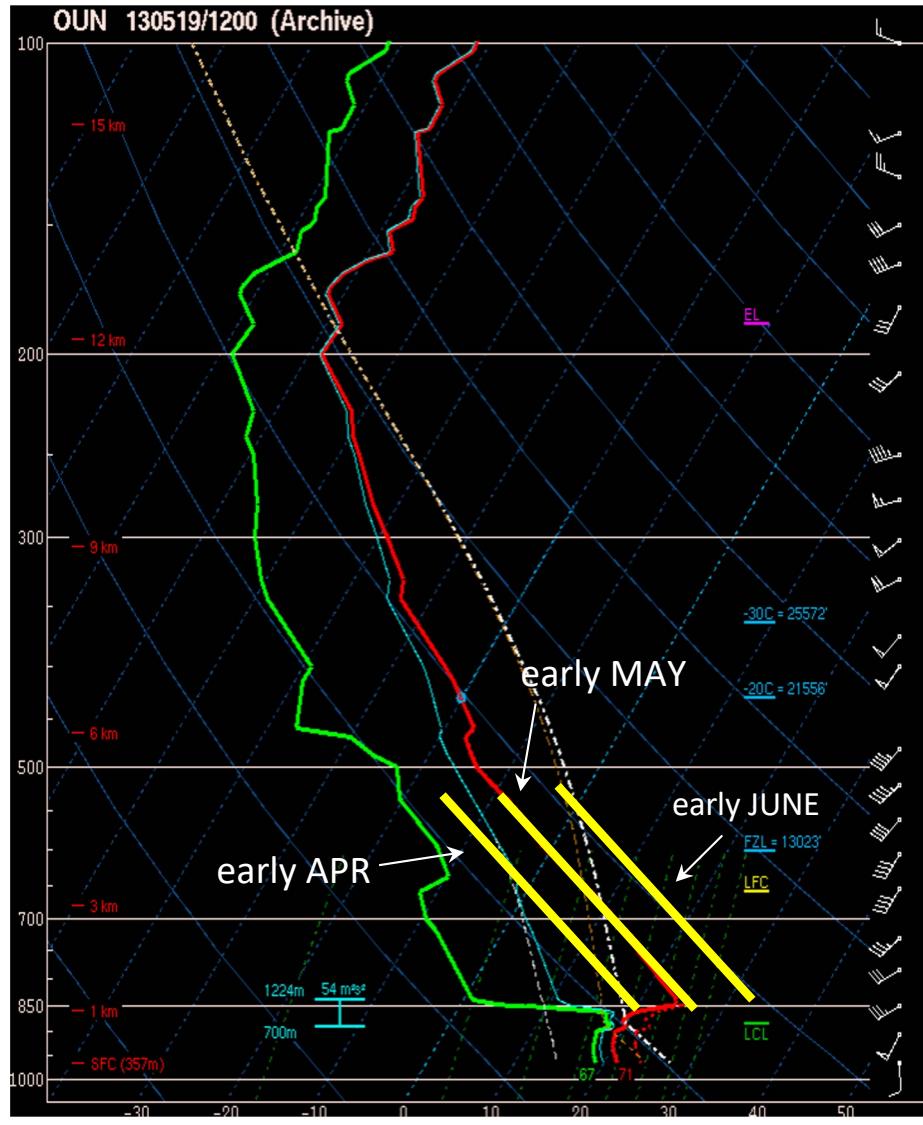
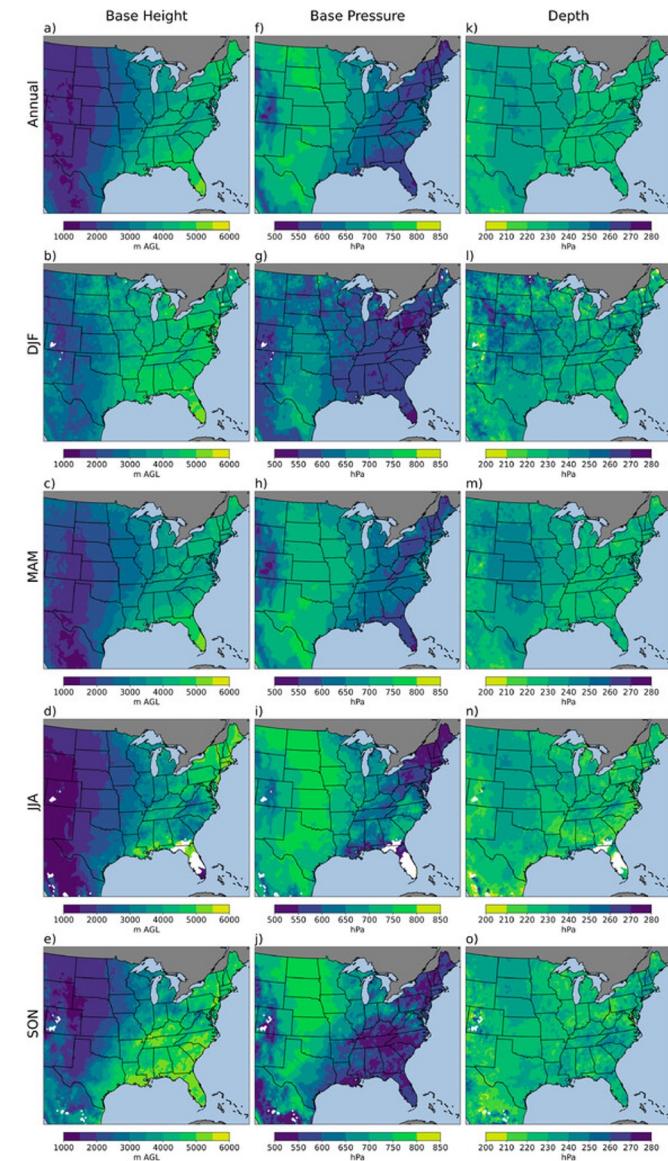
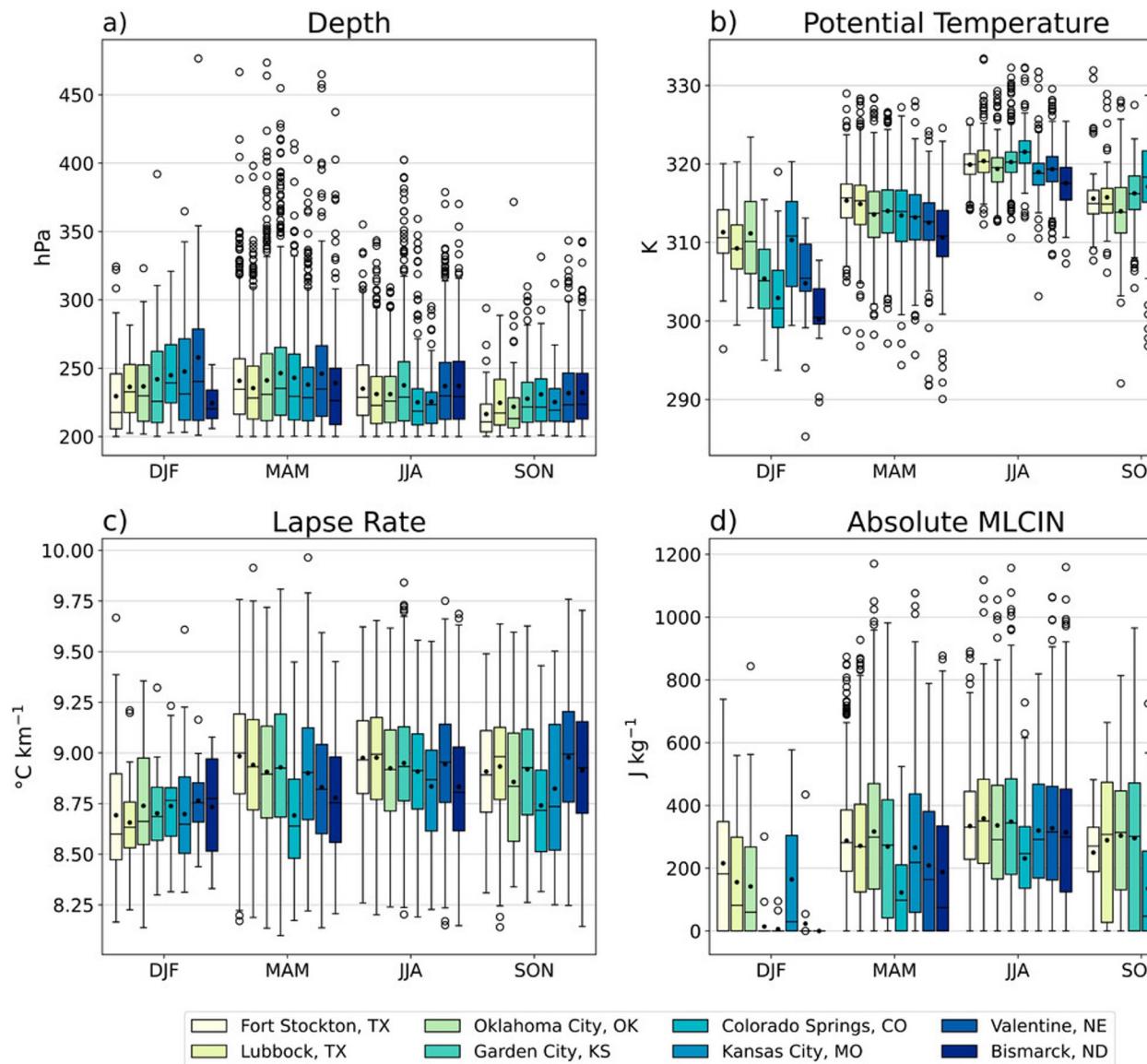
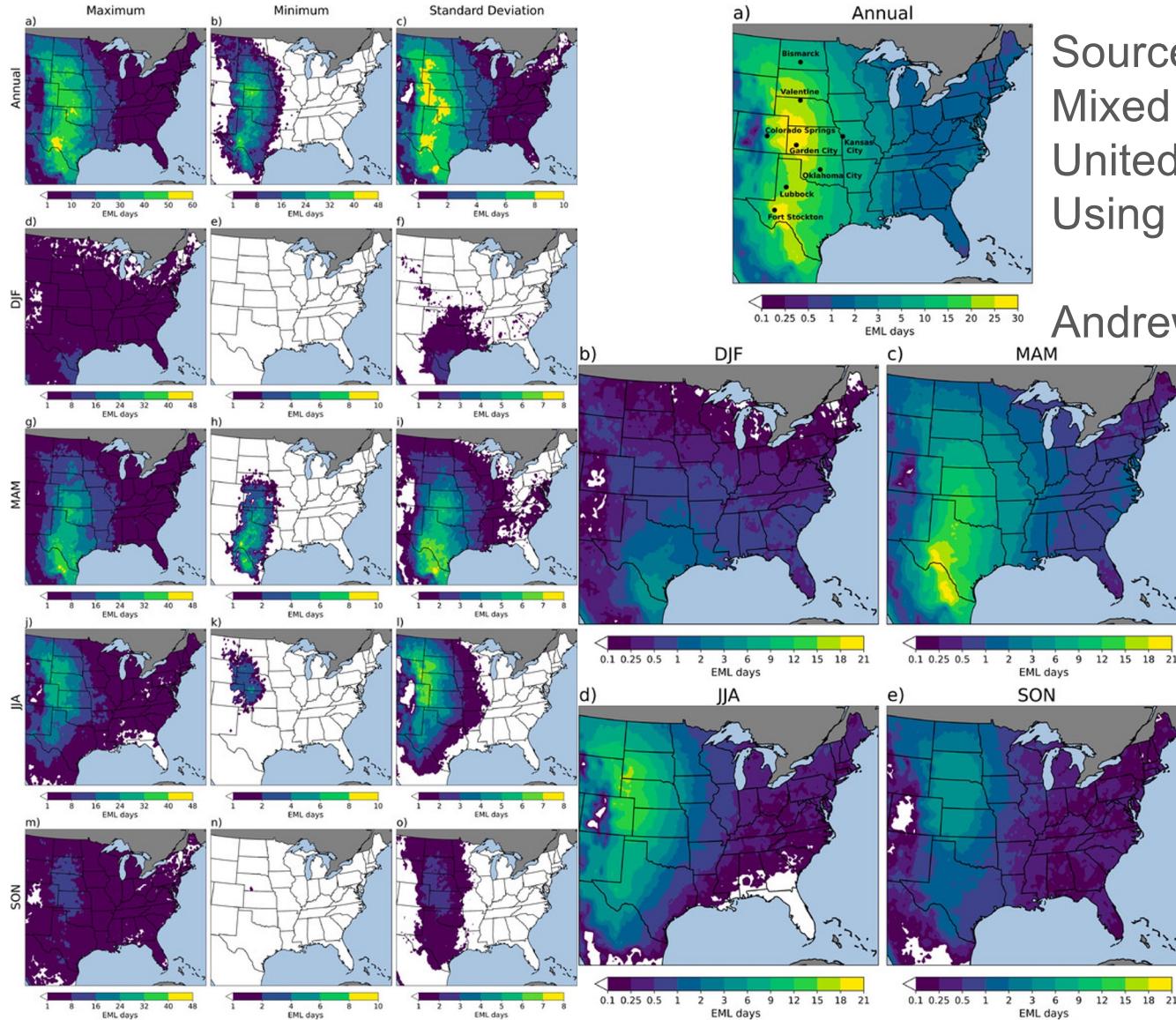


FIG. 6. Climatological mean maximum surface potential temperature analysis (in °C) over northern Mexico and the western U.S. for a) April, b) May, and c) June. Values greater than or equal to 44°C are alternately highlighted in 4°C intervals as shown in the lower left corner of chart (a).

## Climatology of surface theta (and EML)

Lanicci and Warner (1991)





Source: Climatology of the Elevated Mixed Layer over the Contiguous United States and Northern Mexico Using ERA5: 1979–2021

Andrews et., al 2024 JOC

# Lapse Rate Tendency Equation

$$\frac{\partial \gamma}{\partial t} = -\mathbf{v}_h \cdot \nabla_h \gamma - w \frac{\partial \gamma}{\partial z} + \frac{\partial \mathbf{v}_h}{\partial z} \cdot \nabla_h T + \frac{\partial w}{\partial z} (\Gamma_d - \gamma) - \frac{1}{C_p} \frac{\partial q}{\partial z}$$

A      B      C      D      E      F

Term C: vertical lapse rate advection

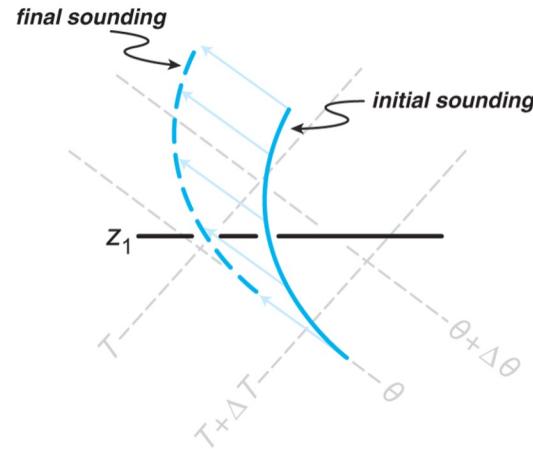


Figure 7.5

Schematic thermodynamic diagram illustrating the effect of vertical lapse rate advection. The light blue arrows indicate dry adiabatic parcel displacements. At level  $z_1$ ,  $\partial\gamma/\partial z < 0$ , so when upward motion is imposed ( $w > 0$  but  $\partial w/\partial z = 0$ , so that all of the parcels are displaced upward by the same distance) larger lapse rates are advected from below  $z_1$  upward to  $z_1$ , increasing the lapse rate there. Note that this process occurs adiabatically, so that cooling has occurred at  $z_1$  in addition to increasing the lapse rate there. This cooling associated with upward motion is typically more important for cap removal and thunderstorm initiation than just the increasing lapse rate. For example, dry adiabatic large-scale ascent *always* leads to cooling (and cap weakening) when lapse rates are less than dry adiabatic, but lapse rate changes resulting from large-scale ascent may or may not be significant, depending on the initial  $\gamma$ ,  $\partial\gamma/\partial z$ , and  $\partial w/\partial z$ .

(Markowski and Richardson 2010, Fig. 7.5)

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Term C: vertical lapse rate advection

Positive lapse rate advection will contribute to increasing lapse rates

In this case, lapse rates at level  $z_1$  increase as steeper lapse rates from below are advected upward

Can be order of magnitude larger than term B on mesoscale

What mesoscale features might this be important for?

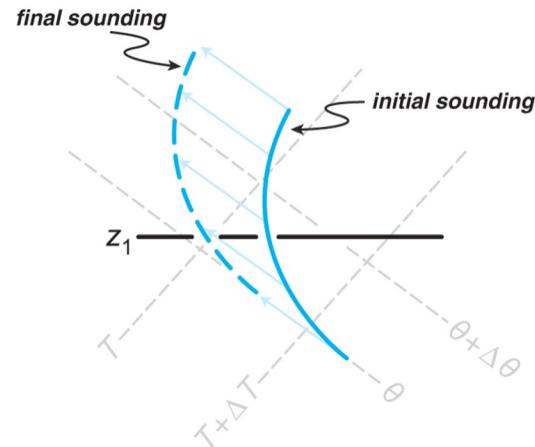
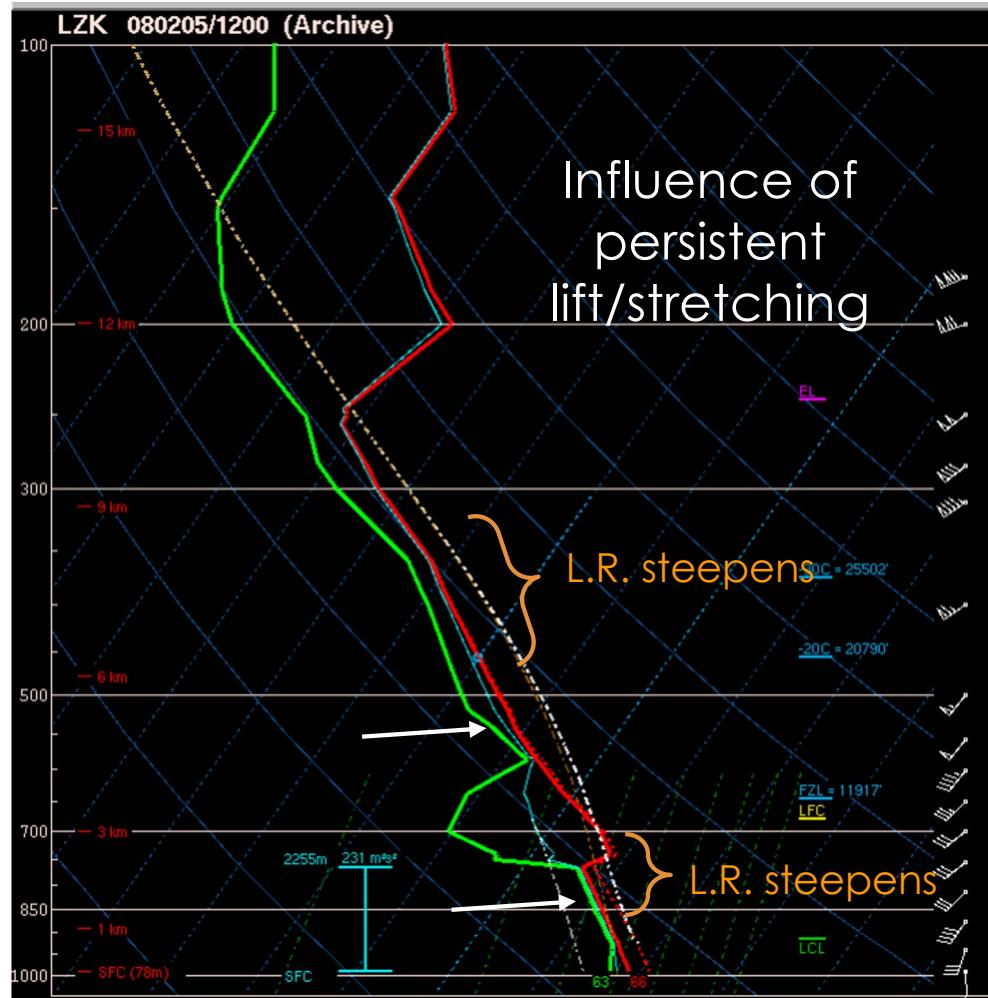


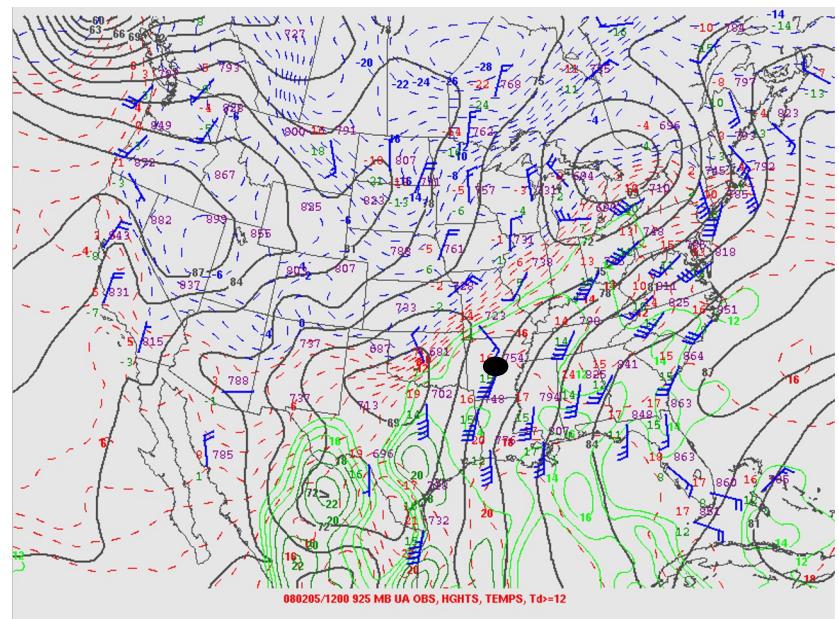
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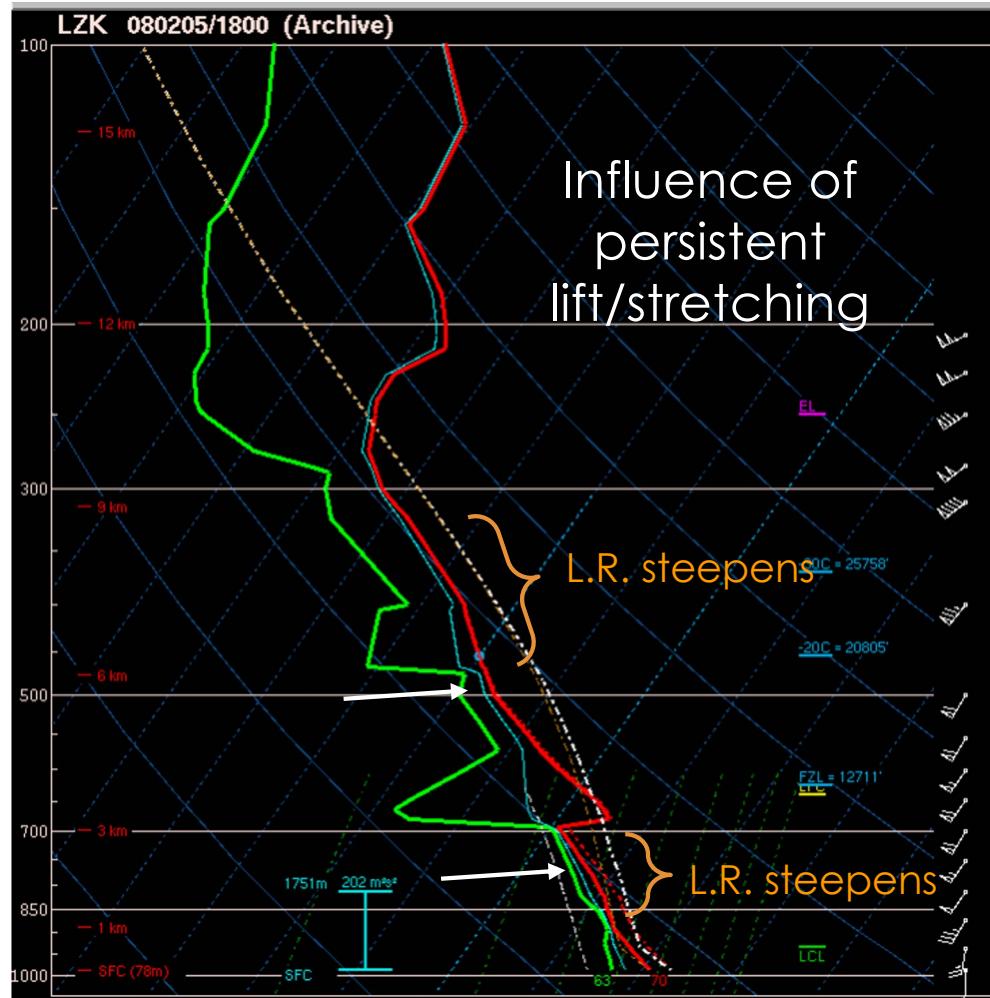
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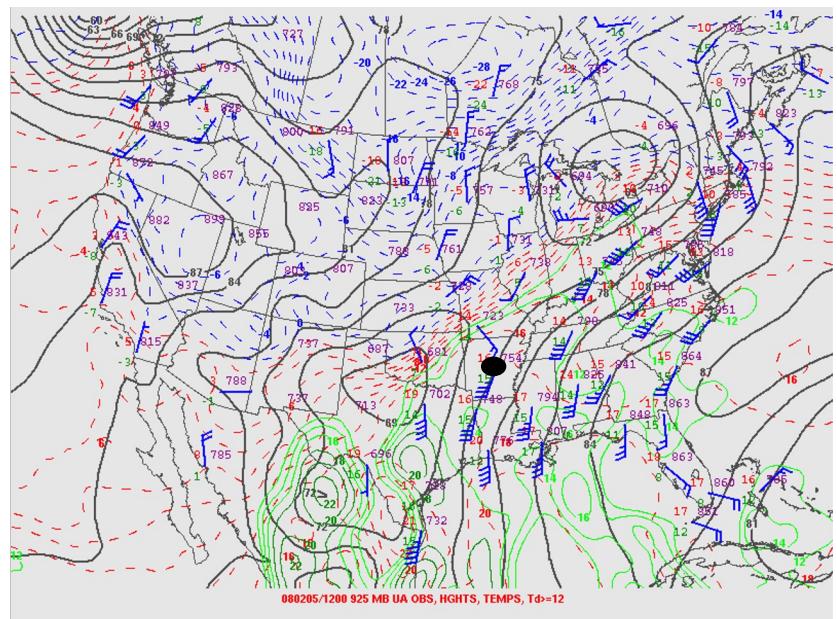


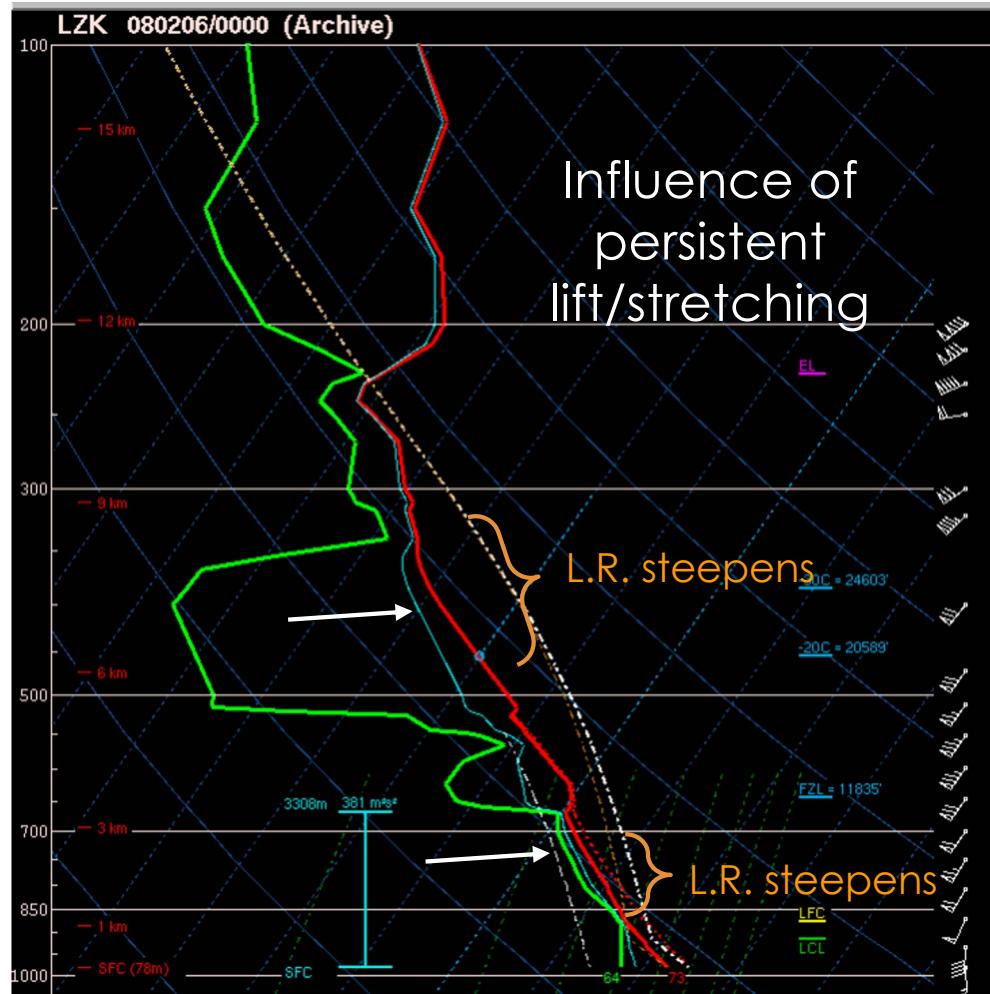
## Influence of Lift/Stretching



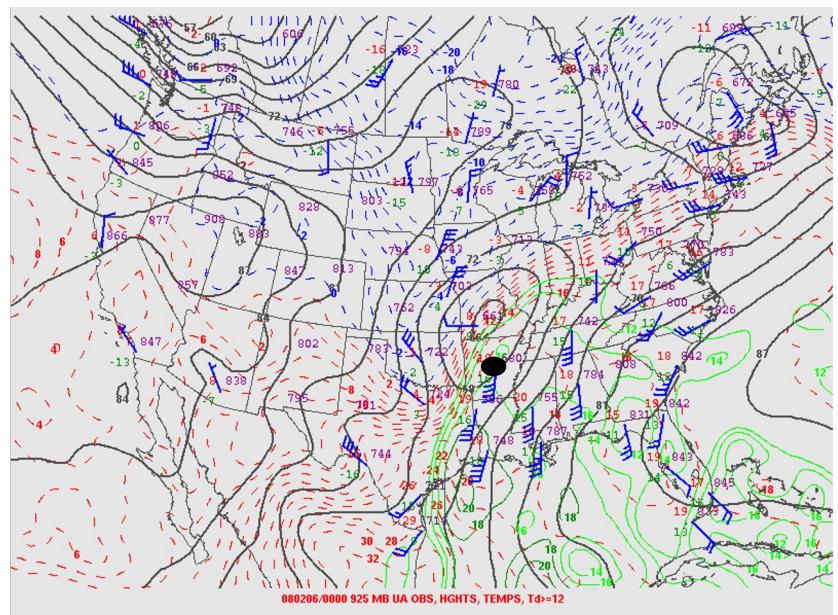


## Influence of Lift/Stretching





## Influence of Lift/Stretching



# Lapse Rate Tendency Equation

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A      B      C      D      E      F

Term D: when combined with term B, this term represents differential temperature advection

$$\frac{\partial \mathbf{v}_h}{\partial z} \cdot \nabla_h T - \mathbf{v}_h \cdot \nabla_h \gamma = \boxed{-\frac{\partial}{\partial z} (-\mathbf{v}_h \cdot \nabla_h T)}$$

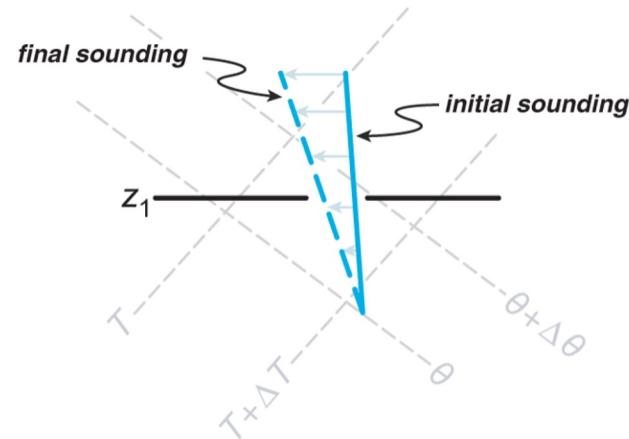


Figure 7.6

Schematic thermodynamic diagram illustrating the effect of differential horizontal temperature advection (by the ageostrophic wind) on the lapse rate (temperature changes are indicated by the light blue arrows). Cold advection increases with height at level  $z_1$ , which leads to an increase in the lapse rate at that level. This effect is really the same effect as illustrated in Figure 7.4.

# Lapse Rate Tendency Equation

$$\frac{\partial \gamma}{\partial t} = -\mathbf{v}_h \cdot \nabla_h \gamma - w \frac{\partial \gamma}{\partial z} + \boxed{\frac{\partial \mathbf{v}_h}{\partial z} \cdot \nabla_h T} + \frac{\partial w}{\partial z} (\Gamma_d - \gamma) - \frac{1}{C_p} \frac{\partial q}{\partial z}$$

A      B      C      D      E      F

Term D: when combined with term B, this term represents differential temperature advection

$$\frac{\partial \mathbf{v}_h}{\partial z} \cdot \nabla_h T - \mathbf{v}_h \cdot \nabla_h \gamma = \boxed{-\frac{\partial}{\partial z} (-\mathbf{v}_h \cdot \nabla_h T)}$$

Lapse rates will increase in situations where cold advection is increasing with height or warm advection is decreasing with height

In this case, lapse rates at level  $z_1$  increase in response to cold air advection increasing with height

Can be order of magnitude larger than term B on mesoscale

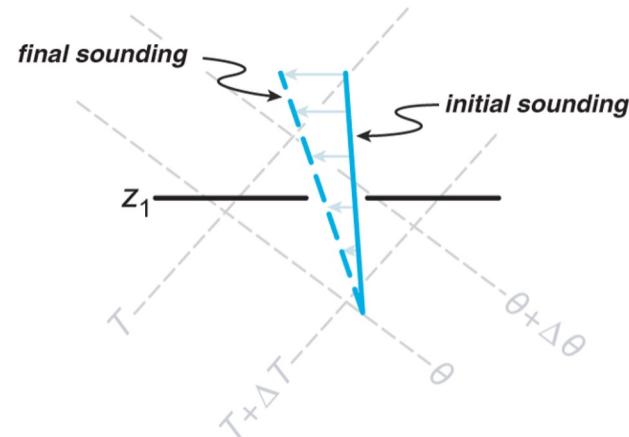
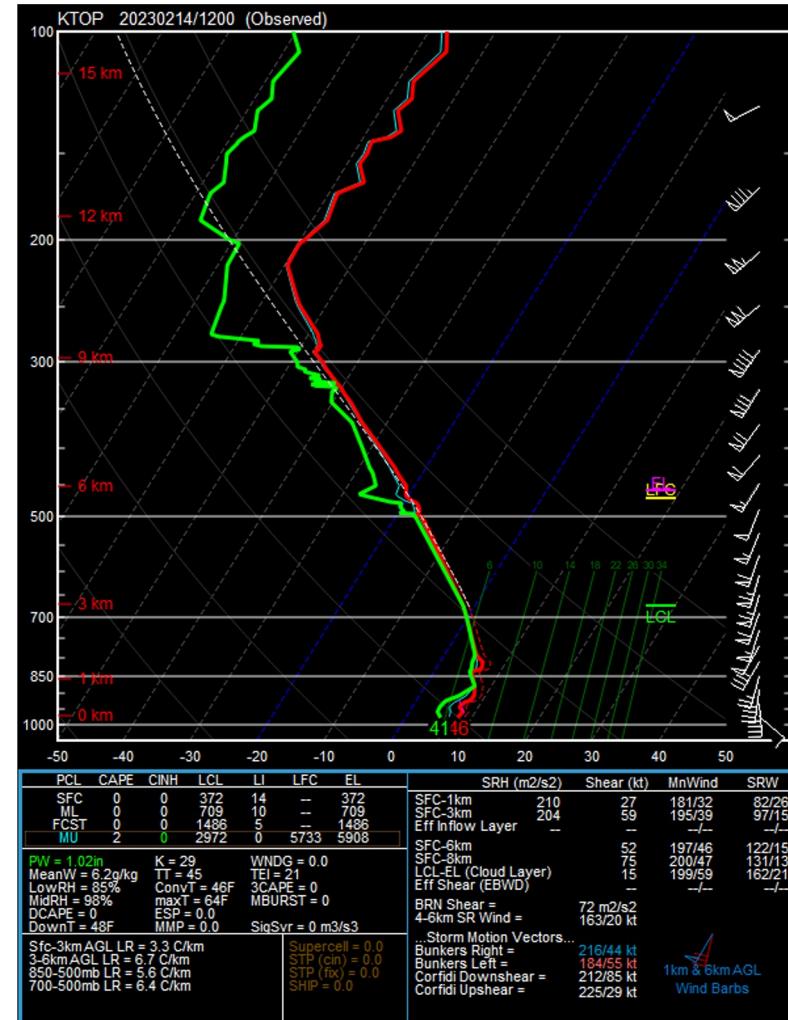
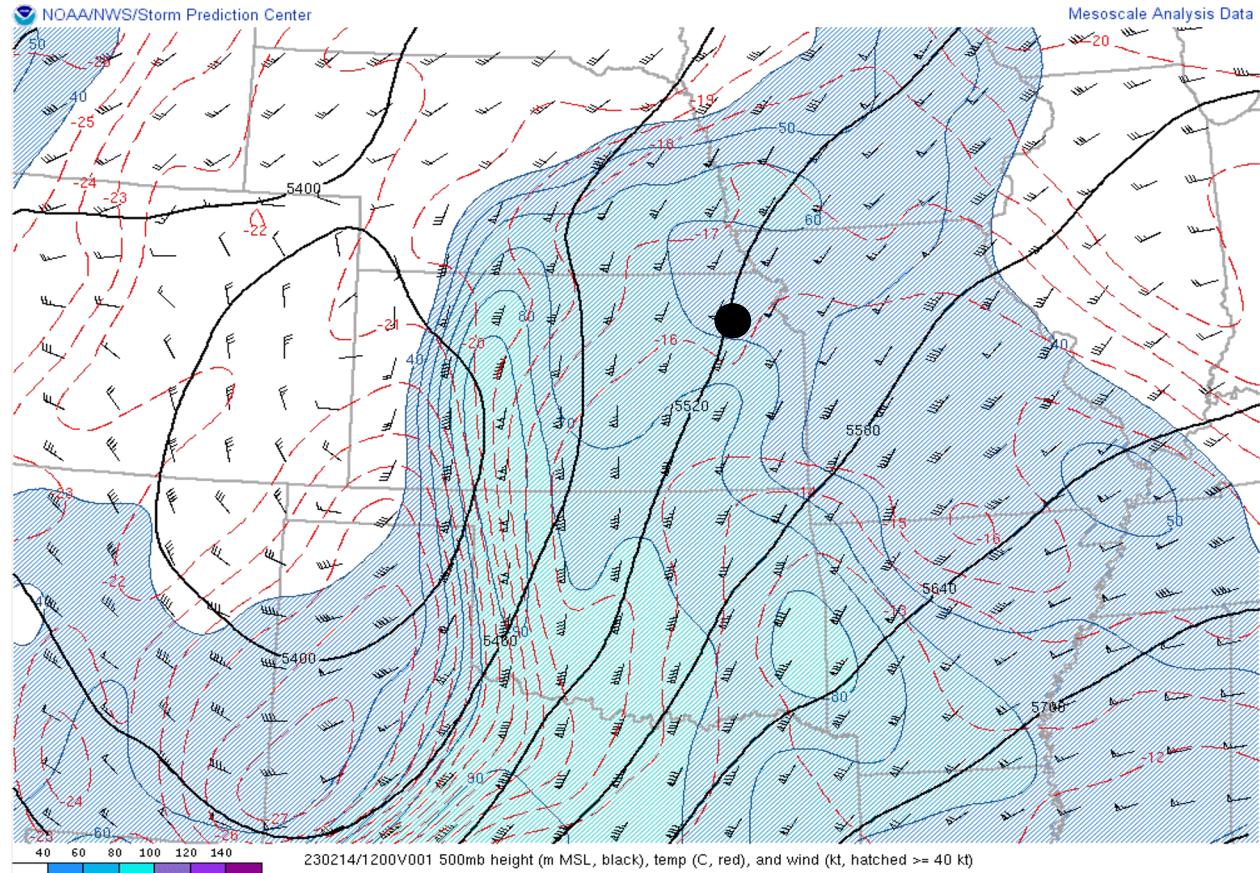


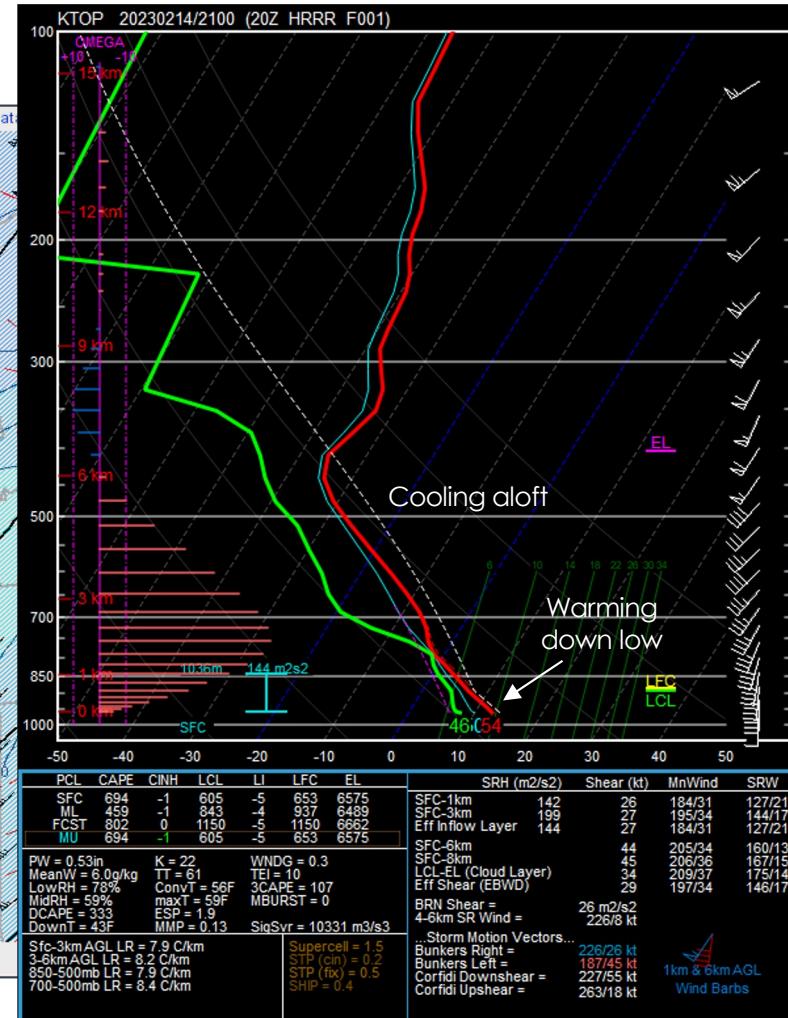
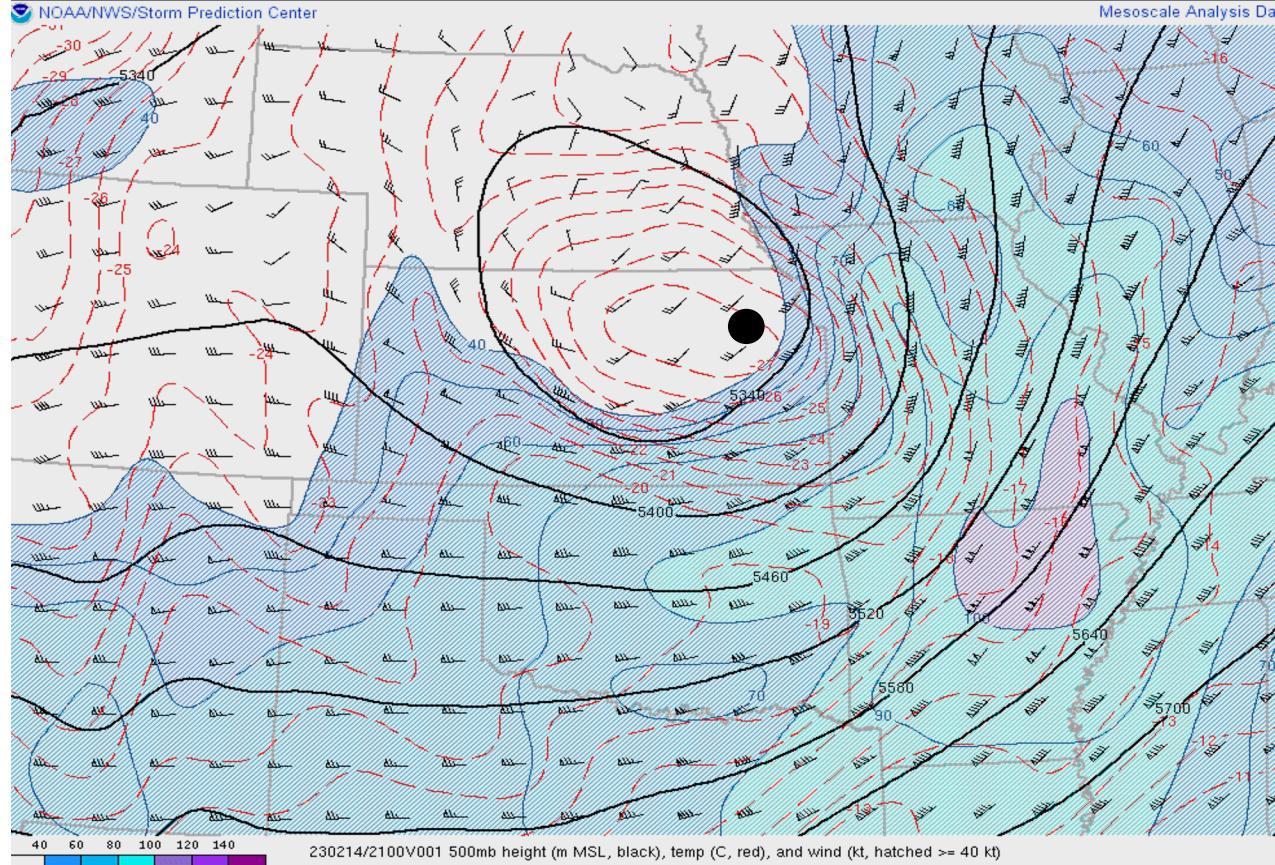
Figure 7.6

Schematic thermodynamic diagram illustrating the effect of differential horizontal temperature advection (by the ageostrophic wind) on the lapse rate (temperature changes are indicated by the light blue arrows). Cold advection increases with height at level  $z_1$ , which leads to an increase in the lapse rate at that level. This effect is really the same effect as illustrated in Figure 7.4.

# Differential Thermal Advection



# Differential Thermal Advection



# Lapse Rate Tendency Equation

$$\frac{\partial \gamma}{\partial t} = -\mathbf{v}_h \cdot \nabla_h \gamma - w \frac{\partial \gamma}{\partial z} + \frac{\partial \mathbf{v}_h}{\partial z} \cdot \nabla_h T + \boxed{\frac{\partial w}{\partial z} (\Gamma_d - \gamma)} - \frac{1}{C_p} \frac{\partial q}{\partial z}$$

A      B      C      D      E      F

Term E: stretching effect on lapse rate

Horizontal convergence increases lapse rate  
 Horizontal divergence decreases lapse rate  
 Term = 0 when environment lapse rate is dry adiabatic ( $\gamma = \Gamma_d$ )

In this case, lapse rates at level  $z_1$  increase in response to convergence ( $\frac{\partial w}{\partial z} > 0$ )

Can be order of magnitude larger than term B on mesoscale

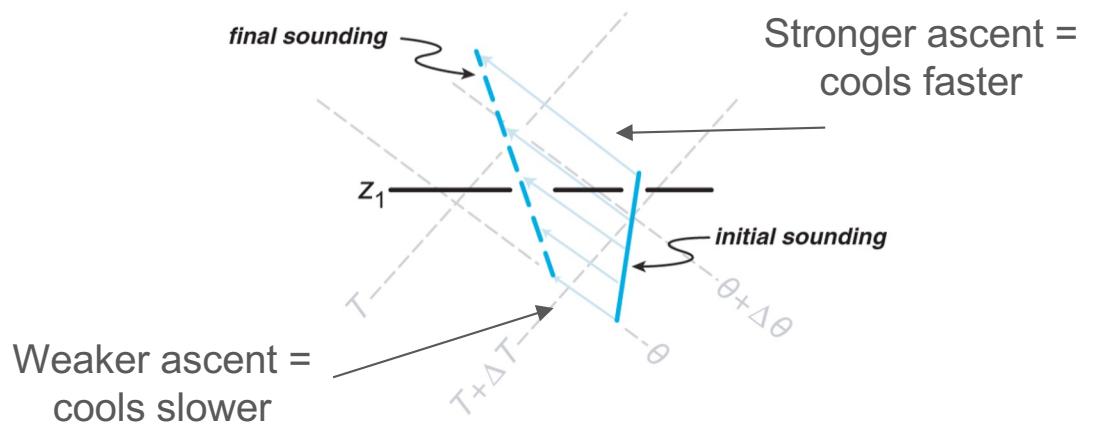
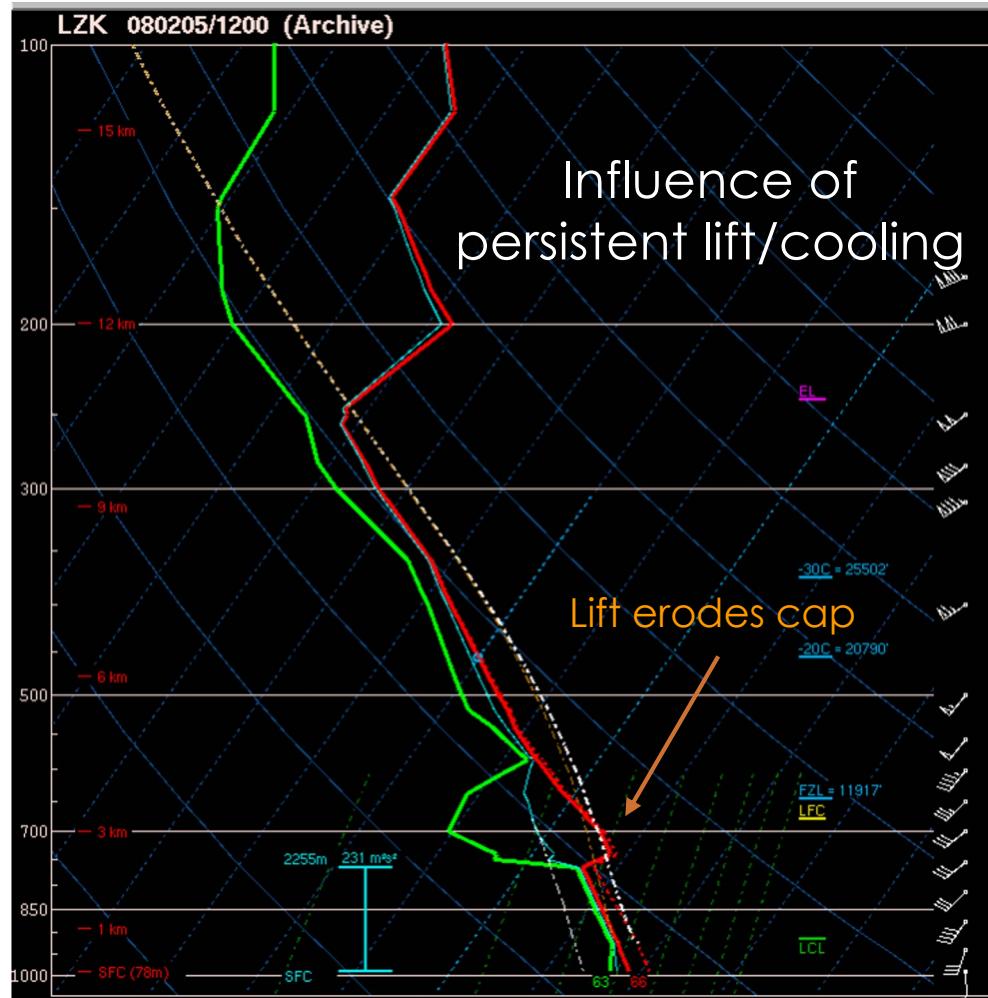


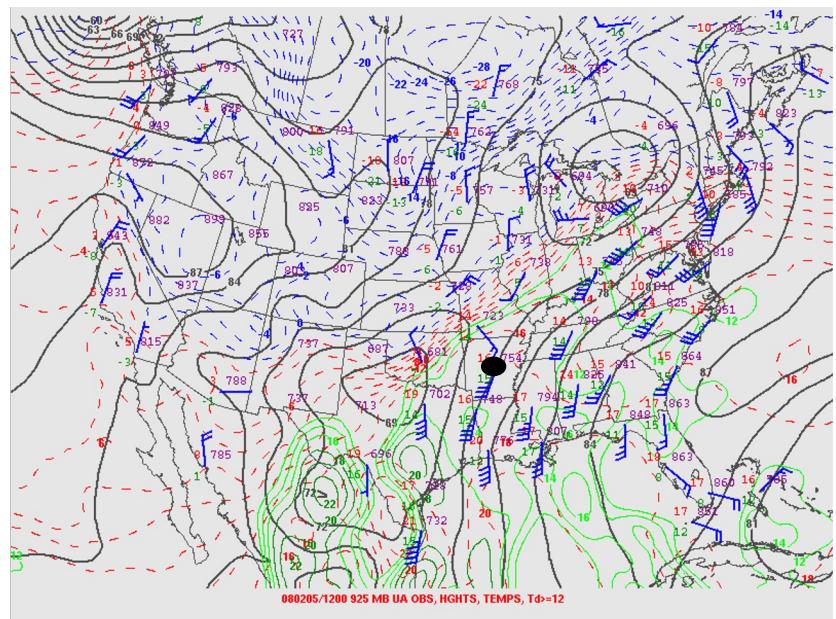
Figure 7.7

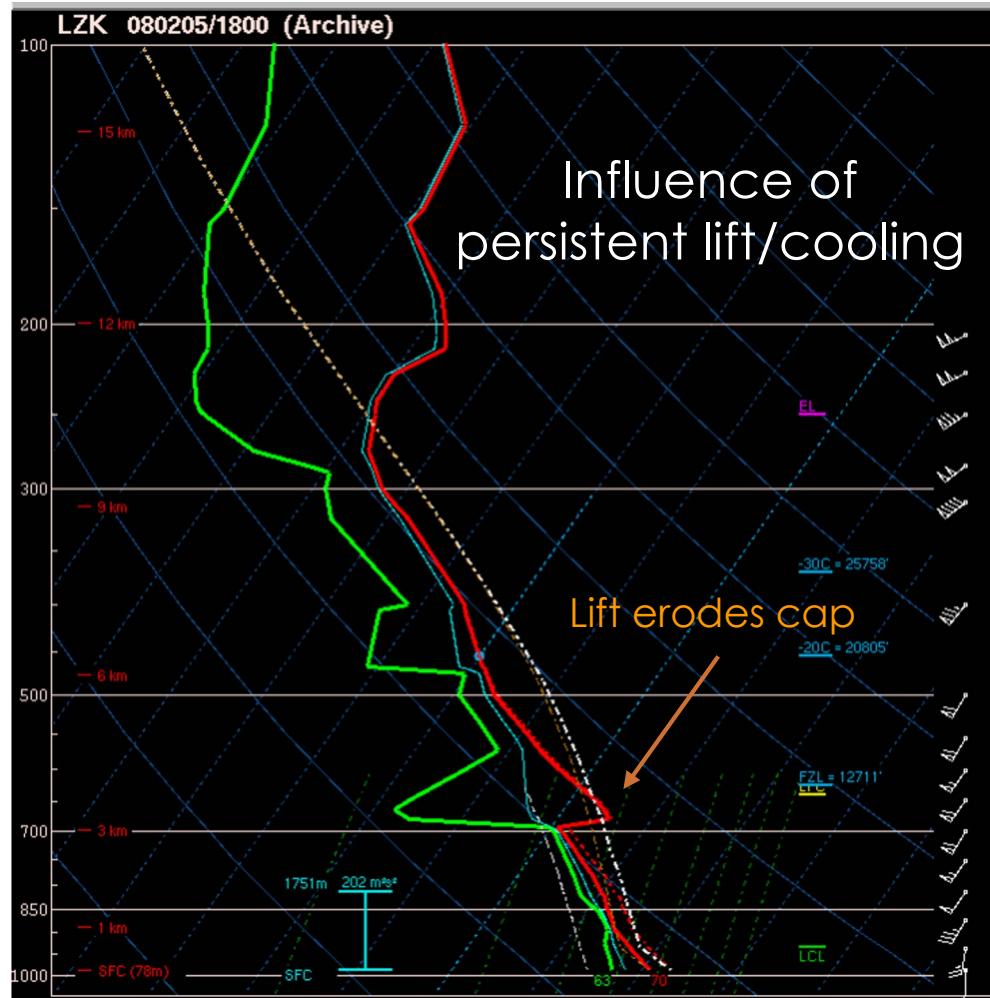
Schematic thermodynamic diagram illustrating the stretching effect on lapse rate. In this example,  $\Gamma_d > \gamma$  and  $\partial w / \partial z > 0$ , therefore the lapse rate at level  $z_1$  increases in time. The light blue arrows indicate dry adiabatic upward parcel displacements (because  $\partial w / \partial z > 0$ , the displacements increase with height).

(Markowski and Richardson 2010, Fig. 7.7)

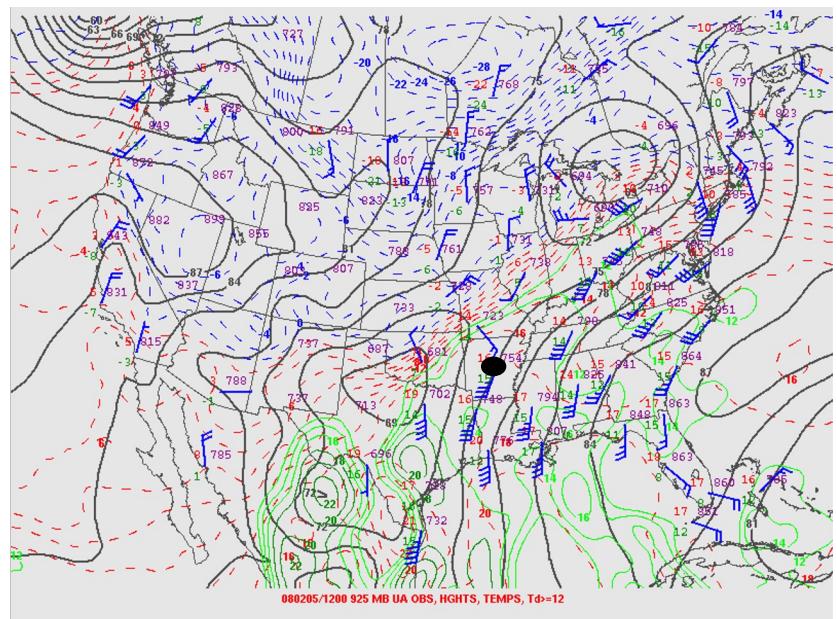


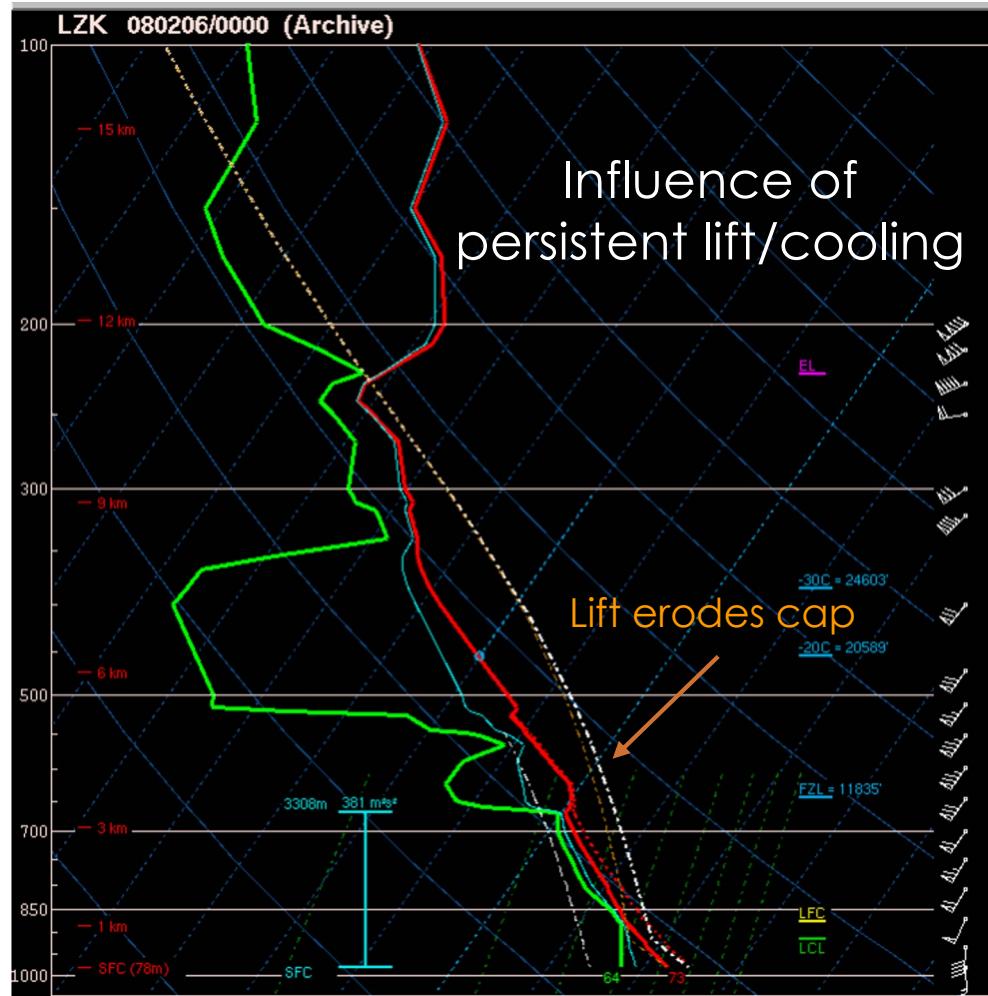
## Influence of Lift/Stretching



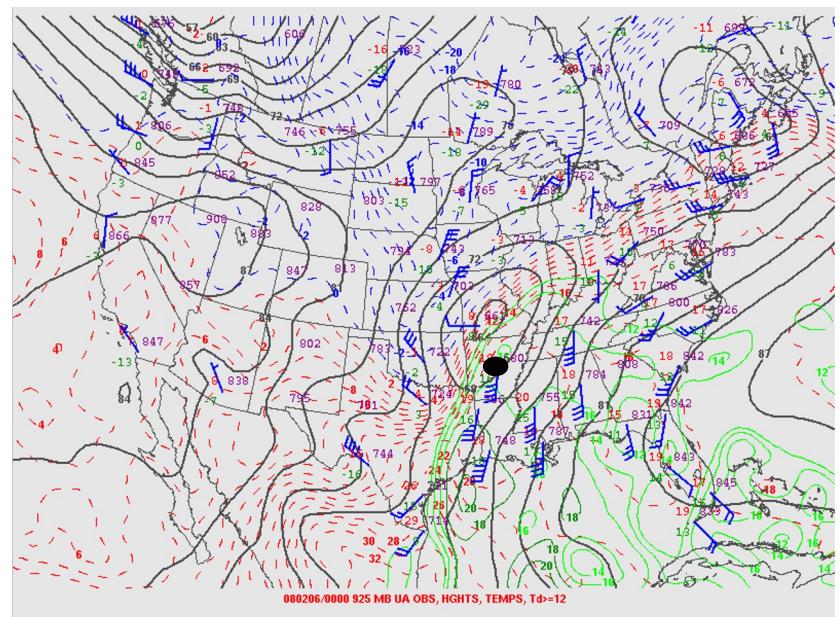


## Influence of Lift/Stretching





## Influence of Lift/Stretching



# Lapse Rate Tendency Equation

$$\frac{\partial \gamma}{\partial t} = -\mathbf{v}_h \cdot \nabla_h \gamma - w \frac{\partial \gamma}{\partial z} + \frac{\partial \mathbf{v}_h}{\partial z} \cdot \nabla_h T + \frac{\partial w}{\partial z} (\Gamma_d - \gamma) - \frac{1}{C_p} \frac{\partial q}{\partial z}$$

A      B      C      D      E      F

Term F: diabatic heating effect on lapse rate

In this case, in response to a diabatic heating maximum at level  $z_1$ , lapse rates increase above and decrease below level  $z_1$ .

Where does most diabatic heating occur?

Can be order of magnitude larger than term B on mesoscale

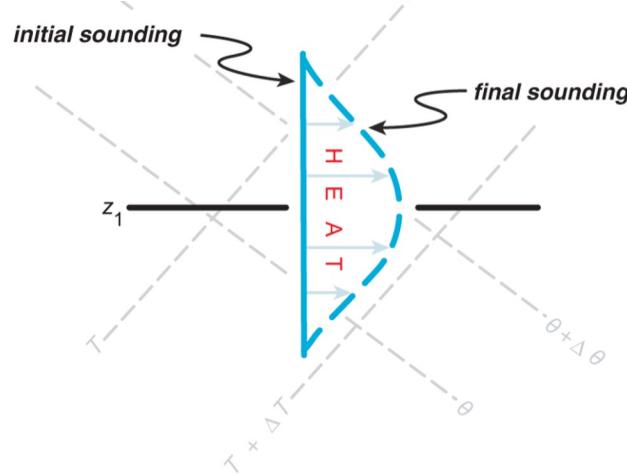


Figure 7.8

Schematic thermodynamic diagram illustrating the effects of differential diabatic heating on lapse rate (temperature changes are indicated by the light blue arrows). The maximum latent heating occurs at level  $z_1$ , where  $\partial q/\partial z = 0$  and the lapse rate is unchanged. The lapse rate increases above the level of maximum heating ( $z > z_1$ ) and decreases below the level of maximum heating ( $z < z_1$ ).

(Markowski and Richardson 2010, Fig. 7.8)

T=morning

Maximum in  
diabatic cooling

T=mid day

Radiation has reversed  
sun warming the  
ground

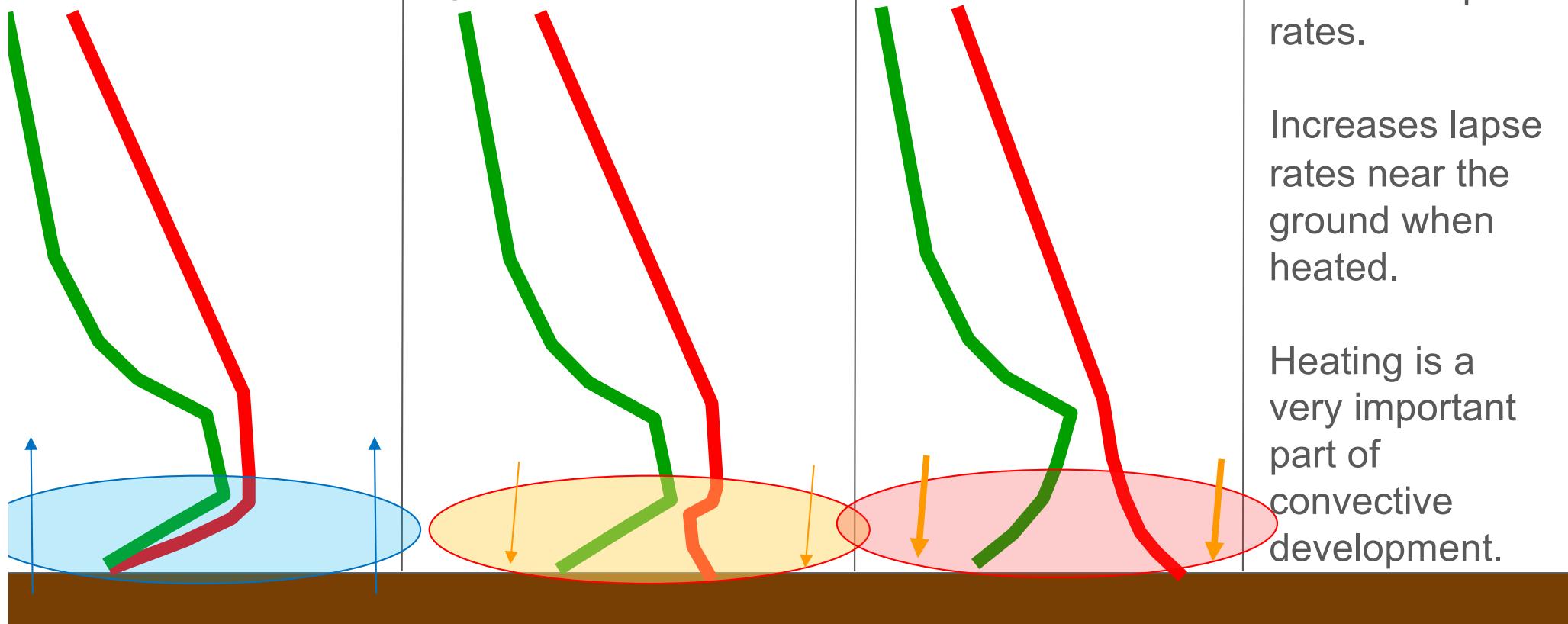
T= afternoon

Maximum solar  
heating

Solar/terrestrial  
radiation of near  
surface air is a  
primary driver of  
low-level lapse  
rates.

Increases lapse  
rates near the  
ground when  
heated.

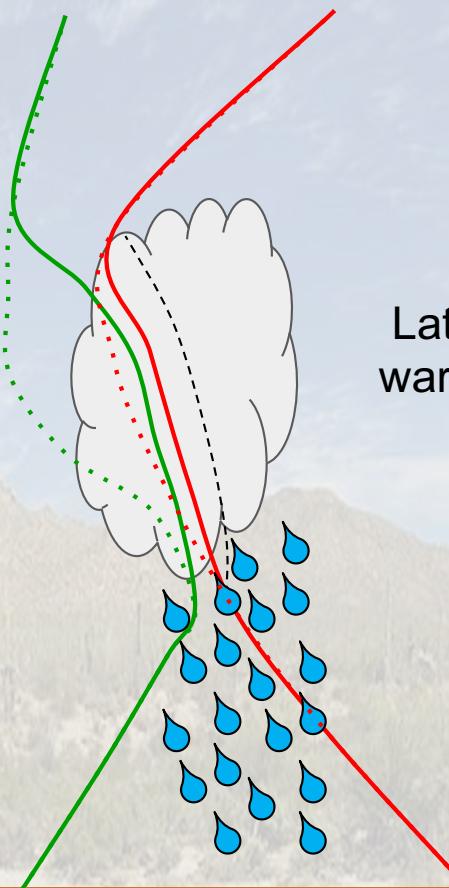
Heating is a  
very important  
part of  
convective  
development.



Initial Profile



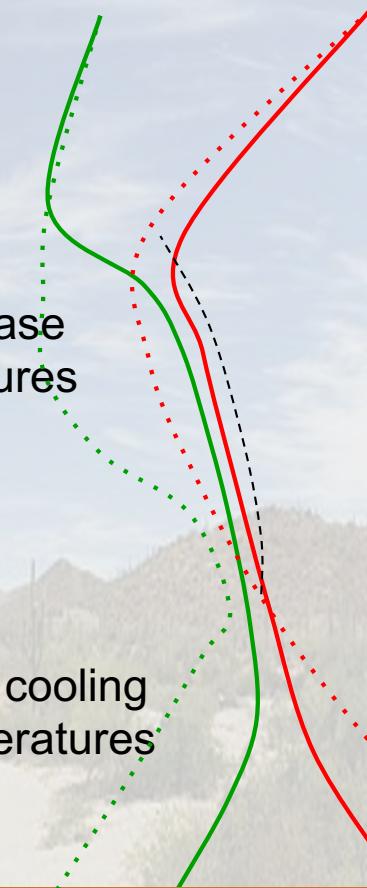
Convection Occurs



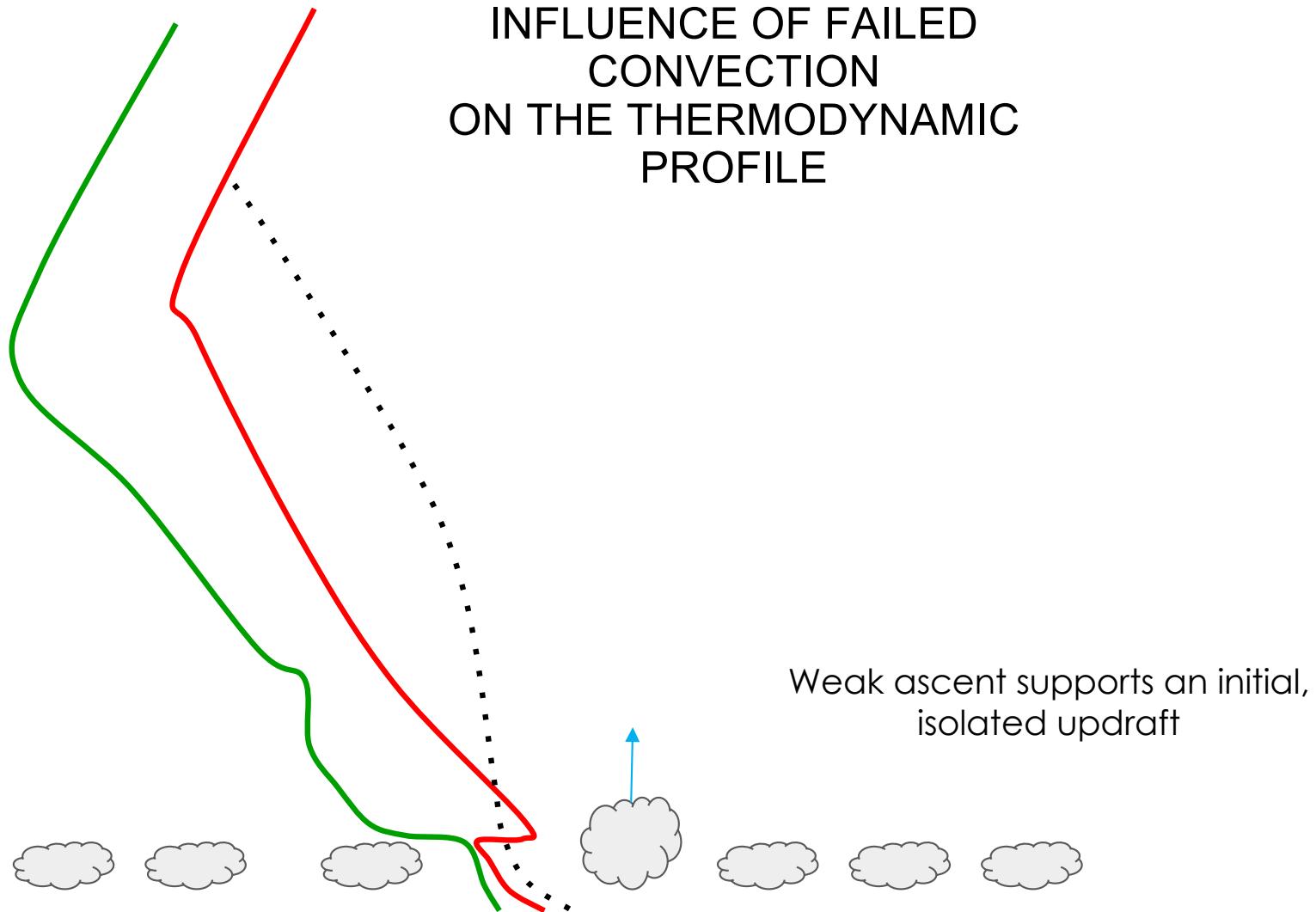
Latent heat release  
warms temperatures

Evaporative cooling  
lowers temperatures

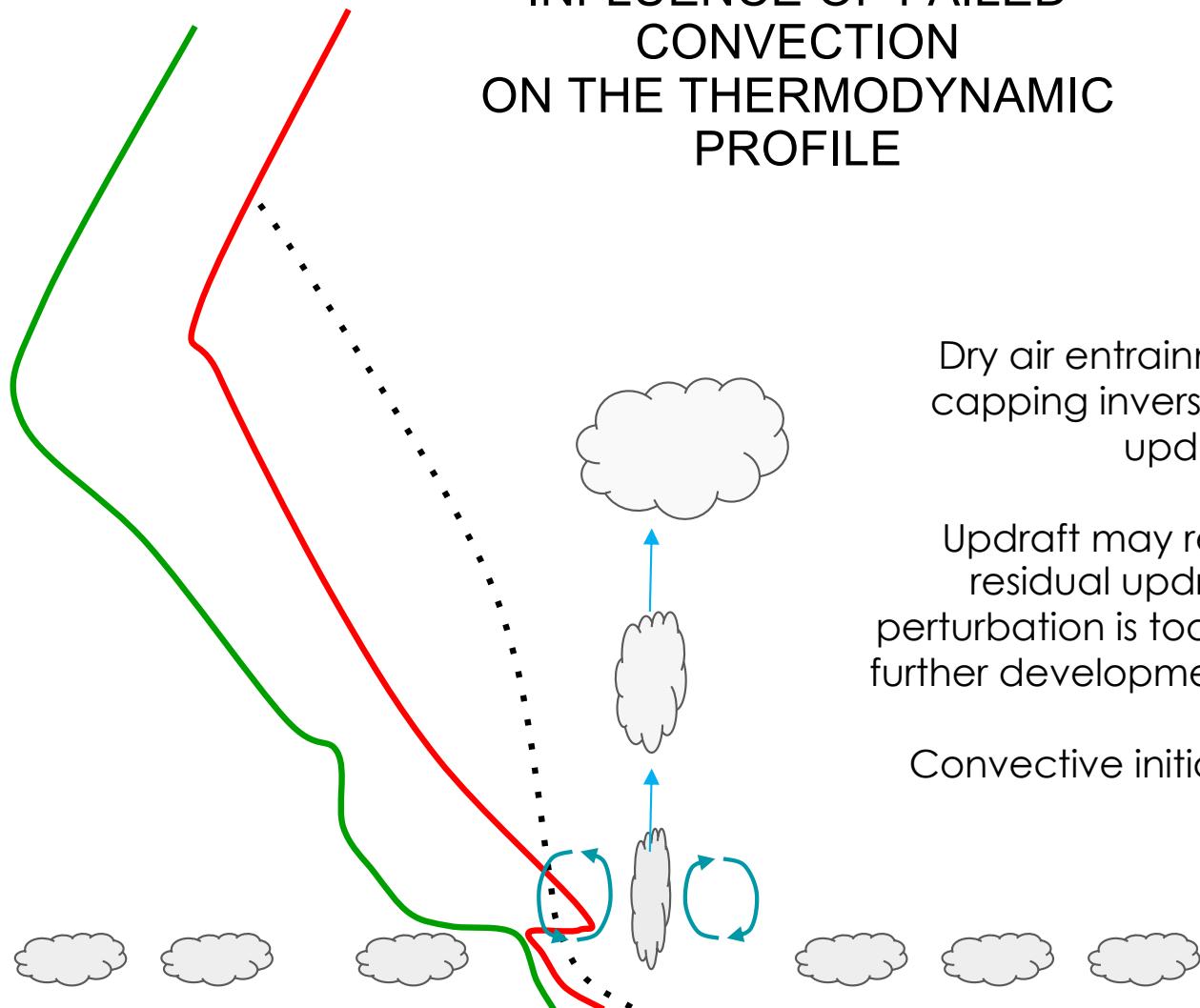
Final Profile



## INFLUENCE OF FAILED CONVECTION ON THE THERMODYNAMIC PROFILE



## INFLUENCE OF FAILED CONVECTION ON THE THERMODYNAMIC PROFILE

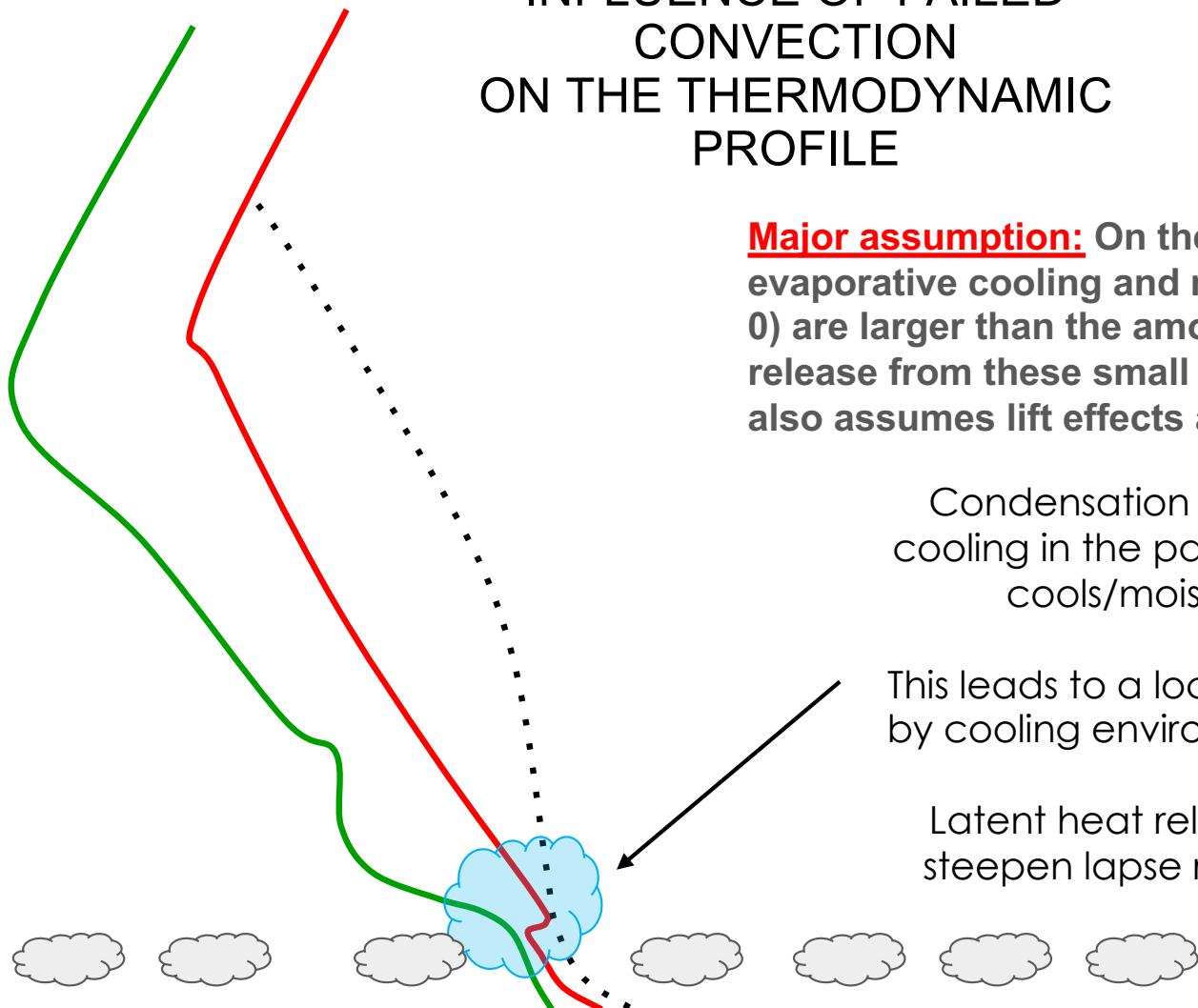


Dry air entrainment near the capping inversion erodes the updraft.

Updraft may reach LFC, but residual updraft/pressure perturbation is too weak to support further development (turkey tower).

Convective initiation has failed.

## INFLUENCE OF FAILED CONVECTION ON THE THERMODYNAMIC PROFILE



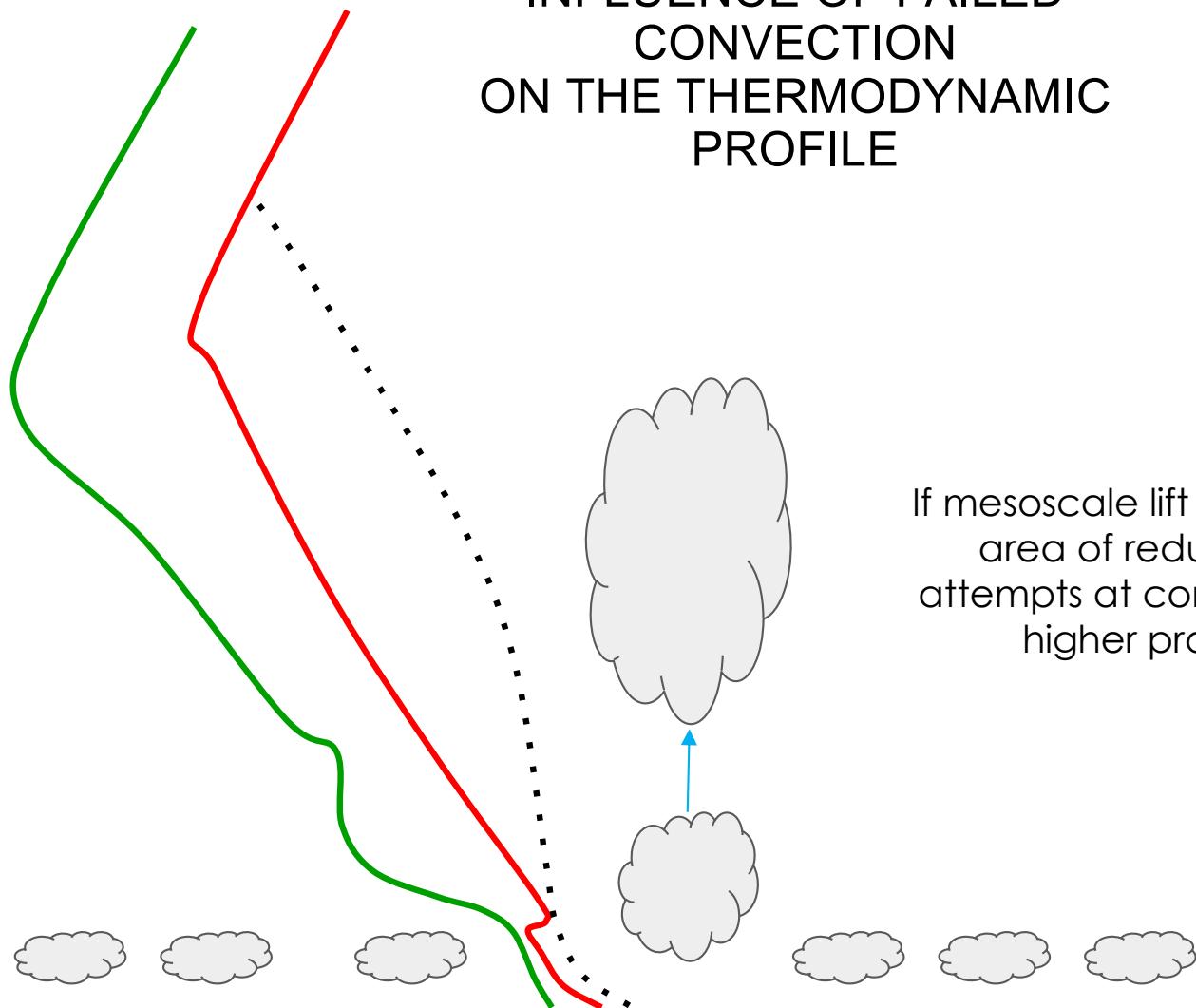
**Major assumption:** On the mesoscale, the effects of evaporative cooling and mixing in a small layer ( $dz \sim 0$ ) are larger than the amount of diabatic (latent heat) release from these small convective updrafts. This also assumes lift effects are not dominating.

Condensation leads to evaporative cooling in the path of the failed updraft cools/moistens the column.

This leads to a localized reduction in CIN by cooling environmental temperatures.

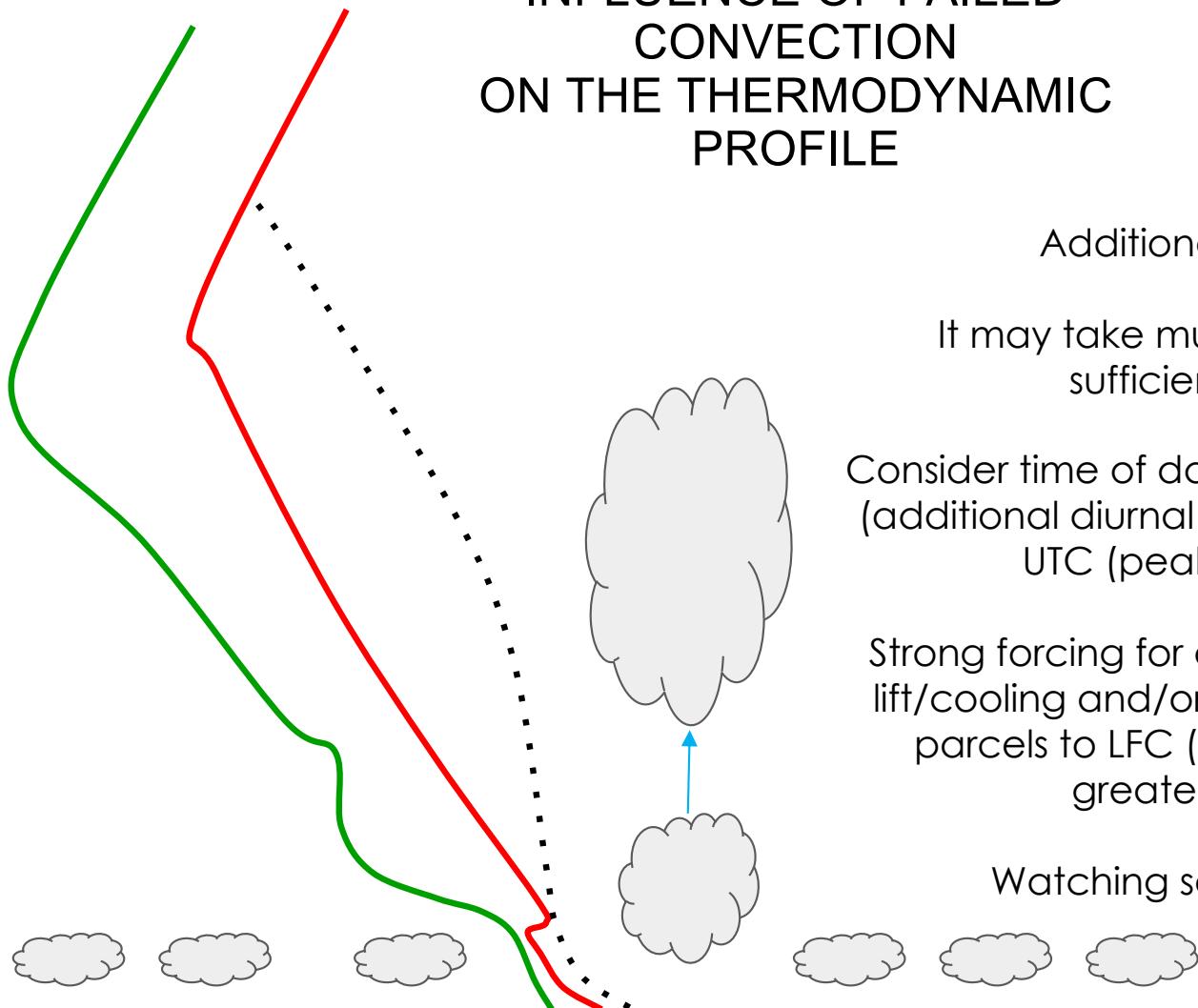
Latent heat release can also locally steepen lapse rates above failed CI.

## INFLUENCE OF FAILED CONVECTION ON THE THERMODYNAMIC PROFILE



If mesoscale lift continues in this localized area of reduced CIN, subsequent attempts at convective initiation have a higher probability of success!

## INFLUENCE OF FAILED CONVECTION ON THE THERMODYNAMIC PROFILE



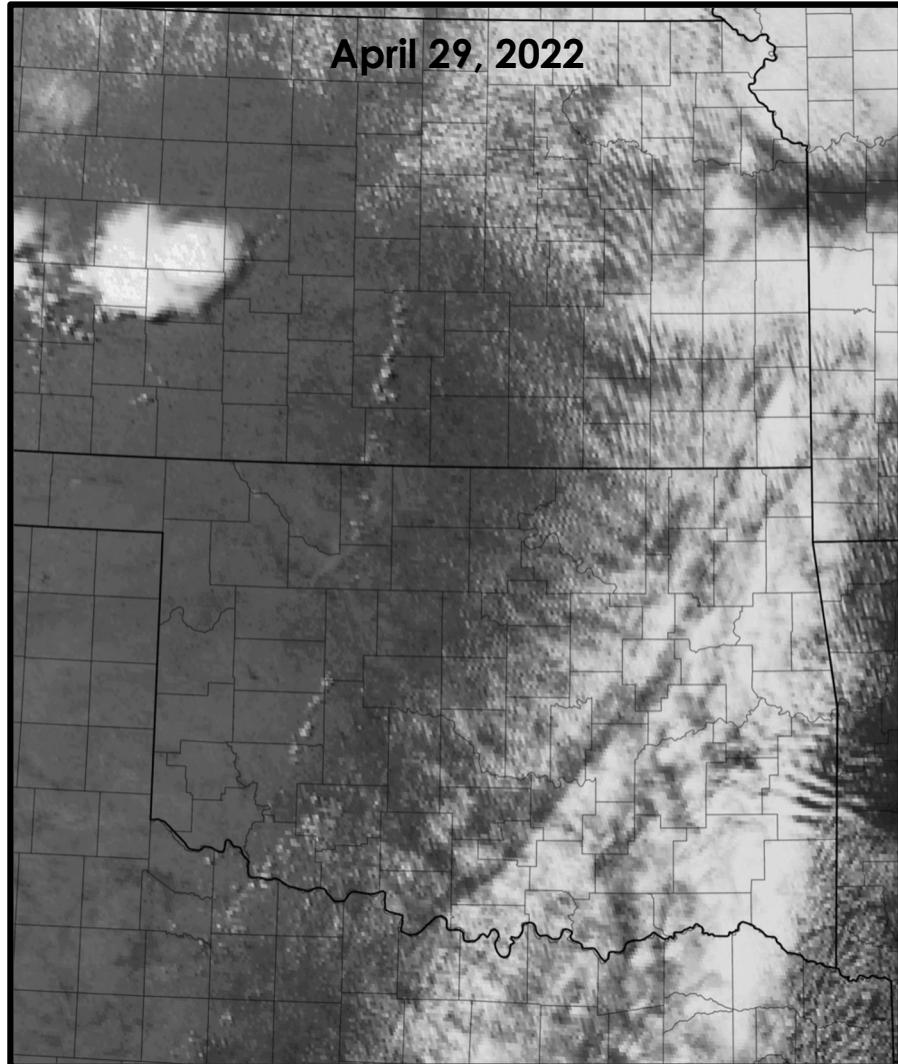
Additional Considerations:

It may take multiple attempts at CI to sufficiently reduce CIN.

Consider time of day (is this occurring at 20 UTC (additional diurnal heating expected) or at 00 UTC (peak diurnal heating)?

Strong forcing for ascent can reduce CIN via lift/cooling and/or overcoming cap by lifting parcels to LFC (i.e. is the depth of the lift greater than the LFC?)

Watching satellite trends is vital!



In this loop, watch for:

- Initial attempts at CI along dryline
- Successful CI following the failed attempts
- Maturation of tornadic supercells

# CAPE/CIN Changes Independent of $\gamma$ Tendency

- CIN can be reduced and/or CAPE increased by:

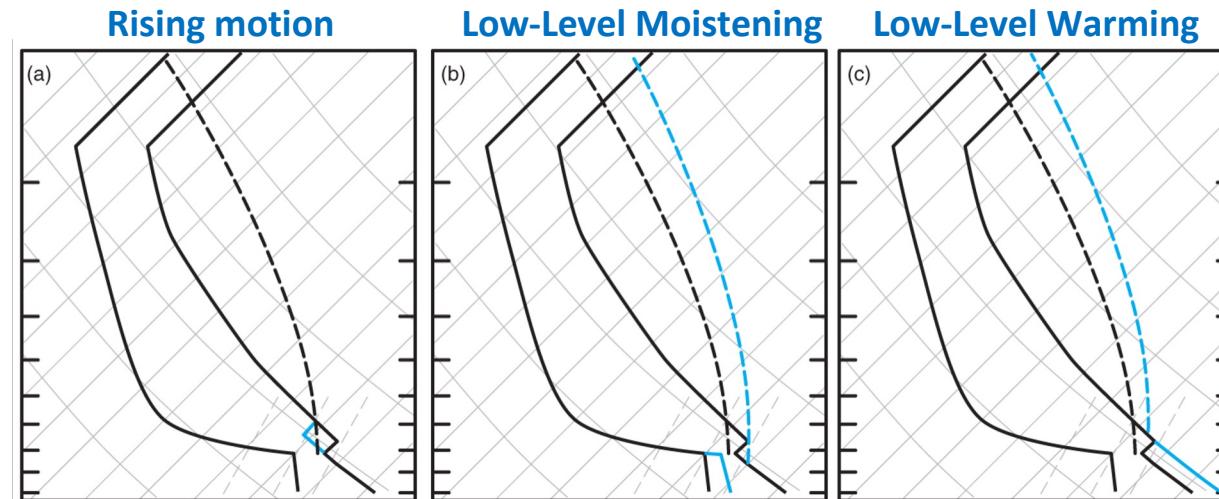


Figure 7.9

CIN can be reduced by (a) large-scale rising motion, (b) low-level moistening (e.g., moisture advection), and (c) low-level warming (e.g., insolation), despite the fact that the CIN modifications may not be accompanied by lapse rate changes, at least not over a significant depth. In (a)–(c), the isotherms and isentropes are solid gray lines, the constant mixing ratio lines are gray dashed lines, the sounding and trajectory taken by an air parcel lifted from the surface are solid and dashed black curves, respectively, and the modified sounding and parcel trajectory are blue solid and dashed curves, respectively. In (a), for clarity, only the temperature profile has been modified (the moisture profile has not been modified in accordance with the vertical motion that has been imposed in the layer of the capping inversion). Note that (b) and (c) are also accompanied by increases in CAPE. Conversely, CIN is augmented by large-scale descent, boundary layer cooling (although this would typically not occur without a concurrent stabilization of the lapse rate), and boundary layer drying (not shown). (Markowski and Richardson 2010, Fig.

# In reality a combination of processes change $\gamma$

$$\frac{\partial \gamma}{\partial t} = -\mathbf{v}_h \cdot \nabla_h \gamma - w \frac{\partial \gamma}{\partial z} + \frac{\partial \mathbf{v}_h}{\partial z} \cdot \nabla_h T + \frac{\partial w}{\partial z} (\Gamma_d - \gamma) - \frac{1}{C_p} \frac{\partial q}{\partial z}$$

- Horizontal lapse rate advection
- Differential thermal advection
- Ascent stretching/vertical advection
- Low-level diabatic heating
- Net Effect: Steep lapse rates!

