3.4 Drylines

The dryline is a mesoscale phenomena whose development and evaluation is strongly linked to the PBL. In this section, we will consider its general description, development, movement, and role in convection initiation.

3.4.1 Introduction

Definition: *A narrow zone of strong horizontal moisture gradient at and near the surface.*

We will focus on drylines that form in the Western Great Plains of the U.S.

- Drylines are generally oriented N/S, with warm, moist air to the east, and hot, dry air to the west.
- The moist air to the east of the dryline originates from the Gulf of Mexico.
- The dry air to the west of the dryline originates from the southwestern states and the Mexican plateau.
- Dew point temperature gradients in the vicinity of a dryline have been observed to range from a fairly diffuse $10\ \mathrm{K}/100\ \mathrm{km}$ to a very strong $10\ \mathrm{K}/1\ \mathrm{km}$.
- A veering wind shift usually occurs with a dryline passage during the day because the dry adiabatic lapse rate behind the dryline facilitates vertical mixing of upper-level westerly momentum down to the surface.
- Horizontal gradients of land-use, vegetation, and soil moisture can also affect the formation and evolution of drylines.
- Sensible heat flux is increasingly dominant in the surface energy budget from east to west due to the westward decline in vegetation and soil moisture.
- The western dry air mass generally has a larger diurnal temperature cycle than the eastern moist air.
- This difference in diurnal cycles means that the dry side tends to be cooler at night and warmer during the day than the moist side.
- Thus, *the dry line is not a front*!. Fronts generally do not have a diurnal reversal of the direction of the temperature gradient.
- Additionally, the density contrast between warm, moist air and hot, dry air is generally small (since dry air is more dense than moist air, the two effects offset each other).
- The dryline is often located near a surface pressure trough (often a lee trough or "heat trough"), but does not have to be coincident with the trough.
- Vertical structure: nearly vertical for $< 1\ \mathrm{km}$ and then “tilts” to the east over the moist air

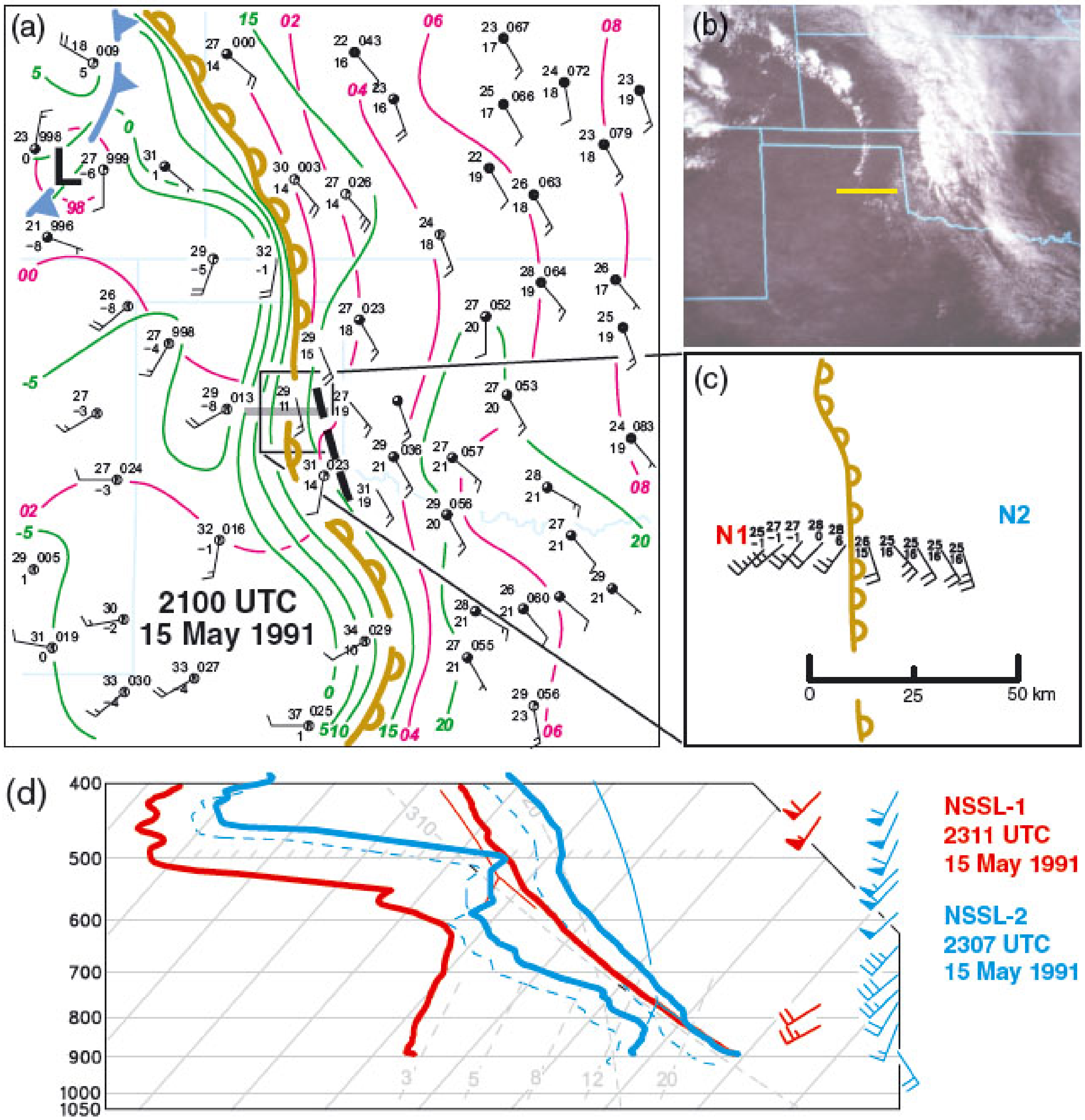

Figure 1: Surface, visible satellite, and sounding observations on 15 May 1991. (a) Manual analysis at 2100 UTC of mean sea level pressure (magenta contours every 2mb; the leading '9' or '10' is dropped) and surface dewpoint, (b) Visible satellite image at 2100 UTC., (c) Close-up of surface observations in the immediate vicinity of the dryline obtained by mobile instrumentation, (d) Soundings obtained west and east of the dryline by NSSL-1 (red) and NSSL-2 (blue), respectively. [From Markowski and Richardson]

3.4.2 Dryline Formation

Recall that the substantial horizontal gradients of moisture present with the dryline are associated with large-scale confluence of different air masses.

Thus, large-scale geostrophic deformation plays an important role in dryline formation.

In fact, this large-scale confluence is a function of the relative strength of lee troughs associated with the Rocky Mountains. Trough formation is explained in a few ways:

- thermodynamically
  - these troughs result from adiabatic compression and warming of sinking air on the lee slope
- dynamically
  - vertical stretching of columns of air descending the lee slope is associated with horizontal convergence and increased relative vorticity.
  - the conservation of potential vorticity means that vertical stretching of these columns must be compensated by an increase of relative vorticity.

Studies (*e.g.*, Schultz et al. 2007) have shown that the behavior in the upstream westerlies modulate the strength of the lee troughs (and thus the dryline strength) according to

- short-wave troughs in the mid- to upper-level westerlies
  - stronger lee troughs
  - stronger confluence
  - larger horizontal moisture gradients (stronger drylines)
- ridging in the mid- to upper-level westerlies
  - weaker lee troughs
  - weaker confluence
  - smaller horizontal moisture gradients (weaker drylines)

As we covered in the introduction, the Great Plains dryline is generally oriented north-south. In other words, the dryline is perpendicular to the horizontal terrain-height gradient. This is because the dryline is basically the intersection of the maritime tropical boundary layer with the ground.

Figure 2 illustrates this idea.

- There is a moist layer that extends from the surface to some fixed pressure level.
- As a result of the terrain gradient, this moist layer is deeper in the east than in the west.
- The intersection of this layer with the ground at some longitude is the dryline.

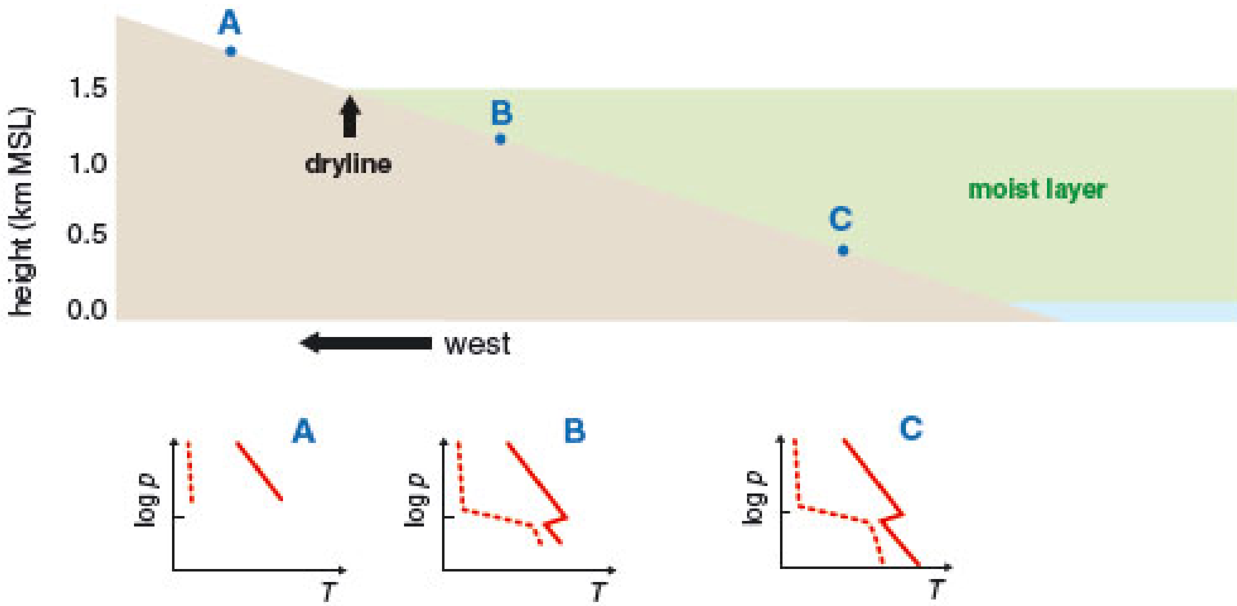

Figure 2: Schematic vertical cross-section of the dryline and its relation to topography. Idealized soundings at points A, B, and C represent the conditions west, just east, and far east of the dryline. [From Markowski and Richardson]

Furthermore, consider the following in regard to dryline formation and structure

- Vertical mixing leads to a dryline that is upright from the ground to an altitude of $\sim$ 1-1.5 km.
- Above this level, the dryline turns quasi-horizontally to the east (see Figure 3).
- Cool, moist air to the east of the dryline is capped by a stably-stratified layer.
- There is a warm, dry layer with large lapse rates that lies on top of this capping layer.
- Since this warm layer started as a mixed layer in higher elevations, it is often called an *elevated mixed layer*.
- This layer extends from the surface to the middle troposphere to the west of the dryline.

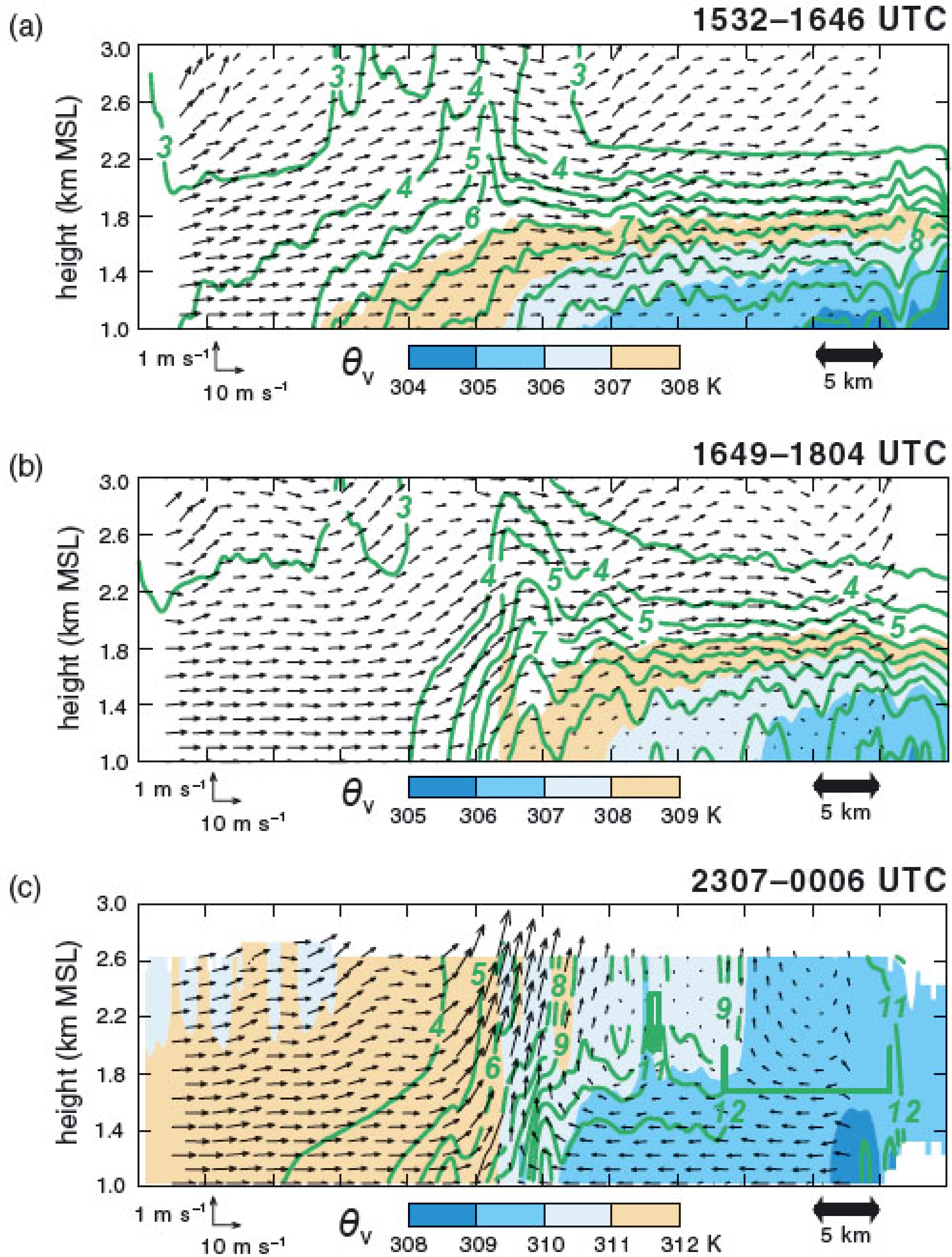

Figure 3: Vertical cross-sections of virtual potential temperature (shaded), water vapor mixing ratio (green contours), and wind. [From Markowski and Richardson]

So far we have identified horizontal gradients of land-use, vegetation, soil moisture, and sensible heat flux, sloping terrain, lee troughs, and vertical mixing as factors that affect the formation and structure of drylines.

However, these factors cannot alone explain the situations where horizontal moisture gradients are relatively extreme ($dT_d/dH > 10 \text{ K}/10 \text{ km}$).

One explanation to describe these situations is frontogenetical dryline dynamics:

- Horizontal temperature gradients lead to solenoidally-forced vertical circulations, which act to enhance the horizontal moisture gradients (see Figure 3).
- Convergence and frontogenesis are present under the ascending branch of this circulation.
- There is likely a positive feedback between the frontogenetical forcing of the horizontal moisture gradient ($d|\vec{\nabla}_h q|/dt$) and the temperature gradient associated with the dryline.

Another explanation of locally enhancement of the horizontal moisture gradient is differential vertical mixing

- The dry adiabatic lapse rate on the hot, dry side of the dryline acts to enhance vertical mixing of westerly momentum to the surface.
- This increased westerly component at the surface behind the dryline acts to enhance low-level convergence at the dryline.
- The enhanced convergence leads to a stronger horizontal moisture gradient.
- The variation in mixing depth across the dryline and the magnitude of the horizontal temperature gradient are likely related.
- A strong temperature difference across the dryline leads to a stronger difference in the depth of vertical mixing, a stronger vertical circulation, stronger convergence, and thus a stronger horizontal moisture gradient.

In short, here is a brief overview of the typical background conditions that favor dryline formation

- Surface anticyclone to the east, allowing moist air from the Gulf of Mexico to flow into the Great Plains.
- Westerly flow aloft, causing a lee trough, and providing a confluence zone for the concentration of the moisture gradient.
- The presence of a stable layer or "capping inversion" or "lid" aloft.
- Because the terrain slopes upward to the west, the moist layer is shallow at the west edge of the moist air, and deeper to the east.

This sets the stage for understanding the movement of the dry line.

3.4.3 Movement of the Dryline

In the absence of strong synoptic-scale forcing, dryline motion can have a strong diurnal variation. Generally, the dryline propagates eastward during daytime, and westward at night.

- As the sun rises, surface heating near the dry line is greater than that of the surface to the east in the deeper moist air (the difference in soil moisture content and low-level cloudiness often also contribute to such differential heating)
- Thus, it takes less surface sensible heating to destabilize the shallow mixed layer just to the east of the initial dry line position.
- The heating reduces static stability just to the east of the dryline, which leads to vertical mixing once the lapse rate becomes dry adiabatic.
- This mixing brings dry air (and westerly momentum) downward, and the position of the dry line moves eastward.
- Continued heating "mixes out" deeper and deeper moist layers, leading to an apparent eastward *propagation* of the dryline.
- We use "propagation" because the dryline movement is discontinuous. It is often observed to "jump" across flat areas of similar terrain to an area where the terrain height abruptly decreases and the depth of the moist layer increases.
- If a well-defined jet streak exists aloft, we often see a "dry line bulge" underneath the jet, as this air has the most westerly momentum to mix downward. The strong westerly momentum mixed down from above provides extra push for the eastward propagation of dryline.
- Eventually, the heating is insufficient to mix out the moist layer and propagation stops.
- During evening hours, dry air to the west cools faster than the moist air to the east, leading to a radiation inversion. The increased static stability inhibits vertical mixing.
- Winds slow and back to a southeasterly direction in response to the pressure gradient force associated with the western lee trough.
- The moist air is advected westward, and thus surface stations will experience an east to west dry line passage.
- In the earliest stages, when the air to the east of the dryline is still relatively cool compared with the dry air to the west, the retreating dryline may morphologically resemble a density current.
- Later in the evening, if the west air becomes cooler compared with that east of the dryline, a retreating dryline may act like a warm front.

The above case assumed quiescent conditions. If the synoptic forcing is strong, the dryline may continue to be advected eastward in association with a surface low pressure system. In other cases, there exists a cold front behind the dryline that eventually catches up to the dry line, which transforms it into a cold front.

3.4.4 Other Aspects of Drylines

Drylines sometimes exhibit complicated structures. For instance, sometimes drylines are associated with a stepwise decrease in dewpoint temperatures instead of the more common monotonic decrease. As a result, multiple drylines are analyzed on a surface map with spacing of $\sim$ 10-50 km. It is still not clear why multiple drylines can exist on one day, while a single, well-defined dryline occurs on another.

Another feature sometimes associated with drylines is the *dryline bulge* (a meso-β phenomena):

- The bulge is associated with locally enhanced convergence and its cause is not well understood.
- Downward mixing of locally faster momentum aloft could lead to a bulge.
- An example of one such a region is a jet streak.
- The ageostrophic motions and transverse circulations associated with the exit region of a jet streak might explain why bulges are associated with increased low-level convergence.
- Specifically, the region poleward of the bulge is often home to storm formation, which coincides with the left exit region of a jet streak.
- A local maximum in surface sensible heat flux can lead to deeper vertical mixing, bringing strong westerly momentum aloft to the surface.

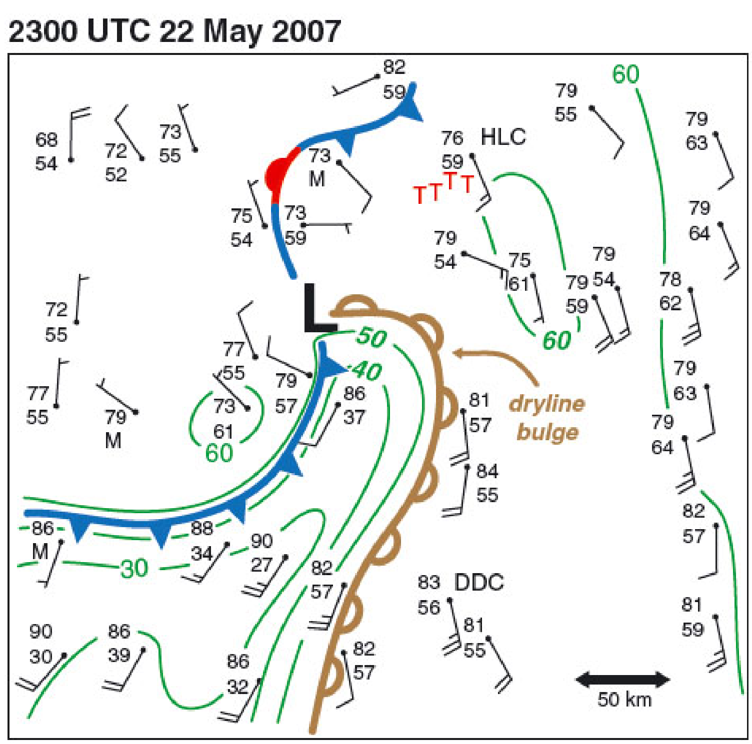

Figure 4: Surface analysis at 2300 UTC 22 May 2007 in western Kansas. A dryline bulge is evident. [From Markowski and Richardson]

3.4.5 The Dryline as a Focus of Convection

Drylines are one of the most important airmass boundaries in the Great Plains since this region experiences the greatest frequency of severe convective weather in the world.

Storms can form in the dry air just to the west of the dryline, co-located with the ascending branch of the thermally-direct circulation. As the storms move eastward into the moist side of the dryline, they can either intensify due to large instabilities, or weaken if the capping layer is strong enough.

Drylines are also prone to initiate isolated storms instead of the solid lines of storms often associated with cold fronts. These isolated storms are generally the ones that become prolific tornado producers. In fact, most major tornado outbreaks in the U.S. involve drylines.

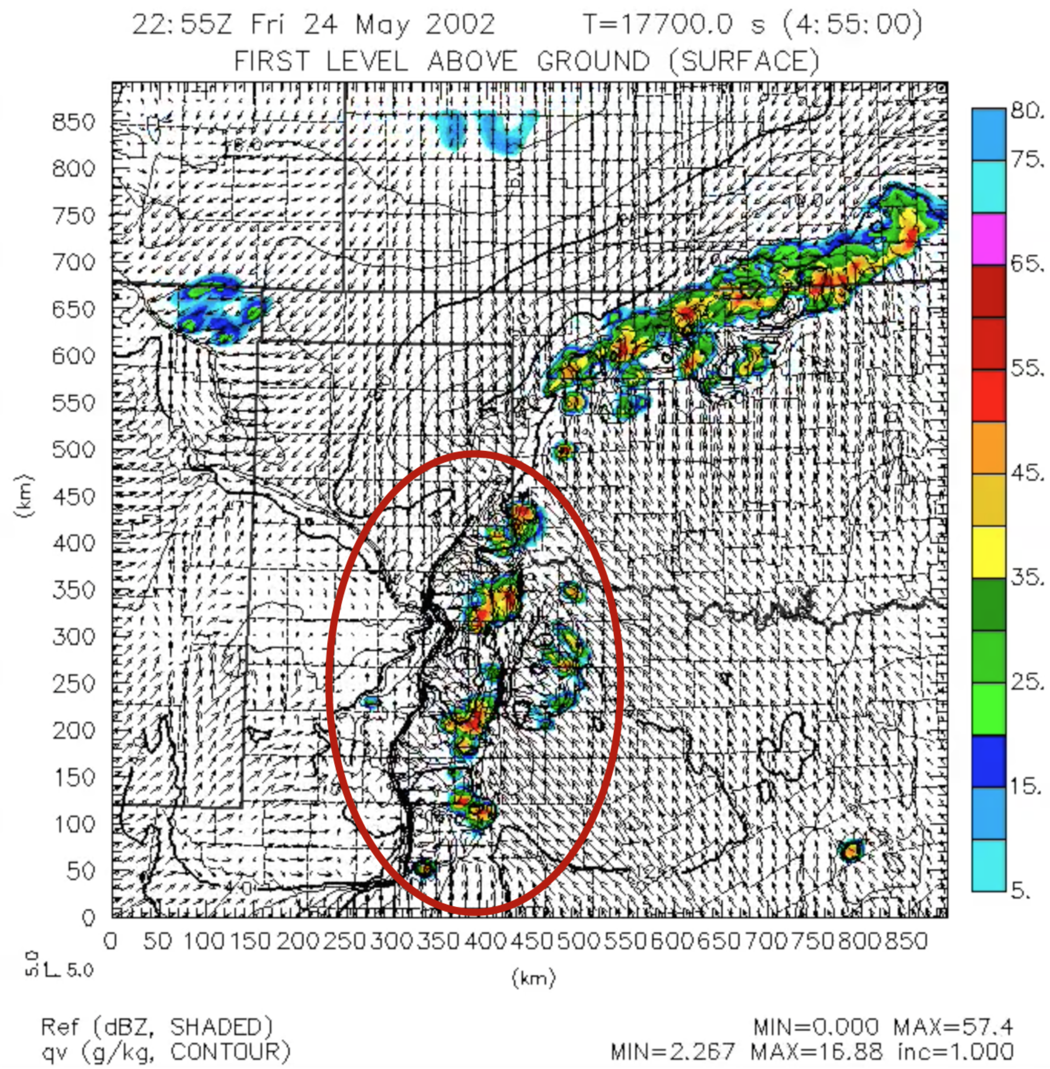

Figure 5: Simulation with 3-km grid spacing depicting convection initiating along the dryline on May 24, 2002. [From Xue et al. 2006]

Recall that drylines are associated with capping inversions on the moist side. The dryline is the horizontal boundary between the dry and humid air masses, while the cap represents their vertical interface. The cap exists due to a warm and dry boundary layer being advected over a moist boundary layer to the east.

The strong stability of the cap acts to suppress deep convection. This can allow the low-level heat and moisture to build up so that the atmosphere is strongly conditionally unstable. In other words, the capping inversion delays the release of convective instability so that moist static energy accumulates in low levels.

Thus, capping inversions allow for the generation of large CAPE values and subsequent explosive thunderstorm development.

Accordingly, the dryline is the westernmost boundary of moist, convectively unstable air. The area along it and immediately east is the first region susceptible to convection encountered by the vertical motion associated with various disturbances. Below are examples of several such disturbances.

- Surface convergence between winds with easterly component east of the dry line and westerly component west of the dry line leads to vertical motion.
- Gravity waves may form on or near the dry line, possibly triggering the first release of potential instability.
- Dryline bulges provide an even greater focus for surface moisture convergence.
- "Underrunning" air (southerly flow below the cap) can move northward until the cap is weaker and/or large-scale or mesoscale forcing is strong enough to release the instability. Convective temperature may be reached just east of the dry line.

Days with the greatest potential for severe weather are also the days with the greatest potential for failed forecasts. The reason for most tornado chase “busts” is that the advection of warm, dry air over the moist layer strengthens the cap or lid faster than the surface heating can overcome its stability, and thus convection never occurs.