CHAPTER 1
INTRODUCTION

1.1 Purpose of research

One of the most important and challenging tasks for the operational meteorologist is the forecast of thunderstorm activity. Severe thunderstorms in particular provide a major challenge because of the threat they pose to life and property. Two of the primary factors in severe thunderstorm formation are the availability of sufficient moisture and low-level convergence (Doswell, 1982). The dryline, simply defined as a large gradient of moisture across a narrow zone near the earth’s surface, defines the geographical extent of the former and often provides the latter. Additionally, the rainfall and wind climatology of a region is affected by the presence of the dryline. This will be of interest to the agricultural and wind energy industries. Therefore, exploring the structure and evolution of the dryline is an important research objective.

1.2 Large-scale setting

Although drylines occur in various parts of the world (Schaefer, 1986), this study is concerned with dryline occurrence across the southern Great Plains (hereafter referred to as the SGP) of the United States. It is no coincidence that the SGP is renowned as one of the world’s most prolific breeding grounds of severe thunderstorms. These storms often bring the threat of high winds, hail, flooding and tornadoes. The geography of the SGP plays a preeminent role in achieving this standing. Straddling the middle latitudes
of the Northern Hemisphere, the region often shares the same latitude as the polar jet stream in the spring and early summer months. The jet stream transports wave depressions into the region providing synoptic-scale upper-level divergence and lift. The elevation of the region increases from near sea level along the Gulf of Mexico to over 4 kilometers along the steep slopes of the Rocky Mountain range. These mountains stretch mainly longitudinally from Mexico through Colorado, and air flow impinging on the mountains may be altered in a manner favorable for the formation of a cyclone on their lee side. Due to the elevation increase and the variable distance from the Gulf of Mexico, a natural gradient of moisture often exists across the SGP. As will be shown in Chapter 2, this gradient varies with the season and is typically the strongest during the spring. A climatological study of moisture in the United States by Dodd (1965) showed an average gradient of 4 °C per 100 km across the region in May. In contrast, many studies of the dryline showed dewpoint gradients of several °C per km (e.g., NSSP Staff, 1963; Bluestein, 1983; Hane et al., 1993). The transition from the climatological “loose” moisture gradient to the steep gradient associated with the dryline is explored in the next section.

1.3 Dryline formation

It has been found that under certain atmospheric conditions, the horizontal gradient of moisture may tighten to a sharp discontinuity of variable proportions. Two primary factors that produce this tightening and thus dryline formation are the lee-side trough and the southerly low-level jet (LLJ). Both the lee-side trough and the LLJ are
themselves the subject of much current research and some debate over their origins. The following discussion reviews some of the current theories.

1.3.1 Lee-side trough

The concept of conservation of potential vorticity is often used to explain the formation of lee-side lows. As westerly mid-level flow impinges on the Rocky Mountains, the column of air first is compressed on the westward side as the elevation increases (the tropopause acts as a barrier to upward motion), and then expands on the leeward side as the air descends the eastern slope. Because the ratio of absolute vorticity to the depth of the column of air must remain constant, the absolute vorticity of the air must first be reduced and then increased. This relationship is reflected in equation 1.1 (following Holton, 1992):

\[ P = \frac{(\zeta_r + f)}{\Delta z} = \text{const} \]  

(1.1)

where: 
\[ P = \text{Potential vorticity;} \]
\[ \zeta_r = \text{Relative vorticity;} \]
\[ f = \text{Coriolis parameter; and} \]
\[ \Delta z = \text{depth of the air column.} \]

Thus, as \( \Delta z \) decreases with an increase in elevation, \( \zeta_r + f \) must also decrease. This conversation is accomplished by an initial southward deflection of the air, which increases the anticyclonic vorticity (decrease in \( \zeta_r \)) and decreases the contribution of the earth’s vorticity (\( f \)). To the east of the mountain crest, \( \Delta z \) increases, and there is a
northward deflection of the air column, which increases $\zeta_r$ and $f$. This net effect of this will be to increase the cyclonic curvature of the wind field downstream of the Rocky Mountains. The importance of the lee-side trough in regards to dryline development is that it acts to increase the southerly component of the wind field over the SGP. Doswell (1982) noted that the necessary precursor to the formation of a dryline is the development of a trough in the lee-side of the Rocky Mountains: the trough producing a southerly wind flow regime over the southern Plains that is instrumental in advecting both dry and moist air into the region. It also leads to streamline confluence of the wind in the region.

1.3.2 The southerly low-level jet (LLJ)

The LLJ is a north-directed stream of relatively strong (supergeostrophic) wind that is often found over the SGP. It varies diurnally, reaching a maximum velocity between 6 UTC and 12 UTC and a minimum between 18 UTC and 0 UTC (Bonner, 1968). An observational study by Whiteman et al. (1997) showed the height of the LLJ to vary between 300-600 m AGL, with most occurrences between 300-400 m AGL. Their study also found that the maximum wind speeds associated with the LLJ usually occur around 2 a.m. LST. The study by Bonner identified an axis of maximum LLJ frequency over the SGP (Figure 1.1).

Two mechanisms that may be responsible for the generation of the LLJ in whole or in part are the development of inertial oscillations due to the evolving
boundary layer and the diurnal oscillation of the horizontal pressure gradient due to the sloping terrain across the SGP.

The inertial oscillation theory (Blackadar, 1957) accounts for the production of the supergeostrophic winds and the diurnal oscillation of the LLJ. With the loss of insolation in the evening, the boundary layer decouples, and the air above is no longer subject to the frictional drag with the earth’s surface. The result is an acceleration of

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Figure 1.1  The geographic distribution of LLJ occurrences at 6 UTC for the period January 1959 to December 1960 (from Bonner, 1968). Elevation above 1 km is shaded.
the wind as it is initially slower than the geostrophic balance according to the existing pressure gradient due to the frictional drag. The Coriolis force then acts on the accelerating wind to produce the inertial oscillation (similar to the oscillation produced by the Coriolis force in lee-side low formation).

The diurnal oscillation of the horizontal pressure gradient may also contribute to the development of the LLJ. Holton (1967) and McNider and Pielke (1981) showed that this oscillation is a response to the temperature gradient produced by differential heating and cooling of sloping terrain – thus providing an explanation for the location of the climatological maximum found by Bonner. Air cools much faster over the higher terrain to the west during the evening due to stronger radiational cooling. Thus pressure at a constant elevation decreases from east to west. The resulting pressure gradient causes air to accelerate westward. The Coriolis force then turns the wind to the north.

There may also be an interaction between the lee-side trough and the LLJ. The lee-side trough is associated with lower pressure to the west (relative to normal diurnal pressure oscillations). The pressure gradient produced by the trough will also accelerate wind to the west, and may augment the diurnal heating effect. However, this interaction may only be significant when strong cyclogenesis occurs over the region in conjunction with a major upper-level disturbance crossing the Rockies, a situation not considered in this work.

The moisture source for the southern Great Plains is the Gulf of Mexico, although secondary sources of moisture are evaporation from lakes, reservoirs and
rivers and evapotranspiration from plants. Vapor flux from the water to the air above and then subsequent advection northward and inland provide the moisture necessary for the moist convective process. The LLJ is the primary mechanism by which this is accomplished.

1.4 Summary

Through the influence of the lee-side trough and the LLJ, there often exists a near-surface moisture discontinuity over the southern Great Plains where dry continental air from the western United States converges with the moist maritime air from the Gulf of Mexico. This sharpened boundary at or near the ground between the air masses of different thermodynamic properties has generally become to be known as the “dryline”, although terms such as “Marfa front”, “dry front” and “dewpoint front” may also be encountered. This boundary normally extends from the surface through the depth of the planetary boundary layer (PBL).

The position of this boundary is a significant influence on the rainfall climatology of the region. On the dry side, boundary-layer moisture is very limited and only isolated thunderstorms may develop that produce little in the way of rainfall. The threat of severe thunderstorms is also minimized; however there exists the possibility of high-based thunderstorms that may produce damaging downbursts. On the moist side, the deeper moisture leads to a greater frequency of storm formation and a significant increase in rainfall climatology.
Final considerations pertain to the relationship between the dryline and convective development. For occasions of southwesterly flow over the higher terrain as previously established, a deep mixed layer of warm and dry continental air may be advected downwind of the Chihuahuan Desert (sometimes denoted the Mexican Plateau). This air mass is known as the elevated mixed layer (EML) and it may override moist air situated in the Southern Plains creating a temperature inversion. The resulting stratification will increase the potential instability of the moist air underneath such that it increases the magnitude of (possible) subsequent convection. Figure 1.2 shows a typical configuration of these features that may lead to dryline formation and/or convective development. In addition to the dryline’s significance as a limiting factor to the westward extent of convective development, it is also a factor in providing the means by which moist surface air parcels may be lifted to their level of free convection. Strong, sustained upward motion is required for an air parcel to rise through the inversion created by the EML. A process (outside of diabatic heating) that accomplishes this is termed a “triggering mechanism.” Some triggering mechanisms according to Stull (2000) include: cold and warm fronts, gust fronts, differential surface heating, sea-breeze fronts, mountains, and drylines.

To summarize, in the SGP, the development of drylines and severe thunderstorms are often linked. When a dryline is present, its position and structure must be considered when attempting to forecast the timing and location of convective initiation on a case by case basis. In the spring of 2002, the ERODE (Experiment to Research the Dryline Environment) was carried out to investigate the structure and morphology of the dryline
in West Texas. A variety of meteorological sampling instruments were utilized along with computer simulations. A primary objective of the experiment was to gain a better understanding of the structure of the quiescent dryline and the advancing phase differs in structure from the retreating phase. A secondary objective was to examine the

Figure 1.2  Terrain and atmospheric conditions conducive to thunderstorm development. Important geographic regions are delineated. The thick lines depict representative 500 hPa height contours. The thin arrows represent the moisture advection from the Gulf of Mexico associated with the low-level jet and the dashed curve represents the typical extent of moist boundary layer air.
performance of numerical models (i.e., how well does the predicted dryline correspond to actual observations) for several cases.

This dissertation presents the results of this research and attempts to relate the findings to the scientific objective of achieving a better diagnosis and prognosis of the convective environment over the SGP. Chapter Two describes historical research on the structure of the dryline. Chapter Three details the design of the ERODE experiment. Chapters Four and Five discuss the results from two case studies. Finescale observations of a quasi-stationary dryline are examined in Chapter Six. The final chapter summarizes this dissertation.