A Lower-Tropospheric Thermodynamic Climatology for March through September: Some Implications for Thunderstorm Forecasting

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ABSTRACT

A thermodynamic climatology was constructed to investigate source regions of low-level moist airmasses and lower mid-tropospheric dry airmasses that contribute to the production of convective instability, and thunderstorms, over the United States. Mean monthly 1200 UTC values of potential temperature, mixing ratio, and geopotential height were computed at the surface and 750 mb for March through September (1966–1980) for 69 upper-air stations in the continental United States and Mexico. Analyses indicated that the Gulf of Mexico is the most significant source of low-level moisture east of the Continental Divide for all months, but the Atlantic Ocean also becomes a significant source in summer. The Gulf of California was found to be the most important source of low-level moisture west of the Continental Divide in summer. A distinct synoptic scale dryline was found over west Texas from March to June and analyses suggested that the strongest drylines occur in April and May. Northwest Mexico and the desert southwest were confirmed to be the source regions of the dryline. At 750 mb, source regions of dry airmasses were found to be the Baja California region and desert southwest in spring, the tradewind easterly dry layer in summer, and the dry, cool airmasses over the northern Pacific and northern Great Lakes regions in spring and summer. The moist, summer, tropical Pacific airstream was found not only to be deeper than that from the Gulf of Mexico, but also to be the primary source of moisture west of the Continental Divide. In summer, significant mean horizontal advection of warm, moist air from higher terrain into the Missouri Valley was noted.

1. Introduction

One of the fundamental aspects of forecasting thunderstorms capable of producing high winds, hail, tornadoes, and excessive rainfall is the diagnosis of the large-scale thermodynamic environment. The depth and magnitude of low-level moisture that fuels thunderstorms, and the thermodynamic characteristics of the overlying airstream, taken in the context of potential triggering mechanisms and environmental dynamics are significant factors to be considered in any thunderstorm forecast. Strong dynamics may compensate for weak instability (Johns and Sammler 1989); nevertheless, a basic knowledge of the source regions of airmasses that contribute to an unstable stratification, and thus thunderstorm formation, is crucial to successful forecasting. Our knowledge of these source regions remains incomplete.

It is widely accepted that the primary source of low-level moisture for the United States east of the continental divide is the Gulf of Mexico. In the western United States there is little doubt that the Pacific Ocean is the primary source of cool season moisture, but Hales (1974) noted that serious questions remain about whether the moisture that floods the desert southwest in summer (southwest monsoon) is of Pacific Ocean or Gulf of Mexico origin, or both.

The sources of overlying dry airmasses and/or dry intrusions are less obvious, but their diagnoses are critical to the severe storm forecast problem. Peterson (1983) noted that the source(s) of the dry air has long been a matter of speculation and controversy. The lower mid-tropospheric dryness and capping inversion contributing to tornadic thunderstorm development can, at times, be attributed to subsidence (Williams 1960). Carlson and Ludlam (1968) attributed the capping inversion, or Lid, and overlying dry air present in some spring severe weather outbreaks to the advection of a hot, dry, mixed layer from the arid Mexican Plateau or the southwest United States over cooler, moist air flowing off of the Gulf of Mexico. Schaefer (1986) found that the dry air above the inversion in the dryline region can come from the southeast around a well-developed Bermuda High. Hagemeyer and Darkow (1988) and Hagemeyer (1988) demonstrated that during summer the tradewind airstream flowing around the southern flank of the Bermuda High and over the Gulf of Mexico was typically characterized by very dry air above the moist layer, and could be a source of lower mid-tropospheric dry intrusions contributing to tornadic thunderstorm development over the Midwest. Hagemeyer (1989) showed that it was possible to dis-

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tinguish between potential dry intrusions of Mexican highland and tradewind origin by monitoring 700-mb θw analyses for several days prior to a tornado event.

The problem of discerning airmass sources lingers, partly because in recent years there has been a lack of routine airmass identification and tracking (Peterson 1983), and a tendency for severe storm case studies to concentrate on the significance of certain airmasses over limited areas. As a result much of the information about airmasses that affect various regions remains anecdotal. Recently Lanicci and Warner (1989) produced a physically based climatology for the elevated mixed layer (EML) and Lid over the southern plains in springtime that addresses some of the airmass issues, but a more complete picture is desired.

This paper attempts to give a more complete picture of the low-level thermodynamic climatology for the primary thunderstorm months of March through September. This investigation concentrates on the lowest 300 mb or so of the atmosphere where most of the moisture resides, and instability is built up, constrained, and ultimately released. Physically meaningful conservative variables are used to identify the seasonal characteristics of airmasses important to the production of severe weather and excessive rainfall. The results should help reduce the ambiguity surrounding certain airmass source regions, give forecasters some historic perspective, and aid in the fundamental understanding of large-scale thermodynamic processes that contribute to thunderstorm formation.

2. Data selection and analysis procedures

Mean values of surface and 750-mb potential temperature (θ), wet-bulb potential temperature (θw), mixing ratio (w), and 750-mb streamlines, were calculated from 15 years of 1200 UTC monthly mean soundings for 69 upper-air stations in the continental United States and Mexico. Data were extracted from the National Climatic Data Center publication *National Summary* for the months March through September for 1966 through 1980, the publication's last year. This 15-year sample is sufficient considering other notable large-scale climatological studies, such as Ratner (1957), Crutcher and Halligan (1967), and Dodd (1965), used samples of 10 years or less. Figure 1 shows the upper-air stations used in this investigation. The density and extent of this network were considered sufficient to sample the various synoptic scale airmasses important to thunderstorm production over the United States. For example, Ratner (1957) used only 43 stations, none Mexican, to cover the same area.

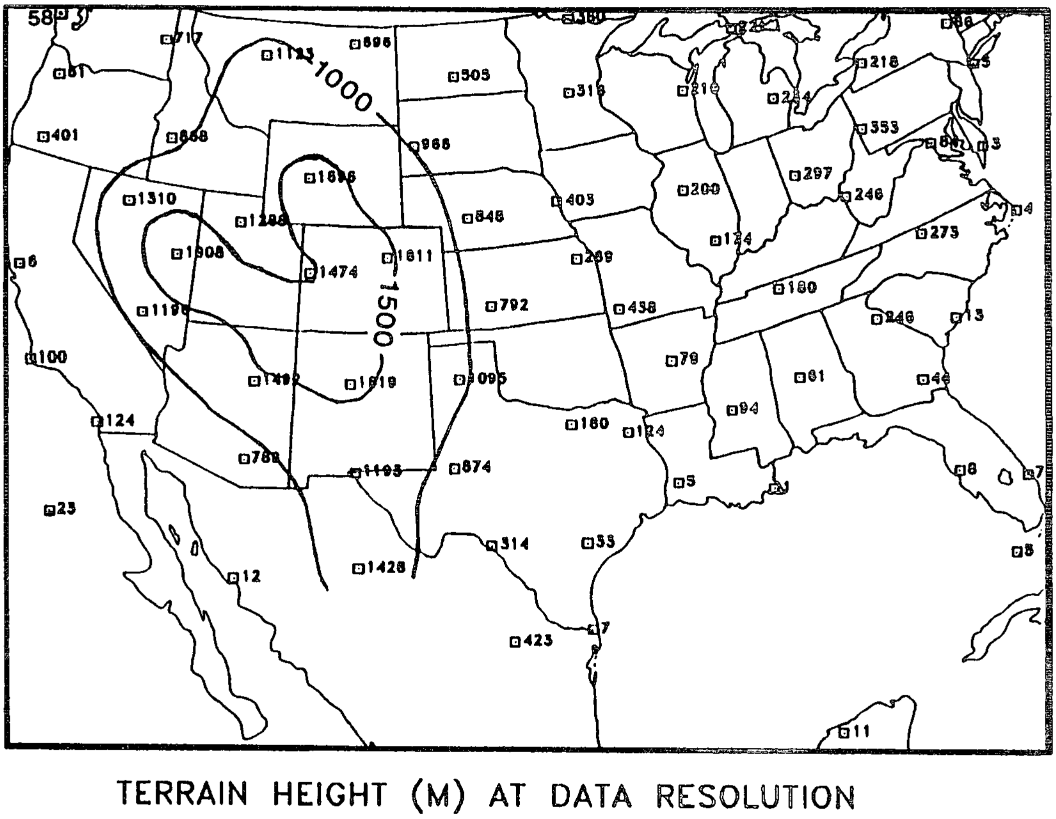


FIG. 1. Location and elevation (m) of the 69 upper-air stations used in this study. The 1000- and 1500-m terrain height contours shown are resolved from this data only.

Data analysis and map plotting were done with a commercial software package that used the "Kriging" method of optimal interpolation that takes advantage of regional variable theory (Burrough 1985; Ripley 1981).

Potential wet-bulb temperature, a function of θ and w, is conservative with respect to moist and dry adiabatic processes and evaporation from falling rain, and is an excellent tracer of airmasses (Hewson 1936). The utility of θw in an operational environment has recently been reaffirmed by Hagemeyer (1989). However, only separate analyses of the components θ and w are presented to more clearly identify climatological source regions of heat and/or moisture since the θw analyses contribute little additional unambiguous information.

In order to best discern airmasses above the mean moist layer it was desirable to try to select the lowest mid-tropospheric level in which θw reaches a minimum. In the mean, moisture decreases rapidly with height, and θ increases rapidly with height in the more stable mid-troposphere. This results in a θw minimum at some point in the lower mid-troposphere, above which θw begins to approach θ, and increases with height. Based on analyses of 15-year mean θw profiles to 500 mb for stations representative of the Caribbean, Gulf of Mexico, and west Texas dryline regions, the lowest θw values were found most often near 750 mb (Hagemeyer 1988), and so this level was chosen as that most helpful for discerning distinct lower mid-tropospheric airmasses.

3. Data analyses

Although the discussion presented will focus only on some of the fundamental aspects of the thunderstorm forecast problem, one realizes these analyses have applications beyond thunderstorm forecasting in general, and can be useful in examining other synoptic problems in different areas of the country and this is encouraged.

a. Surface analyses

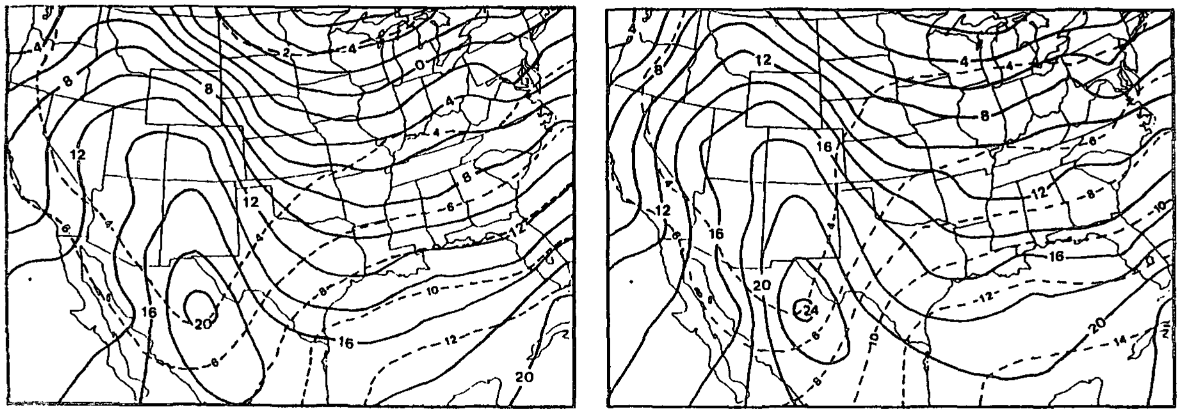
East of the Continental Divide, each month's surface w analysis (Figs. 2a–g) shows, not surprisingly, that the Gulf of Mexico has the highest values, and is the primary source of low-level moisture. As the months progress the moisture spreads steadily poleward over the eastern United States. Mixing ratio increases significantly along the Middle Atlantic Coast from June to July illustrating the increased importance of the summer-warmed Atlantic Ocean as a source of low-level moisture as indicated by the 16 g kg^{-1} contour moving from central Florida in June to north of Cape Hatteras, North Carolina by July (Fig. 2e).

West of the Continental Divide, the Pacific Ocean waters off Mexico are a spring and early summer supplier of low-level moisture to California and the desert southwest, however, by June the warmed waters of the Gulf of California begin to emerge as the source of copious moisture needed to initiate the summer monsoon over this region. In June, higher values of w (≥ 12 g kg^{-1}) appear abruptly along the east coast of the Gulf of California at Empalme, Mexico, and increase dramatically to 18 g kg^{-1} by July to equal or exceed values over the Gulf of Mexico.

The northward movement of low-level moisture over the desert southwest in summer appears closely related to the northward movement of the θ maximum, and indicates a monsoonal effect. For example the 10 g kg^{-1} w contour remains just to the south of the highest values of θ during June through September, and a very strong north-south w gradient develops between Empalme and the dry air over Utah and Arizona. This indicates that the Gulf of California is indeed a significant reservoir of low-level moisture that can surge northward to dramatically increase w over the desert southwest as shown by Hales (1974). This moist air does not come from the open Pacific to the west, but up the Mexican coast from the south since mean w at Guadalupe Island, Mexico (a small island in the Pacific Ocean offshore Baja California) is 7 g kg^{-1} *less* than at Empalme in July and August. This confirms and quantifies Hales' (1974) idea that it is unrealistic to expect that the moist air of the southwest monsoon can come from the Gulf of Mexico. This scenario, if true, would require moist Gulf of Mexico surface air to rise over the Continental Divide and descend to sea level again while conserving a w value of some 18 g kg^{-1}.

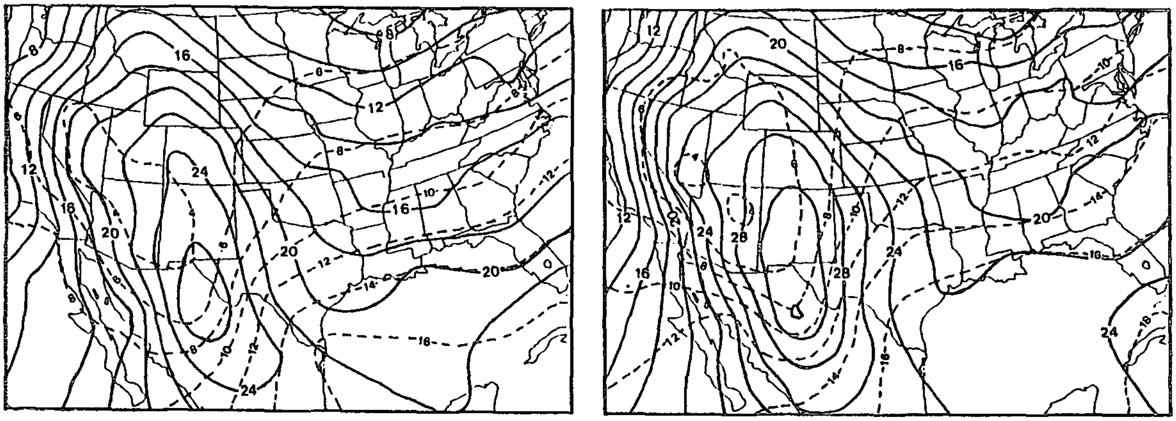
In March the driest air is found over the upper Midwest, where θ is also low, indicating the lingering influence of cold, dry, continental Canadian air over this region. A distinct trough of low w is also found over the high terrain of the desert southwest and northern Mexico. The w contours bend sharply southward over west Texas in April (Fig. 2b) as northward surges of Gulf of Mexico moisture east of the Continental Divide become more frequent, and movement of moisture to the west is limited by higher terrain. The w minimum over northwest Mexico and the desert southwest in April becomes more distinct in May. The strong east-west w gradient over Texas in April, May, and June is indicative of the mean synoptic scale dry line, or boundary between the maritime tropical (mT) and continental tropical (cT) airmasses.

Clearly the area encompassing Arizona, New Mexico, and northwest Mexico is the primary source of low-level dry air in spring, while a moist axis is evident from the western Gulf of Mexico up the lower Rio Grande Valley. Synoptic scale thermodynamic climatological evidence suggests that dry line activity would be most likely in March through June with the strongest dry lines occurring in April and May when w in the dry airmass is lowest and the contrast between airmasses is greatest. Dry line activity should taper off in June and be unlikely over the plains afterward as



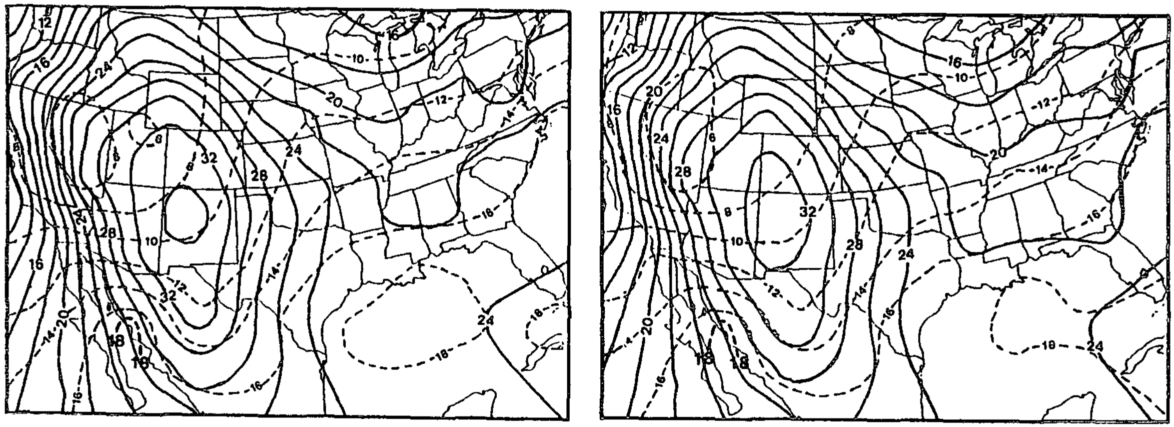
A MEAN MARCH SURFACE θ (°C) 1966-80

B MEAN APRIL SURFACE θ (°C) 1966-80



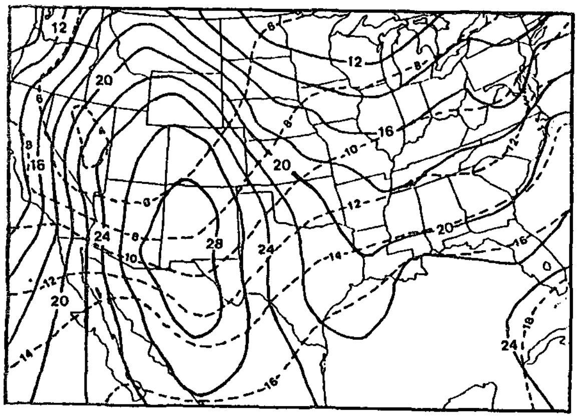
C MEAN MAY SURFACE θ (°C) 1966-80

D MEAN JUNE SURFACE θ (°C) 1966-80



E MEAN JULY SURFACE θ (°C) 1966-80

F MEAN AUGUST SURFACE θ (°C) 1966-80



G MEAN SEPTEMBER SURFACE θ (°C) 1966-80

FIG. 2a–g. Mean monthly 1200 UTC analyses of surface θ (°C, bold solid lines) and w (g kg^{-1}, light dashed lines) for March through September (1966–1980).

the source region of dry air retreats westward to the Great Basin region in July, August, and September. These findings agree in general with those of Schaefer (1973, 1986) and others based on actual dryline climatology over much shorter time periods.

The highest values of surface θ are found over high western terrain for all months. The position of the thermal trough/ridge axis over the mountainous west varies little in location from month to month and is closely correlated with the location of the Continental Divide. However, the magnitude and northward extent of the thermal trough varies greatly from month to month. Potential temperature is the same over northwest Mexico as over the southeastern Gulf of Mexico in March. But as insolation increases in April and May, the elevated continental region becomes significantly warmer. The highest values of θ are centered over Chihuahua, Mexico in March and April, reach north to El Paso, Texas in May, Albuquerque, New Mexico in July, and Grand Junction, Colorado in August before retreating southward in September. These findings generally agree with those of Tang and Reiter (1984) who tracked the month to month migration of the 850-mb warm center over the western United States, and agree closely with the θ analyses for April and May in Carlson and Ludlam (1968) and Lanicci and Warner (1989).

b. 750-mb analyses

The general patterns of θ and w are similar for March, April, and May (Figs. 3a–c). The distribution of θ is generally zonal with a weak thermal ridge from Colorado to west Texas amplifying and moving slightly west with time, but still remaining east of the surface thermal ridge. Drier air is found flowing across Baja California carried on mean westerlies in the spring; and a distinct synoptic scale dry tongue can be seen from around Guadalupe Island to New Mexico in May (Fig. 3c). This dry airstream exists to the rear of general troughing over high terrain and is likely the source of dry tongues that contribute to development of mid-latitude cyclones (Carlson 1980).

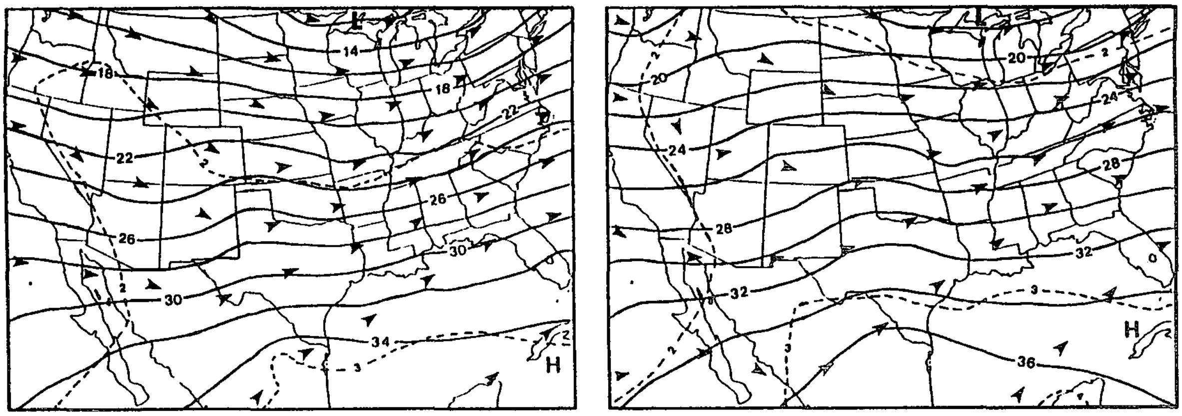
June (Fig. 3d) is the transition month between spring and summer and several significant changes occur. The direction of the mean flow over the Gulf of Mexico shifts 90 degrees from southwest in May to southeast in June, indicative of the strengthening influence of the subtropical high and the onset of tradewind flow over the region. A distinct trough develops over northwest Mexico as θ and w increase and an axis of higher moisture is seen from northern Mexico into southwest Kansas. A maximum of w appears over Chihuahua which is located on the high plateau of Mexico with high mountains and the Continental Divide to the southwest and much lower, discontinuous mountains to the southeast that do not effectively block moisture from the Gulf of Mexico. Clearly, in June the moist axis east of the Continental Divide is of Gulf of Mexico origin as dry westerly flow continues off the Pacific.

The high values of 750-mb θ over the Southwest are not due to the heating of high terrain alone. Indeed high values of θ appear over both Guadalupe Island and Empalme which are nearly at sea level and dominated by flow off of the Pacific Ocean. 750-mb θ at Guadalupe Island is 4°C *cooler* than at Merida in May, but becomes 2°C *warmer* than Merida in June indicating the appearance of an extensive, and significantly warmer, airmass of Pacific origin.

Moisture floods the high plains and desert southwest in July and continues in August (Figs. 3e–f). There is clearly a major change in the circulation over the region during the transition into summer that is monsoon-like as the flow over the Baja region shifts from westerly in June to southerly in July, August, and September, and a deep, moist airstream moves up the Gulf of California. This moist, tropical Pacific airstream is actually much deeper in summer than the Gulf of Mexico airstream and indicates that the moisture flooding the high, western terrain is of Pacific origin. The mixing ratio at Empalme does not decrease below 7 g kg^{-1} in July and August until nearly 3000 m above the surface. This Pacific moisture carried inland aloft may be more significant to thunderstorm production over interior regions of the west such as the Great Basin than moisture at the surface since the movement of low-level moisture is seriously limited by terrain.

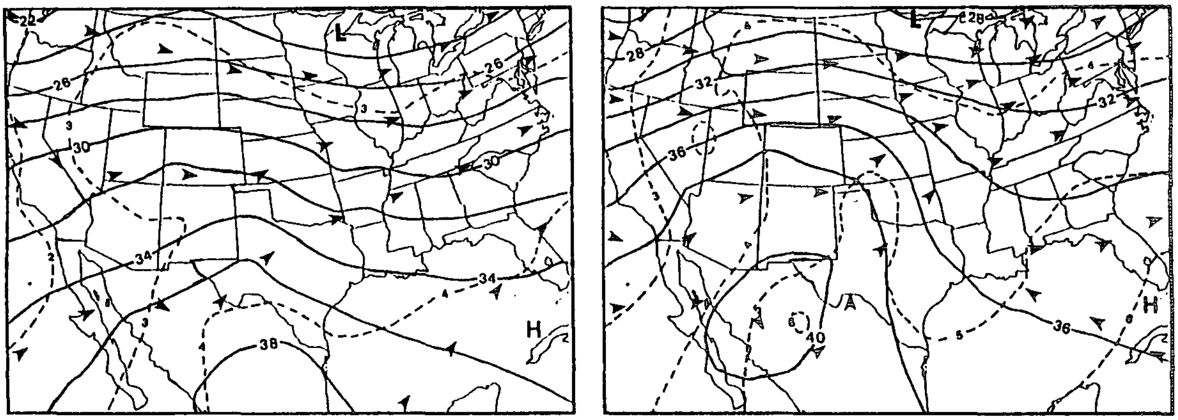
Considering mean 750-mb flow patterns and the high values of θ and w over elevated regions in summer, it is evident that the Midwest in general, and the Missouri Valley region in particular, experience significant mean positive horizontal advection of warm, moist air from higher terrain. Variances of θ, w, and geopotential height were found to be low over the Great Plains, indicating this advective pattern is a reliable summer feature. This is the same general region of frequent nocturnal thunderstorm development (Rasmusson 1971) and Mesoscale Convective Complex (MCC) genesis (Maddox 1983), and the analyses may provide a fundamental climatological thermodynamic mechanism to explain their occurrence. For example, Maddox (1983) found that a pronounced, low-level, warm air advection pattern is characteristic of MCC genesis regions, and Augustine et al. (1989) found the axis of maximum Mesoscale Convective System (MCS) frequency in 1986 in this same area.

The 750-mb analysis indicates three significant summer dry air sources: As mid-level moisture floods high western terrain in summer, air over the northern Pacific coastline remains very nearly as dry as in spring, and relatively quite cool as continued westerly flow off the north Pacific develops a strong θ gradient between the Pacific coast and the four corners region. This north Pacific airstream could certainly be a source of dry intrusions and destabilizing mid-level cool pools that, carried on westerly or northwesterly flow, could con-



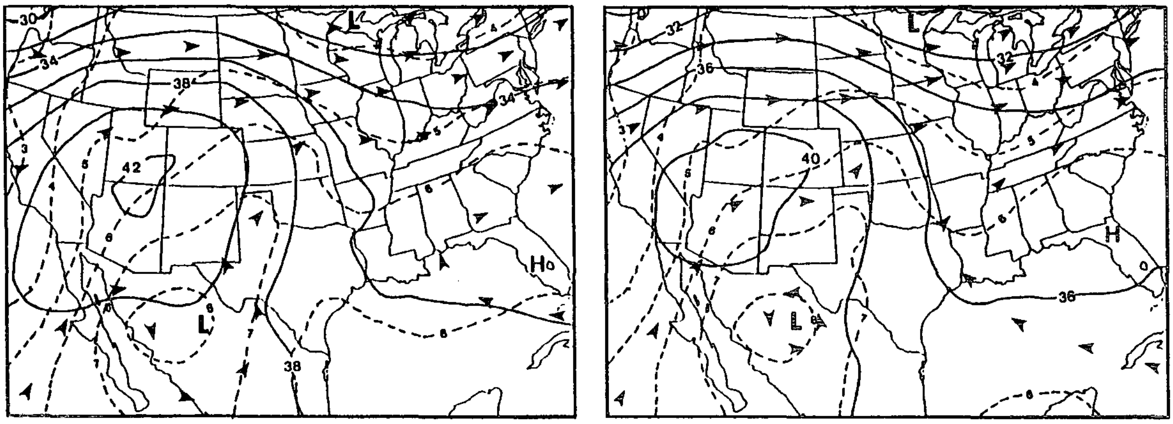
A MEAN MARCH 750 mb θ (°C) 1966–80

B MEAN APRIL 750 mb θ (°C) 1966–80



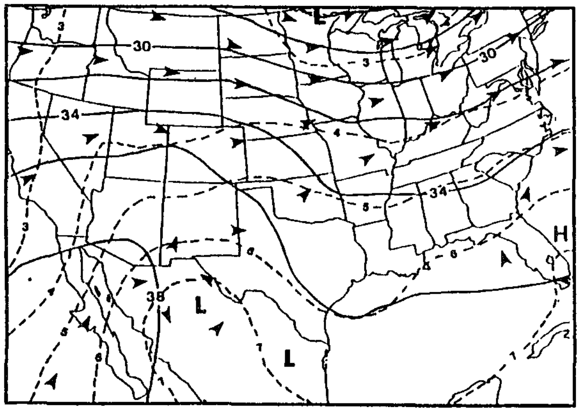
C MEAN MAY 750 mb θ (°C) 1966–80

D MEAN JUNE 750 mb θ (°C) 1966–80



E MEAN JULY 750 mb θ (°C) 1966–80

F MEAN AUGUST 750 mb θ (°C) 1966–80



G MEAN SEPTEMBER 750 mb θ (°C) 1966–80

FIG. 3a–g. Mean monthly 1200 UTC analyses of 750-mb θ (°C, bold solid lines), w [g (kg)$^{-1}$, light dashed lines], and streamlines (arrowheads indicating the direction of flow) for March through September (1966–1980). Centers of high and low 750-mb geopotential height are shown by conventional notation.

tribute to severe weather development from the northern Rockies and Plains into the Midwest in summer (Johns 1982). A relatively cool and dry mid-level airmass also remains over the Great Lakes region in summer and could contribute to severe weather development over the Midwest and northeastern states in west or northwest flow as low-level moisture increases across the region. The tradewind easterly airstream flowing across the Caribbean and southern Gulf of Mexico also becomes a source of mid-level dry air east of the Continental Divide in relation to mean flow patterns in the summer.

The undisturbed tradewinds are typically characterized by very dry air in the lower-mid troposphere above the low-level moist layer and the "tradewind inversion" (Riehl 1979). Figure 4 is an example of a classic tradewind sounding over San Juan, Puerto Rico (USAF 1961) which clearly illustrates the three basic components of the tradewind thermodynamic structure mentioned by Riehl. However, Gutnick (1958) found that, while extremely dry air is present above the moist layer, the tradewind inversion is typically weak, or often non-existent, over the Caribbean region in the summer, and true-capping inversions appear to be predominantly associated with the subsiding side of migratory disturbances (for example, ahead of easterly waves). The mean 1200 UTC June sounding for San Juan, Puerto Rico, (Fig. 5, from Hagemeyer 1988), computed from the same dataset as this study, displays the three general features of a tradewind sounding except that, instead of a tradewind inversion, there is a stable transition layer between the low-level moist layer and the mid-level dry airmass. This agrees in general with studies (Gutnick 1958; USAF 1961) which found that, although a true inversion was often lacking in summer tradewind soundings, a stable, or sometimes isothermal, transition layer, that is referred to as the "Tradewind Inversion," and associated with a rapid falling off of moisture, was usually present.

Carlson and Lee (1981) documented a hybrid tradewind sounding with a dry EML originating over the Sahara Desert above a strong tradewind inversion. This Saharan EML, embedded in the tradewind airstream, has been shown to be carried across the Atlantic Ocean and Gulf of Mexico, and has a significant impact on deep convection over Texas (Caracena and Fritsch 1983). However, the presence of a Saharan EML has not been detected in any of the tradewind dry intrusion cases investigated by the author.

Despite the weakness of the typical tradewind in-

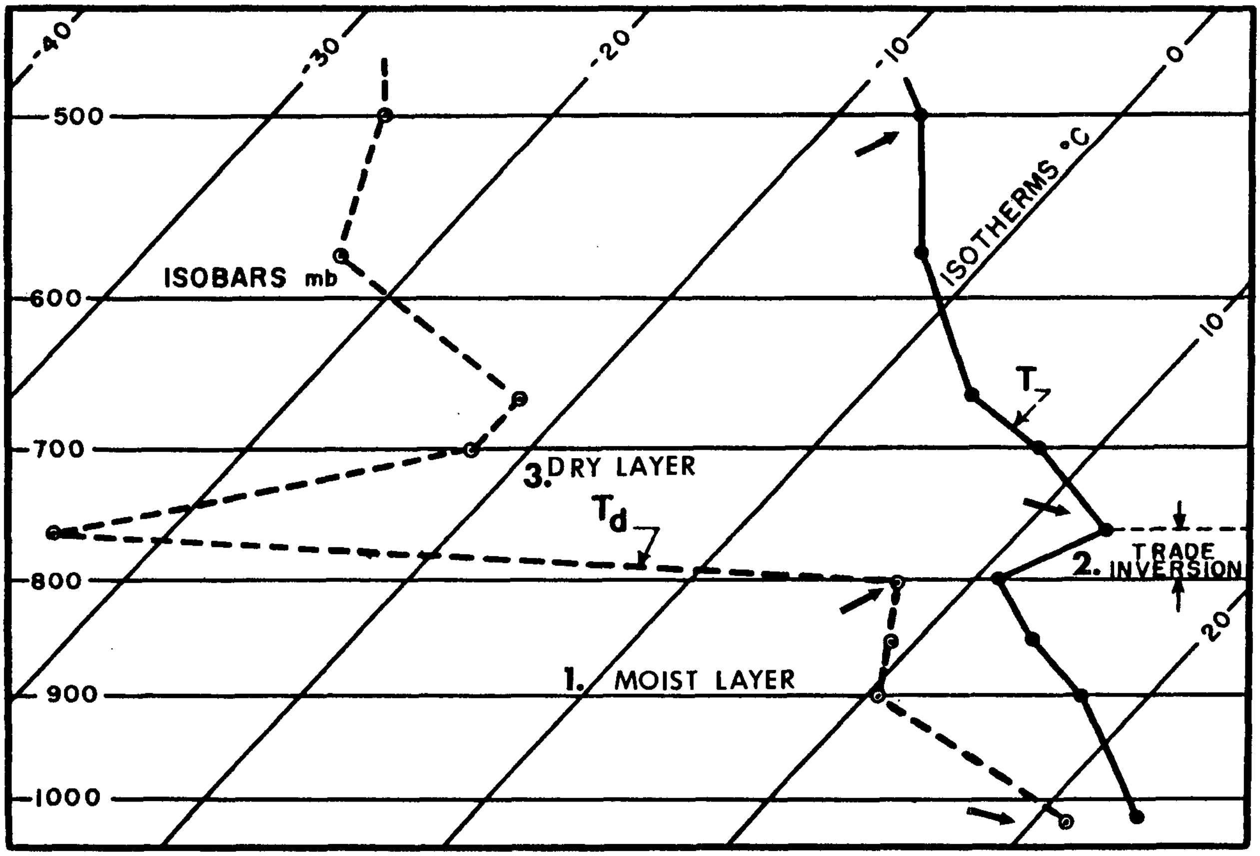


FIG. 4. Skew *T*–log *p* diagram of a tradewind subsidence inversion over San Juan, Puerto Rico (from USAF 1961). The three basic thermodynamic components are labelled: 1. moist layer, 2. trade inversion, and, 3. dry layer.

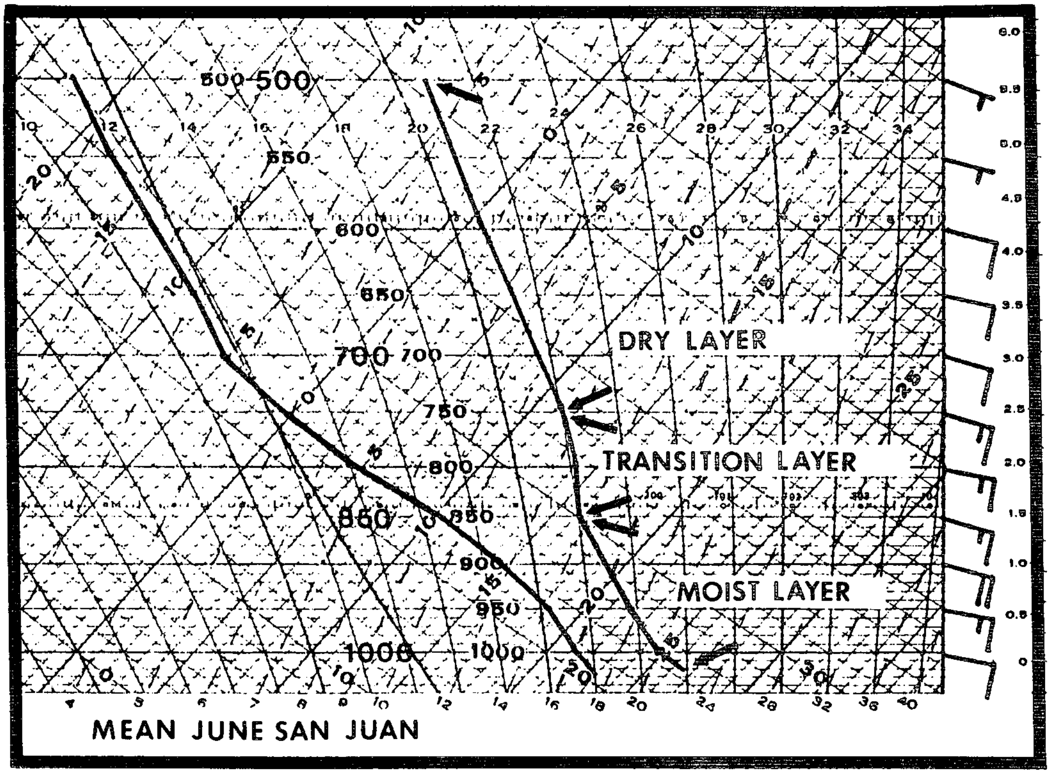


FIG. 5. Mean 1200 UTC June skew T-log p for San Juan, Puerto Rico (1966–80). The three basic thermodynamic components of the *mean* tradewind sounding are labelled: moist, transition, and dry layers.

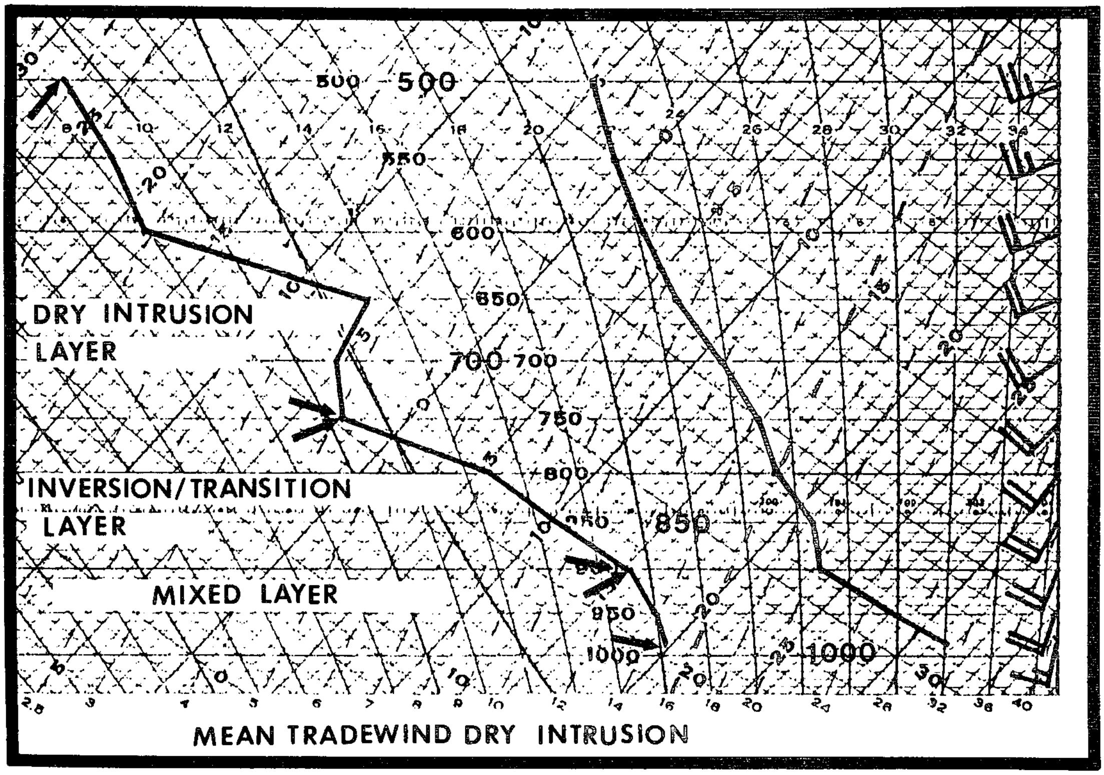


FIG. 6. Mean 0000 UTC skew T-log p for six cases of tradewind dry intrusions over the Midwest (typically 1000 km from the Gulf Coast). The three basic thermodynamic components of the tradewind sounding modified by passage over land are labelled: mixed, inversion/transition, and dry intrusion layers.

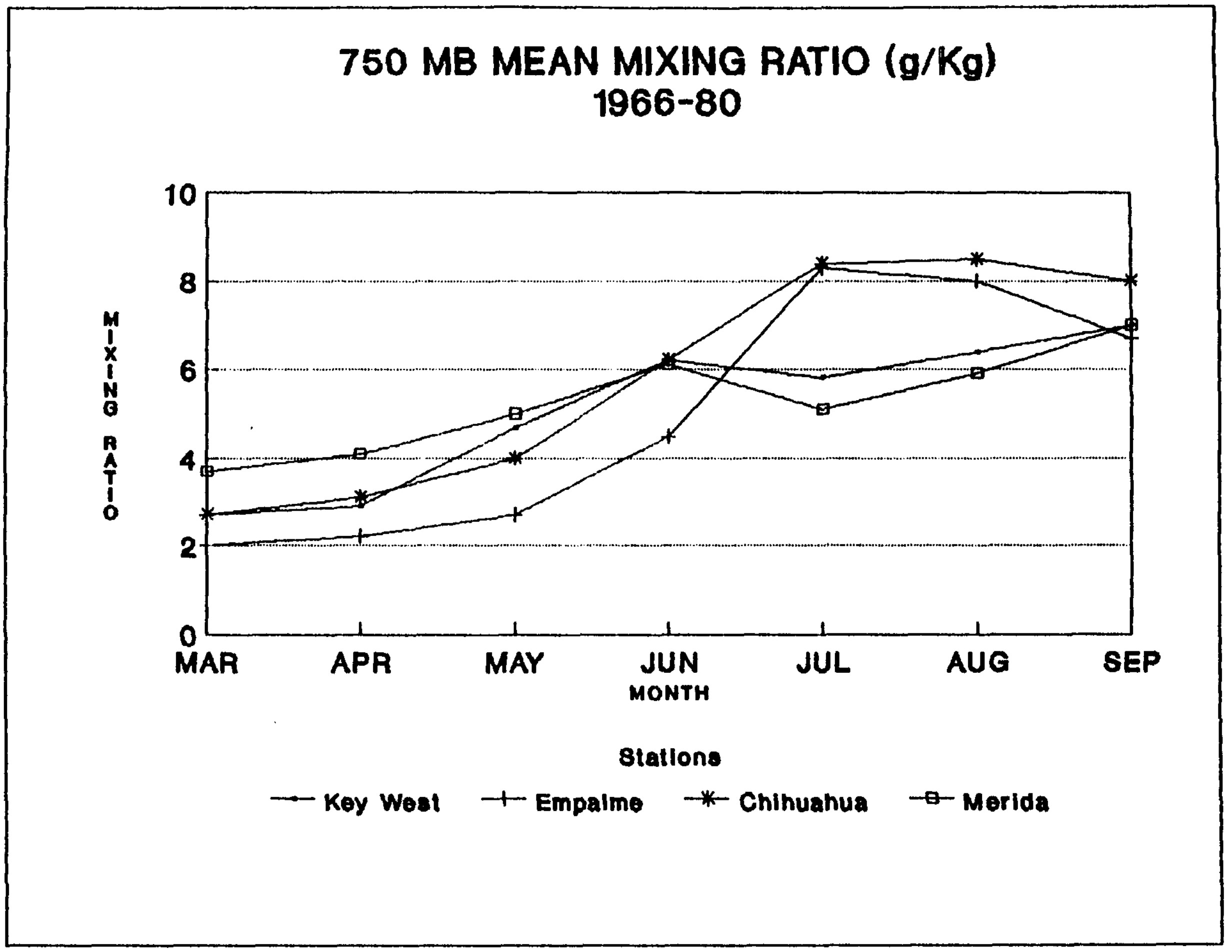


FIG. 7. 750-mb mean monthly 1200 UTC mixing ratio (g kg^{-1}) for March through September for stations representative of the Gulf of Mexico (Merida and Key West), continental Mexican (Chihuahua), and Gulf of California (Empalme) regions.

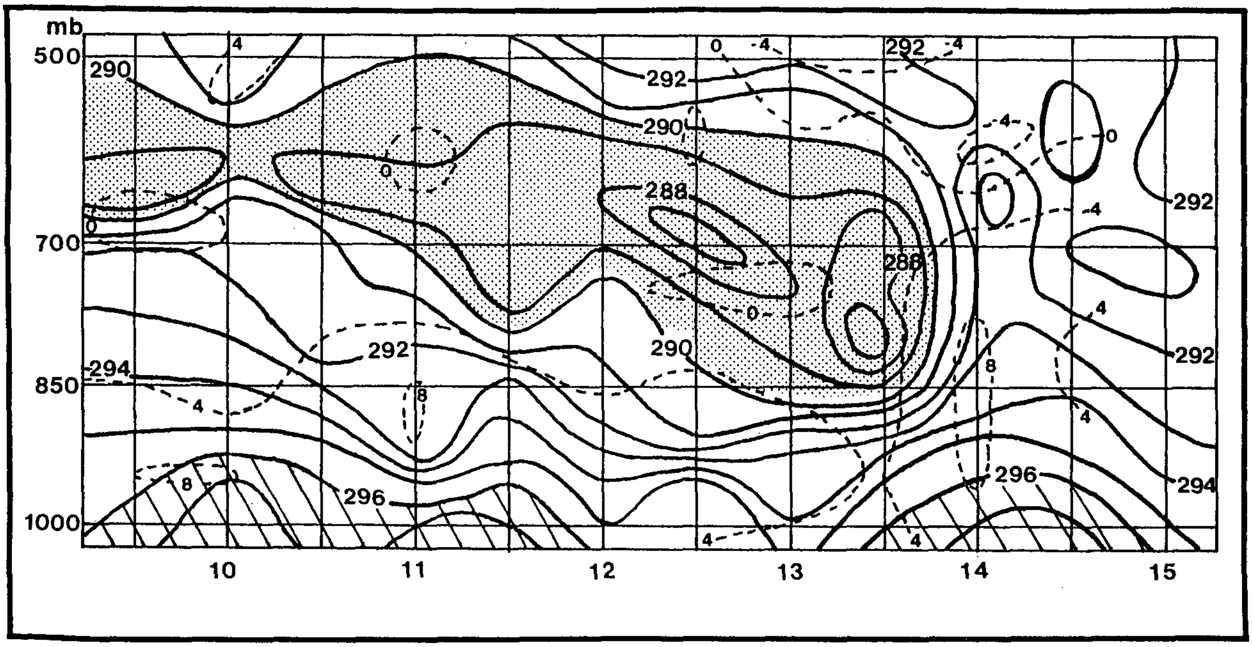


FIG. 8. Time section to 500 mb of θw (K) and east wind component (m s^{-1}) for Key West, Florida from 1200 UTC 9 June to 0000 UTC 15 June 1984. θw greater than 296 K is hatched and θw less than 290 K is shaded (from Hagemeyer 1988). Easterly wave passed Key West early on 14 June.

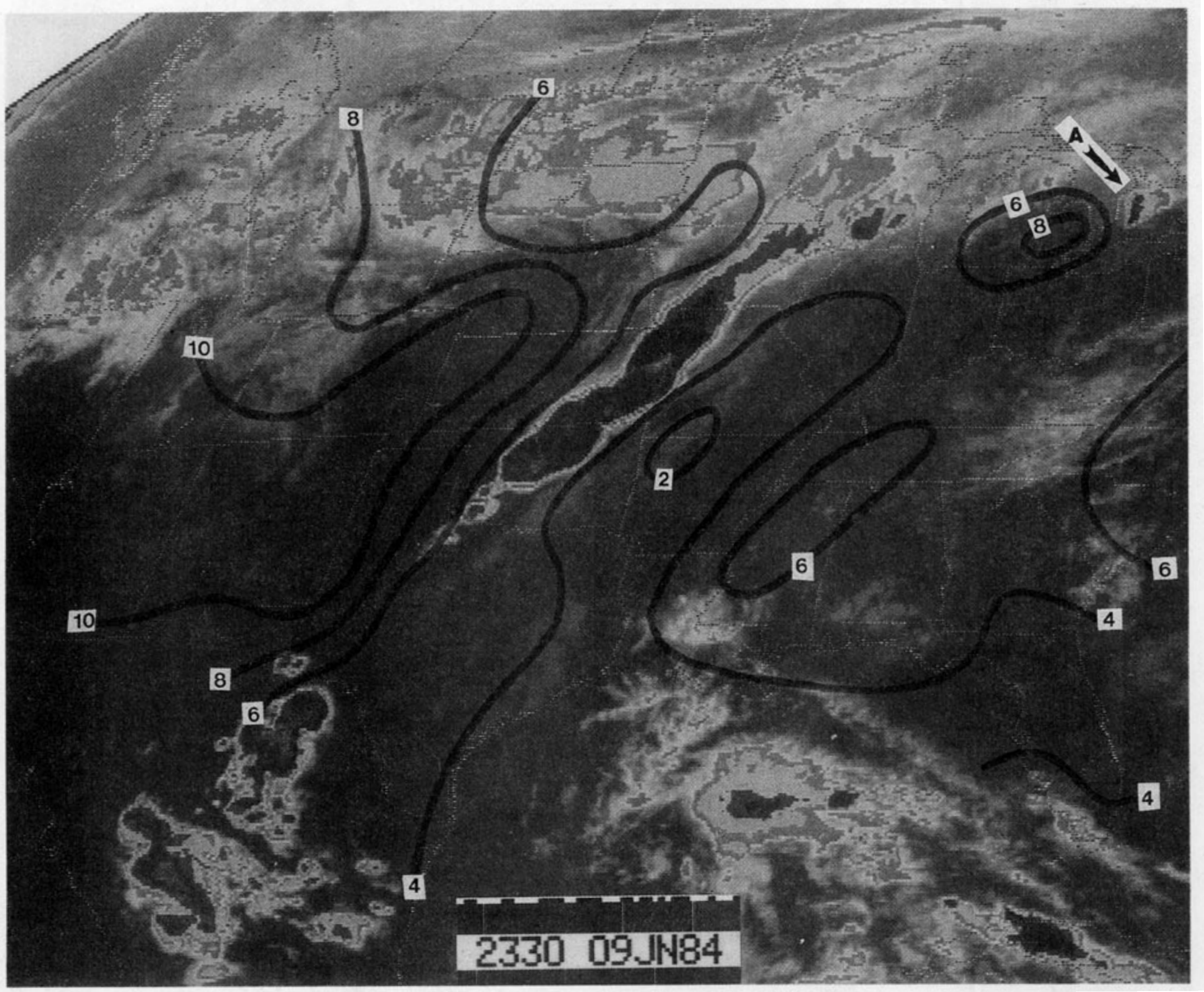


FIG. 9. 2330 UTC 9 June 1984 GOES IR imagery with 0000 UTC 10 June 1984; 850–700-mb lapse rates (°C km^{-1}) superimposed. Thunderstorm that produced a tornado over Michigan at 1943 UTC is now over southern Ontario, as indicated by the arrow at "A."

version over oceanic areas in summer, Hagemeyer (1988) has found that as the tradewind airmass spreads well inland over the United States, and is subjected to strong surface heating and mixing in the lower levels, the "inversion" can be re-established and become quite intense. Figure 6 is the mean 0000 UTC tradewind dry intrusion sounding for six cases of severe and tornadic events over the Midwest in summer. The soundings were taken in the warm sector on the west side of the Bermuda High, and were typically 1000 km or more from the Gulf Coast. The soundings were collected for the closest upstream stations from the stations nearest to where the events occurred (typically 150 to 200 km) which were polluted by convective debris. The 0000 UTC soundings are characterized by a low-level adiabatic layer 100 to 200 mb deep, caused by intense solar heating over land, capped by an inversion between 900 and 750 mb, and overlain by low θw air above 750 mb which provides the dry intrusion. Pressure averaging the six soundings with inversions at six different levels where the air is nearly saturated, and relative humidity is much lower above and below, results in an averaging out of the inversion layer into a very stable layer; but a rapid decrease in moisture is evident in the transition layer. An example of an individual tradewind dry intrusion sounding will be given in the next section.

As the tradewind airstream becomes a much more stable feature of the circulation over the Gulf of Mexico and northwest Caribbean, 750-mb w actually *decreases* from June to July while *increasing* significantly at all other stations in the analysis, except those in the northern Great Lakes and along the Pacific Northwest coast where w remains low. Indeed in July, 750-mb w is as low over the northwest Caribbean as it is over portions of Utah and Wyoming. Figure 7 shows a monthly plot of mean 750-mb w for stations representative of the Gulf tradewind regime (Key West and Merida, Mex-

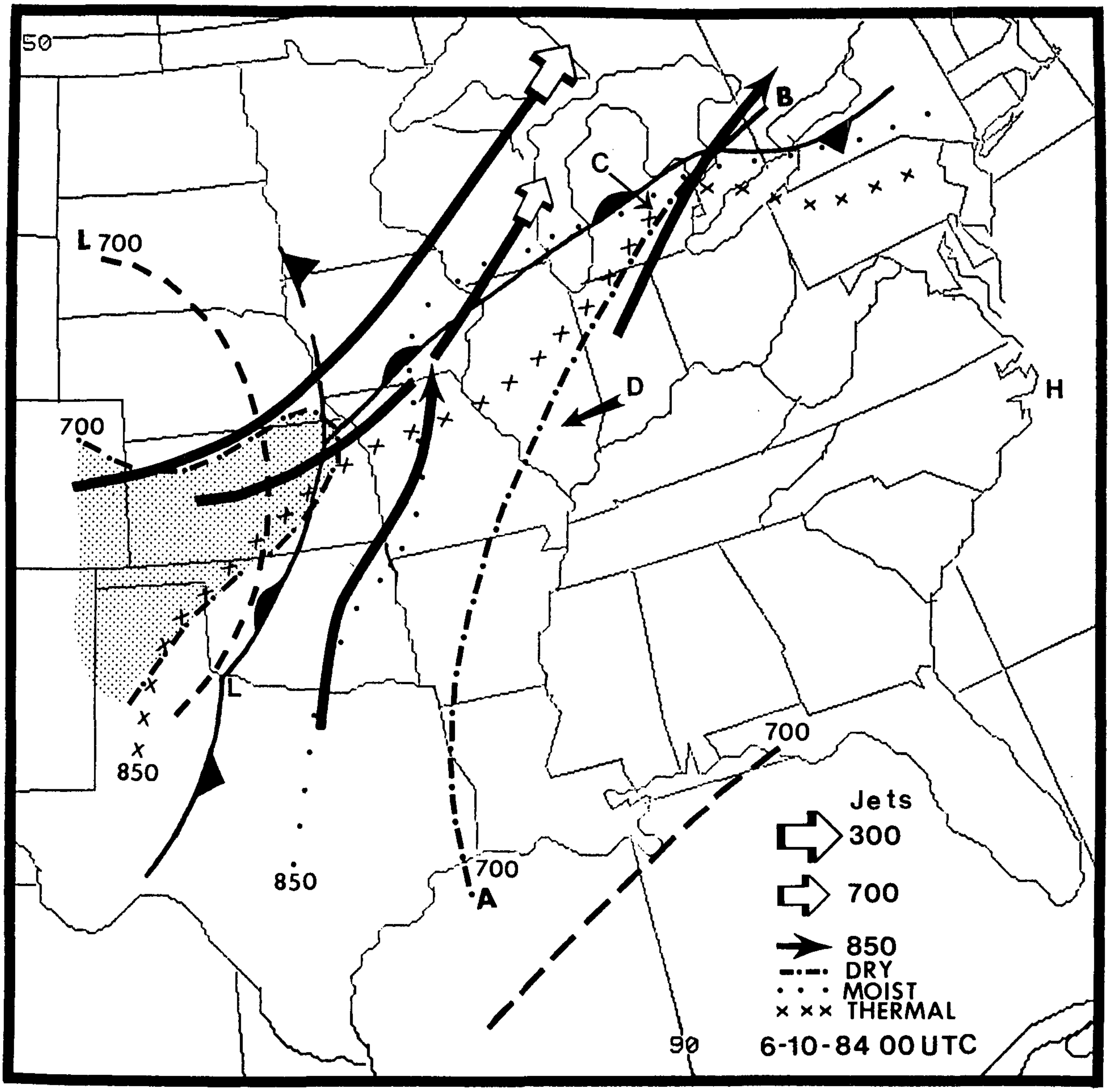


FIG. 10. Composite analysis for 0000 UTC 10 June 1984. Surface fronts and 700-mb troughs shown by conventional notation. Other analyzed features are identified in the legend. The location of the Lake Charles, Louisiana to Buffalo, New York cross section (Figs. 14a & b) coincides with the dashed-dot dry axis from "A" to "B." Arrow over Michigan at "C" points to location of tornado at 1943 UTC, and arrow at "D" indicates location of Salem, Illinois upper-air site (see Fig. 11).

ico) and the continental monsoonal regime (Empalme and Chihuahua). The June to July moisture *decrease* in the tradewind airstream at Merida and Key West is distinctive, while Pacific moisture *increases* dramatically at Empalme and Chihuahua to the point where 750-mb w at Empalme (elev. 12 m) is more than 3 g kg^{-1} *higher* than at Merida (elev. 11 m).

What few other climatological investigations that have been done in the region have also indicated, or implied, is a unique drying over the tradewind regime in summer. Ratner's (1957) calculations showed a relative humidity decrease between 850 and 600 mb at San Juan, Puerto Rico and Swan Island, West Indies between June and July, even as temperatures cooled, or remained nearly the same, implying a decrease in w. Gutnick (1958) found that mean w between the top of the tradewind inversion and 500 mb for several Caribbean stations in July was only 4 g kg^{-1}.

It is significant that the 750-mb dry airstream over the Gulf of Mexico shows up in the July and August

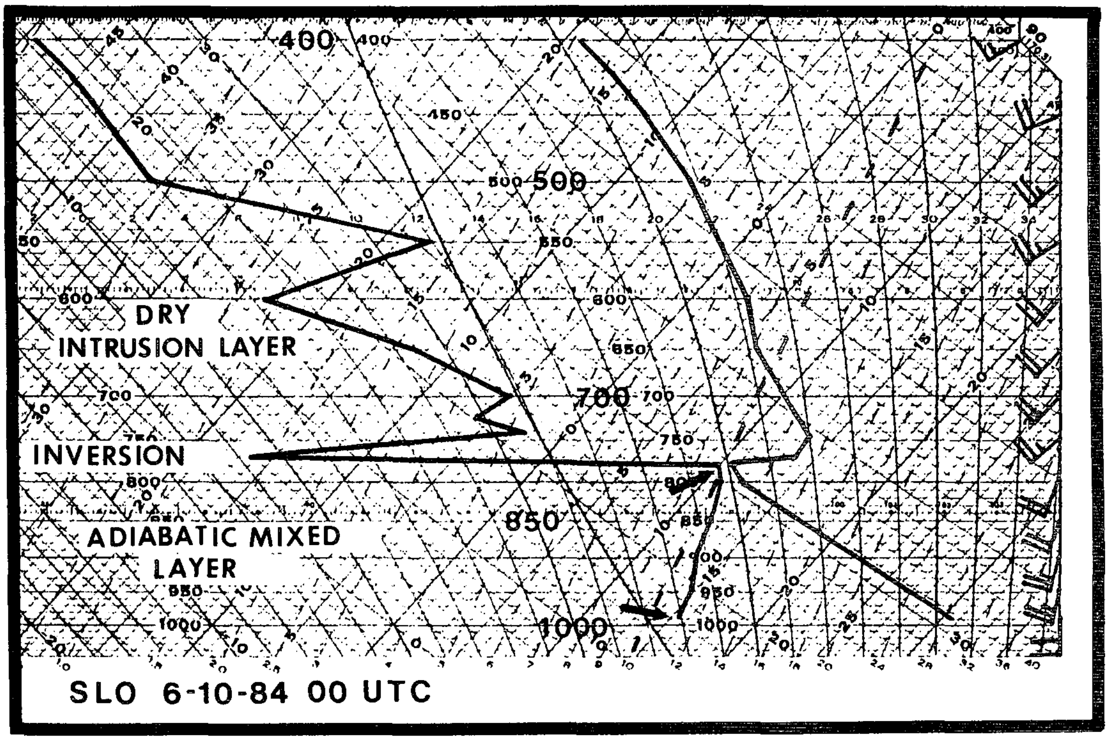


FIG. 11. 0000 UTC 10 June 1984 skew T–log p for Salem, Illinois (located at "D" on Fig. 10). The three thermodynamic components of a tradewind dry intrusion sounding are labelled: adiabatic, inversion, and dry intrusion layers.

data at all, as case studies have shown that extreme tradewind dryness typically occurs for several days ahead of westward traveling disturbances in the easterlies followed by several days of deeper moisture. The fact that the tradewind dry layer is not averaged out entirely is an indication of its influence in those summer months before disturbances in the easterlies reach a climatological maximum in September (NOAA 1985), and w increases over the Gulf of Mexico and Caribbean. Figure 8 (from Hagemeyer 1988), a time section of θw and east wind component for Key West, Florida from 9 to 15 June 1984, is presented to show the evolution of an extremely dry tradewind airmass ahead of an easterly wave that passed Key West on the 14th. This tradewind airstream with surface θw values of 297 K and lower mid-troposphere θw values as low as 286 K is characterized by extreme potential-convective instability, and eventually contributed to tornadic thunderstorm development over the Midwest as it interacted with a mid-latitude disturbance in the westerlies.

The onset of the tradewind dry airstream typically appears first over upper-air stations along the lower or middle Gulf Coast as an abrupt decrease in the depth of the moist layer, often below 850 mb. Despite the existence of significant potential-convective instability, thunderstorm development is typically inhibited in this airstream in the absence of strong forcing, or a focusing mechanism, due to the shallowness of the moist layer and the detrimental effect the extremely dry overlying air has on moist convection. The instability is then typically released well north of the Gulf region where the low-level moisture, mid-level dryness, and inversion interact with mid-latitude disturbances and contribute to severe weather development. Because this is a concept many forecasters may not be familiar with, a case study of a tradewind dry intrusion event is presented in the next section.

c. *A case study of a tradewind dry intrusion event*

In practice it is often difficult to establish whether the restraining inversion and overlying dry airstream are from heated, arid, high terrain, or due to pronounced subsidence in the tradewind airstream, unless the airmasses are tracked for several days using conservative variables. A clue for forecasters is that θ increases very slowly, or is nearly constant with height (high temperature lapse rates) in a true EML (Carlson and Farrell 1983), but θ typically increases steadily with height (low temperature lapse rates) above the moist layer in an elevated dry tradewind airmass resulting from subsidence (Hagemeyer 1988). The EML and the subsided tradewind dry airstream are significant to the severe storm forecast problem. They have fundamental differences in thermodynamic structure, formative mechanisms, and source regions, but can exist over the same geographic area! It is important that

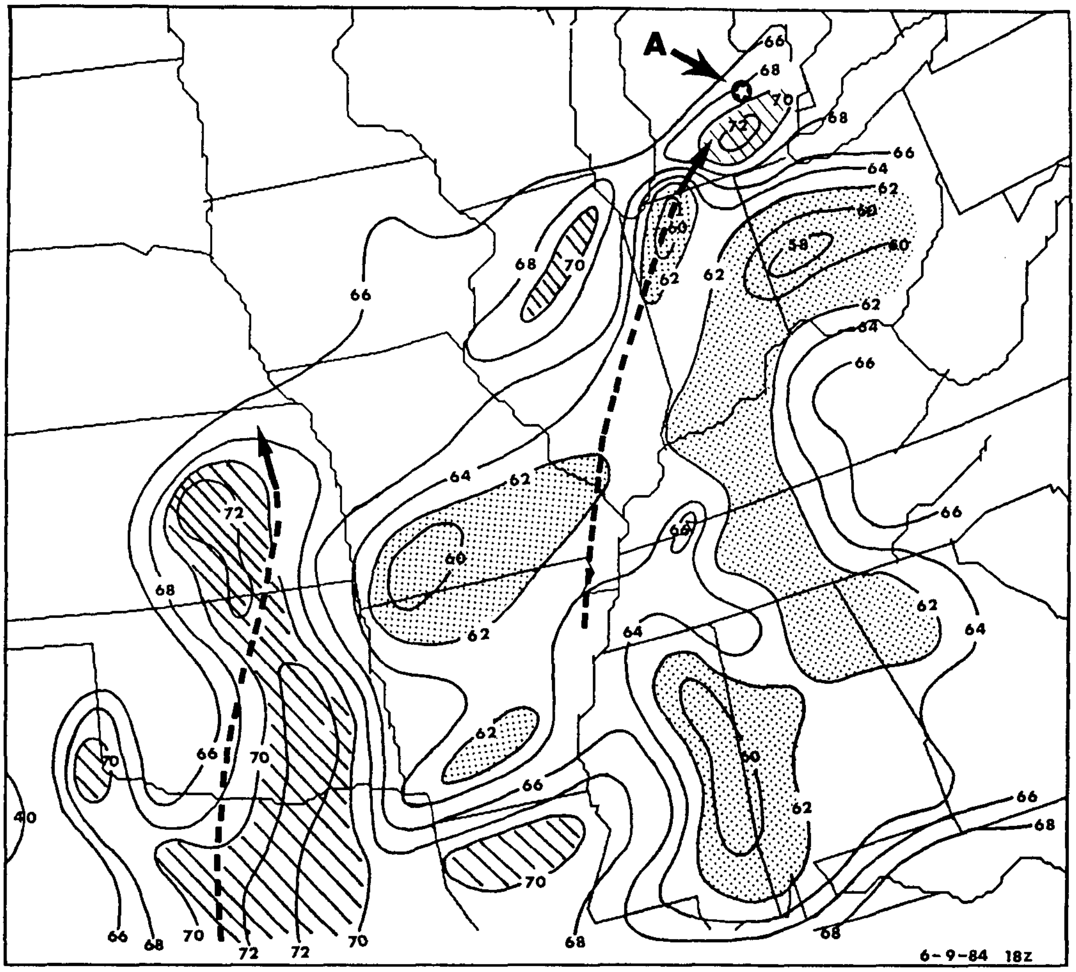


FIG. 12. 1800 UTC 9 June 1984 surface dewpoint analysis (°F, dewpoints greater than 70°F hatched, lower than 62°F shaded) with LLJs analyzed from surface winds indicated by dashed lines with arrowheads. Location of tornado at 1943 UTC is at "A."

forecasters recognize this and improve diagnostic procedures accordingly. The case study presented was chosen because it shows these two types of dry airmasses existing over the United States at the same time.

On the afternoon and evening of 9 June 1984 severe weather was associated with both the EML from the desert southwest and the tradewind dry layer. Figure 9 is the GOES IR image for 2330 UTC 9 June 1984 with analysis of 0000 UTC 10 June 850–700-mb temperature lapse rates superimposed. A dry airstream with *high* lapse rates ($\geqslant 10°C\ km^{-1}$) flowing from the desert southwest is contributing to a long line of severe thunderstorms from Iowa to Oklahoma. To the east an area of *low* lapse rates, that is, the tradewind dry airstream, extends from east Texas and the western Gulf Coast to a small area of *high* lapse rates [$\geqslant 8°C\ km^{-1}$] that had earlier contributed to the development of a tornadic thunderstorm over Michigan at 1943 UTC. This isolated, strong storm was now over southern Ontario (arrow at "A").

The composite analysis for 0000 UTC 10 June 1984 (Fig. 10) shows the two 700-mb dry airstreams (dashed-dot lines): 1) the axis of the tradewind dry airstream, ahead of a weak 700-mb wave in the easterlies over the Gulf of Mexico, and extending from east Texas to Michigan, and, 2) the hot, dry airstream (enclosed shaded area) from the desert southwest extending into northeast Kansas. Strong dynamics and favorable thermodynamics over the nation's midsection obviously indicated that the area was prime for severe weather development. However, note that a low-level jet (LLJ) and tradewind dry airstream in the warm sector were intersecting the warm front, and 850 moist and thermal axes, over eastern Michigan and southern Ontario.

The 0000 UTC skew T–log p for Salem, Illinois (Fig. 11, Salem is located by the arrow at "D" on Fig. 10) illustrates what a tradewind dry intrusion sounding looks like (note general similarity to Fig. 4). Strong surface heating has produced a deep surface-based adi-

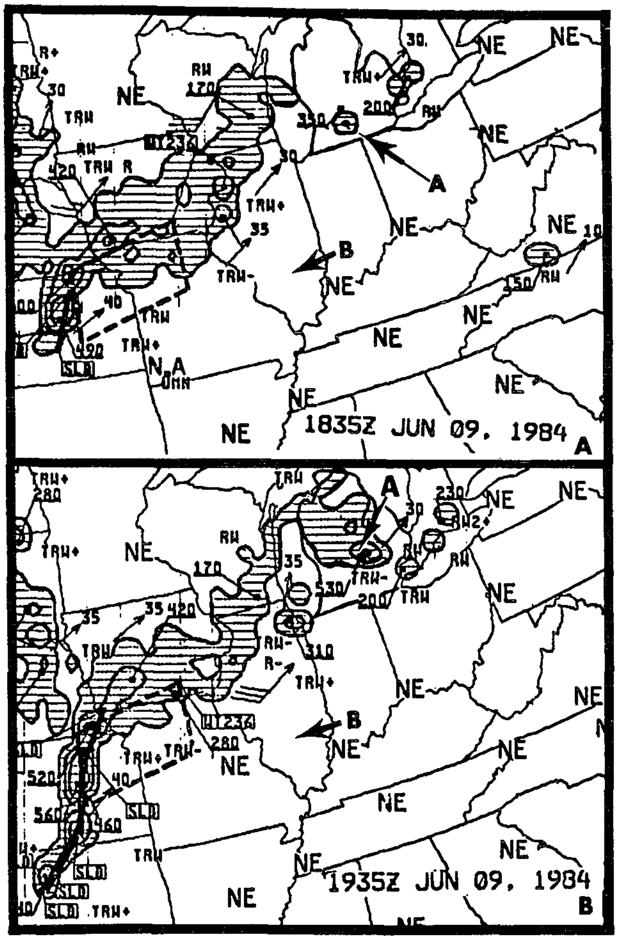


FIG. 13a–b. Radar summaries for 1835 UTC 9 June 1984 (Fig. 13a) and 1935 UTC (Fig. 13b). Developing tornadic thunderstorm is at "A" on Fig. 13a. Location of tornado touchdown at 1943 UTC is indicated by arrow at "A" on Fig. 13b. Arrows at "B" note location of Salem, Illinois upper-air site.

abatic layer capped by a strong inversion and dry, tradewind air has been mixed down from above, resulting in a significant drop in surface dew point by mid-afternoon. Convective development in this airstream is suppressed, and at best a few cumulus cloud streets may form, but *in most cases the area under the tradewind dry intrusion is devoid of clouds* (see Fig. 9), and its axis can be analyzed, and tracked, in visible imagery and surface dewpoint analyses as the day progresses, depending on soil moisture conditions (Hagemeyer 1988).

The 1800 UTC dewpoint analysis for 9 June with the axes of the two LLJs analyzed from surface wind reports (Fig. 12) shows a moist/dry couplet over northwest Indiana and south Michigan where the eastern LLJ and tradewind dry intrusion intersect the warm front. The location of the resulting tornadic thunderstorm at 1943 UTC is shown by the arrow at "A." *It is important to remember that dewpoints will drop during the afternoon, and be low, upstream of where the LLJ intersects the warm front in tradewind dry intrusion cases.* This may give conflicting signals to forecasters who have been taught that dewpoints should always rise, or at least remain high, upstream of a severe weather threat area, as is the case with the moist axis over Kansas and Oklahoma in Fig. 12. This is why it is important that forecasters know the characteristics of different dry airmasses. In tradewind dry intrusion cases the LLJ maximizes overrunning and low-level moisture convergence along the frontal zone at the same time that dry tradewind air is injected into the developing storm environment by mid-tropospheric wind maxima *resulting in explosive convective development over a relatively small area north of the warm front.*

Radar summaries illustrated the rapid development of the tornadic thunderstorm. At 1835 UTC (Fig. 13a) an isolated thunderstorm had developed just north of where the LLJ and dry intrusion intersected the warm front over southwest Michigan (arrow at "A"). By 1935 UTC (Fig. 13b) the thunderstorm had intensified rapidly, and by 1943 UTC had produced a F2 tornado (maximum wind speed 113 to 157 mph) one mile northeast of Bennington, Michigan. A funnel cloud was reported 15 miles east northeast of Bennington 25 min later. The approximate location of these reports is shown by the arrow at "A" in Fig. 13b (Note: reports regarding this tornado are incorrectly ascribed to 10 June in *Storm Data* for June 1984).

This intense tornadic thunderstorm over Michigan was the only significant convection that developed besides that in the favorable area from Oklahoma into Iowa. But of the several tornadoes reported in the United States on the afternoon and evening of 9 June, the strongest (the only F2) was the one reported in Michigan. The relative importance of the tradewind dry intrusion event is evident.

The cross section of θw and wind velocity (Fig. 14a) from Lake Charles, Louisiana (LCH) to Buffalo, New York (BUF) shows the tradewind dry airstream (approximated by the shaded area with $\theta w \leqslant 17°\mathrm{C}$) above the inversion layer from Longview, Texas (GGG) to near Flint, Michigan (FNT). The θ cross section (Fig. 14b) shows that, downwind from the inversion layer in the warm sector, pronounced cooling had occurred between 800 and 650 mb over Flint (reaching a maximum of 5°C cooling at 750 mb between 1200 UTC and 0000 UTC). This layer of cooling corresponded to the layer of minimum θw in the intruding and surrounding dry tradewind mid-level air. The cooling occurred at the same time that the LLJ maximized overrunning of warm, moist, low-level air resulting in the production of high lapse rates. The significance of the stable tradewind dry layer, which can suppress convection, and be a drought maker in the warm sector, is that *it provides potentially cool (low θw) lower mid-tropospheric air that can produce high lapse rates, and*

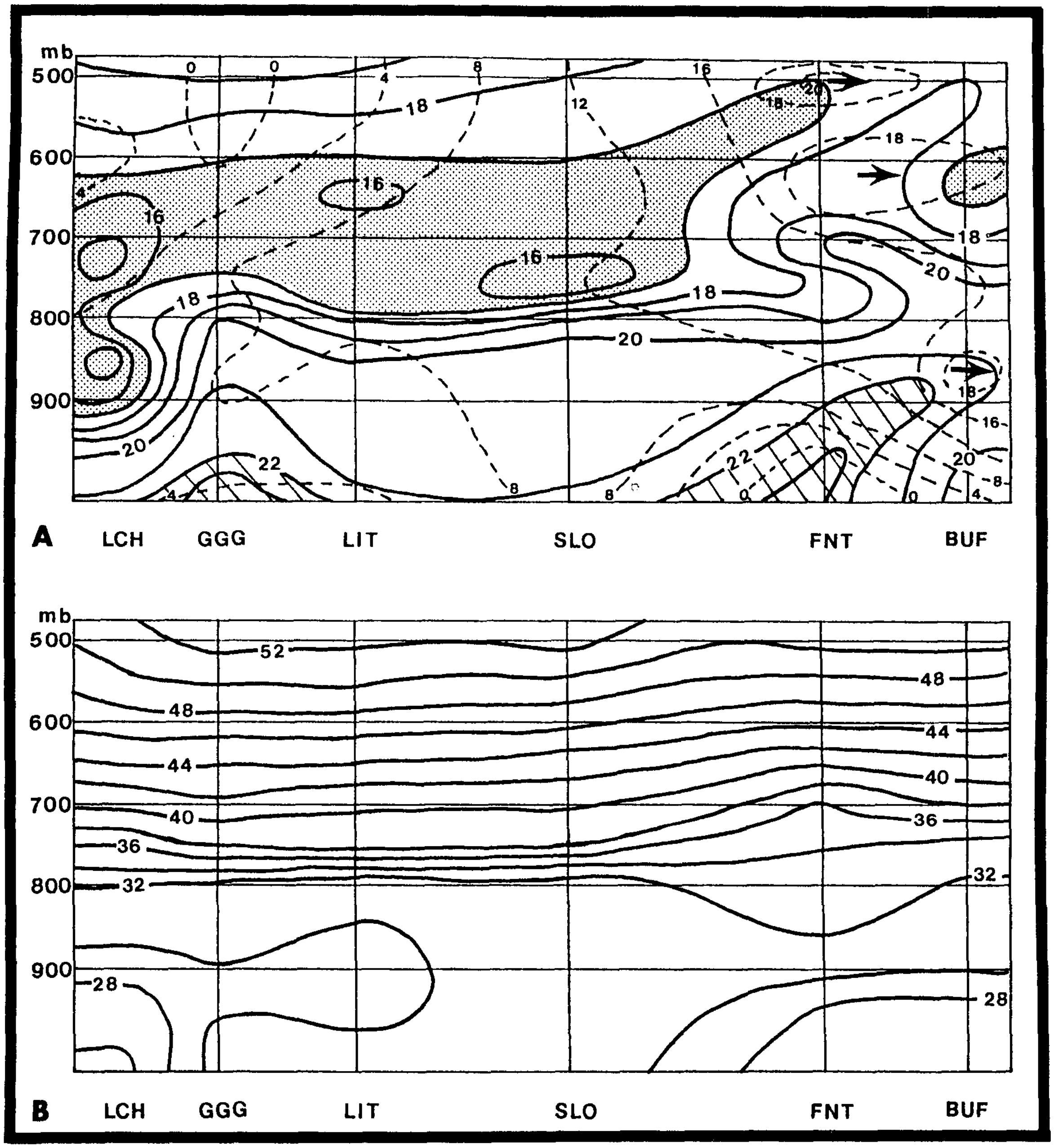


FIG. 14a–b. 0000 UTC 10 June 1984 cross sections to 500 mb of θw (°C) and wind velocity (m s^{-1}) along the cross section (Fig. 14a), and θ (Fig. 14b) from Lake Charles, Louisiana to Buffalo, New York (line AB on Fig. 10). θw values greater than 22°C are hatched and values less than 17°C are shaded. Horizontal arrowheads indicate wind velocity maxima.

strong downdrafts, when injected into the developing severe thunderstorm environment in the over-running zone. This is why an isolated area of high lapse rates is found downwind of low lapse rates in the tradewind airstream on Fig. 9.

The potential for a strong dry intrusion seems obvious when presented in this manner, but the tradewind dry airstream was not diagnosed in real time. Surprise development of a significant tornadic thunderstorm was the result. This is a classic example of why forecasters need to have access to detailed thermodynamic cross sections, and be aware of potential source regions of mid-level dry airmasses, particularly in the summer when synoptic forcing may be subtle and large scale events unfold slowly.

4. Summary and concluding remarks

The results of the thermodynamic climatology presented here indicate that there are distinct seasonal

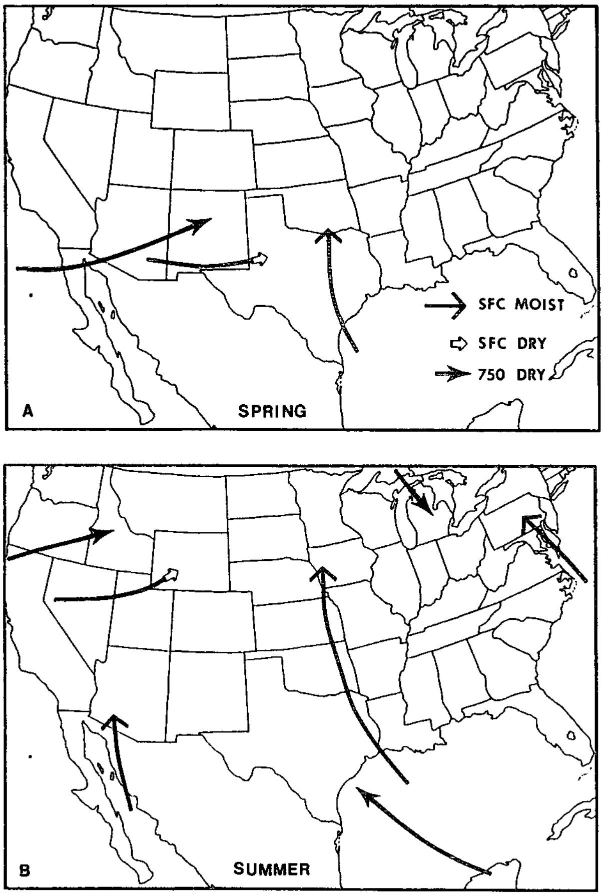


FIG. 15a–b. Composite schematic representations of major source regions of surface moist and dry airmasses, and lower mid-tropospheric dry airmasses important to thunderstorm production in spring (Fig. 15a) and summer (Fig. 15b). Lines with different arrowheads represent the different airmasses as indicated by the legend on Fig. 15a. The tails of the arrows indicate the source region and the heads approximate the mean extent of the leading edge of the airmass.

changes in lower-tropospheric airmass source regions, and differing large-scale mechanisms for the production of a thermodynamic environment favorable for thunderstorm development. This investigation does not solve all the airmass questions, but does represent an improvement in our knowledge that can be applied to the thunderstorm forecast problem. Complete information about the characteristics of airmasses that could effect a region is desirable. A forecaster might track large-scale airmasses for days prior to an event, but the actual release of instability brought about by dynamic processes that results in thunderstorm development over an area is typically a 0–12-h forecast problem. Knowledge of one scale without consideration of the other will lessen the chances for a successful forecast.

Figures 15a & b are presented as schematic synoptic generalizations of the findings of this paper for airmasses significant to the thunderstorm forecast problem in spring and summer. In spring (Fig. 15a) the Gulf of Mexico is the primary source of low-level moist airmasses and the desert southwest is the source of the dry airmass that forms the surface dryline. A 750-mb dry airstream is found flowing over the desert southwest to the rear of mean troughing. The typical spring development of severe thunderstorm outbreaks over the central and eastern United States downstream of these mean source regions indicates that differential advection is a most effective mechanism for producing an environment conducive to severe thunderstorm generation. The development of surface cyclones leeward of the southern Rockies would generally result in a favorable thermodynamic structure for severe thunderstorm development. This agrees in general with the results of Fawcett and Saylor (1965) who found that 80% of the "Colorado Cyclones" forming in stable and relatively dry airmasses in February through April produced severe thunderstorms as they moved eastward and tapped low-level moisture from the Gulf of Mexico.

The focus for severe thunderstorm activity based on thermodynamic evidence, and without regard to case studies, moves northward from the southern plains in spring, to the northern plains and upper Midwest in summer (Fig. 15b). By summer, high values of surface w have spread well northward from the Gulf of Mexico, and the Gulf of California and Atlantic Ocean become significant regional moisture sources. The Gulf of California, rather than the Gulf of Mexico, is the most significant source of moisture for the summer Southwest monsoon. Flow over the Baja California region shifts from westerly in June to southerly in July through September and a deep, moist airstream, that is much deeper than that over the Gulf of Mexico, moves up the Gulf of California indicating an increased potential for thunderstorms and heavy rainfall. The area of low surface w shrinks northward and westward, and is largely restricted to the Great Basin region by midsummer.

The analyses presented here indicate that improvements in thunderstorm forecasting could be made by recognizing that there are several source regions of mid-level dry air intrusions in summer other than the desert southwest, such as those found over the Pacific Northwest and upper Great Lakes region, and the tradewind airstream flowing over the Gulf of Mexico.

The existence of a dry airmass over Texas or the middle Gulf Coast in the late spring and summer could be a result of an EML advected from high, arid terrain, or subsidence in the tradewind easterlies flowing around the Bermuda High. These airmasses are important to severe storm formation and have distinctly different thermodynamic characteristics. The emphasis on the EML is probably due to the focus on dryline convection via case studies, but it might be expected that the extensive airmass flowing around the southern flank of the Bermuda High has a much greater influence on the suppression and/or organization of thunderstorms over the central and eastern United States in the warm season than the relatively small region of the desert southwest, especially outside of the dryline region.

Acknowledgments. This paper is an expansion of an original unpublished investigation by Bartlett C. Hagemeyer and Grant L. Darkow which included 49 upper-air stations and covered the area from the continental divide eastward for March through August. Dr. Darkow's significant contribution to this study is greatly appreciated and hereby acknowledged. Thanks also to Dr. Joseph T. Schaefer for his review of the first paper and subsequent encouragement to persevere to publish the results. Appreciation is also extended to Brynn W. Kerr for his assistance in tabulating the data, and to John R. Duymeyer who wrote the computer program to calculate the thermodynamic variables.

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