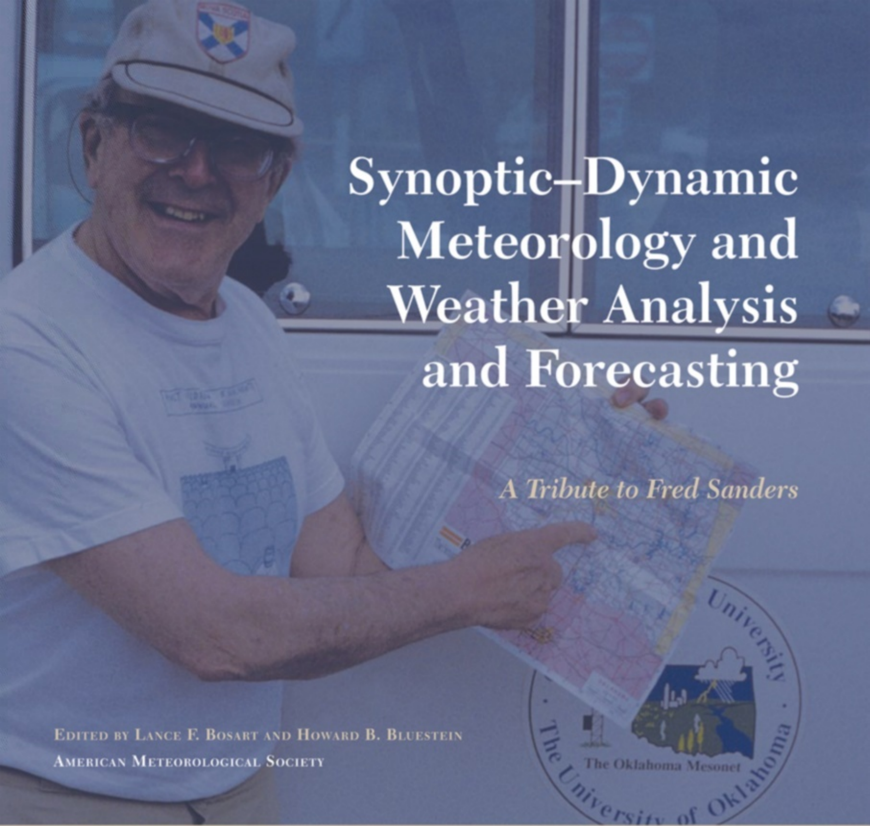
Synoptic–Dynamic Meteorology and Weather Analysis and Forecasting

A Tribute to Fred Sanders



Edited by Lance F. Bosart and Howard B. Bluestein

American Meteorological Society

SYNOPTIC–DYNAMIC METEOROLOGY AND WEATHER ANALYSIS AND FORECASTING

A TRIBUTE TO FRED SANDERS

Edited by

Lance F. Bosart
Howard B. Bluestein

Published by the American Meteorological Society

DEDICATION

There was once an MIT professor named Fred
Who in his leisure time sailed out of Marblehead
He expounded on the weather
To a bevy of those who on the 16th floor of the Green Building he kept on a tether
Wondering about the next front, the next storm, and the Logan ob the next morning at 12 ‘‘zed’’

—Howie ‘‘Cb’’ Bluestein

This monograph is dedicated to Fred Sanders (AKA ‘‘Olde Dad’’), shown here in full foul weather gear, aboard his 39-foot sailboat, the *Stillwater* (not aptly named, for Fred and his sailboat cruised in water that was far from still), summer 1973. Many of Fred’s students spent memorable afternoons sailing with him out of Marblehead, MA. Courtesy of Howie Bluestein.

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Lance F. Bosart
Howard B. Bluestein

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FOREWORD

The Fred Sanders Legacy in Synoptic–Dynamic Meteorology and Weather Analysis and Forecasting

The field of synoptic meteorology, which seeks to understand weather systems such as fronts and cyclones by careful analysis and interpretation of weather observations, was much influenced by the late Frederick Sanders, emeritus professor of meteorology at the Massachusetts Institute of Technology (MIT). Professor Sanders, universally known as ''Fred,'' made important contributions to the analysis, understanding, and prediction of fronts, extratropical cyclones, hurricanes, squall lines and other warm-season convective weather systems, and flood-producing storms. He coined the term ''bomb'' to describe explosively intensifying winter storms. His classic oft-cited 1955 paper on an investigation of the structure and dynamics of an intense frontal zone established the critical role of low-level horizontal confluence and convergence in leading to ''frontal collapse'' in intense fronts. He also invented the field of oceanic mesometeorology, applying careful analysis of meteorological conditions experienced by a fleet of sailboats participating in races from Newport, Rhode Island, to Bermuda.

Born in Detroit on 17 May 1923, Fred was the eldest of the three children of Frederick William and Dorothy Martin Sanders. After spending much of his childhood in Bloomfield Hills, Michigan, Fred attended Amherst College, where he studied mathematics, economics, and music. This was during World War II, and the Army Air Corps was determined to train 10,000 weather forecasters, canvassing colleges and universities for students who were studying math and physics. Fred signed up around Christmas 1941 and was sent for infantry basic training at Jefferson Barracks outside St. Louis, thence to MIT for six months of intensive study in math and physics, followed by nine months of meteorology.

Fred graduated as a second lieutenant shortly after D-Day in Normandy, and requested and was granted assignment to Greenland, where he discovered that flight crews keenly valued his forecasting skills. On return to the United States at the end of the war, he worked briefly as an air inspector at Headquarters Eighth Weather Group at Grenier Air Force Base in New Hampshire.

Just before separating from the military, Fred met Nancy Brown, whom he married in 1946. In the same year, he decided to become a professional weather forecaster rather than to join his father's candy manufacturing business. He became a transatlantic aviation forecaster for the U.S. Weather Bureau at La Guardia Field, but after two years returned to MIT as a graduate student under the G.I. Bill, intending to get a master's degree and return to the Weather Bureau as a researcher. But he was persuaded by his MIT mentors to enter the doctoral program, and he earned an Sc.D. degree in 1954 under the guidance of Thomas Malone, after which he joined the faculty of the MIT Department of Meteorology, where he remained until his retirement in 1984.

In the 1960s, Fred began to think about the importance of forecast verification studies as one key to unlocking some of the scientific mysteries of the atmosphere. His 1963 paper on subjective probability forecasting demonstrated the scientific insights that could be obtained by rigorously and quantitatively evaluating the skill of daily weather forecasts and applying the knowledge gained to improve weather forecasts. His 1975 paper (with Pike and Gaertner) reported on one of the first successful computer models based on the barotropic vorticity equation (SANBAR) that was used for operational hurricane track forecasting. In 1980, Fred published two seminal papers. The first paper (with Miller) analyzed the mesoscale conditions associated with the jumbo tornado outbreak of 3–4 April 1974, from which it was deduced that the many tornadoes in that event tended to cluster in three main bands that possessed distinctive atmospheric structure. The second paper (with Gyakum) shed light for the first time on the systematic distribution and structure of explosively deepening oceanic cyclones (aka bombs) in the Northern Hemisphere and resulted in an avalanche of research papers on this topic over the next 10–20 years.

In the 1980s, Fred turned his attention to individual case studies of warm-season convective weather systems and cold-season winter storms with a particular emphasis on mesoscale structures embedded within these weather systems; many publications resulted from this effort. In 1988, Fred published a seminal paper on the life history of mobile troughs in the upper westerlies. In this paper, Fred established that preferred regions for 500-hPa trough genesis events in the Northern Hemisphere occurred over and downstream of major north–south-oriented mountain barriers such as the Rockies, while 500-hPa trough lysis events occurred preferentially over the eastern-ocean basins. A critical aspect of this paper was Fred's demonstration that upper-level trough genesis typically occurred well upstream and prior to surface cyclogenesis in the oceanic storm-track entrance regions immediately adjacent to the east coasts of North America and Asia rather than simultaneously with surface cyclone development, as postulated in theories of classical baroclinic instability.

In the 1990s, Fred became interested in assessing the skill of operational dynamical models in predicting oceanic cyclogenesis as typified by his 1992 paper that showed that skills were improving, and he returned to his roots with the publication of a paper in 1995 (with Doswell) on the case for detailed surface analyses. The latter paper, and several others on the same topic, were motivated by what Fred saw as a need to arrest a perceived decline in the quality of operational surface frontal analyses by calling attention to the importance of these analyses to understanding observed weather systems, and by new science opportunities that could be uncovered from careful mesoscale analyses of the life cycles of surface fronts. Fred argued that real surface fronts should be defined on the basis of the magnitude of the observed surface potential temperature gradient. In his last paper, published in 2005, he applied a potential temperature gradient criterion to distinguish between what he called ''real fronts'' (surface boundaries characterized by significant potential temperature differences) and ''baroclinic troughs'' (surface boundaries marked by wind shifts but little or no potential temperature contrast).

Fred's strong interest in weather analysis and forecasting enabled him to pioneer methods for evaluating the skill of both human and computer weather forecasts, stressing the need for quantifying the uncertainty of the forecasts; this work also led to improvements in numerical weather prediction models and his demonstration that a consensus forecast made up of a group of equally skilled forecasters would usually beat individual forecasters in the group over the long haul. Fred watched the weather every day and impressed his students by what he could ''see'' on the many weather maps that were posted in the 16th-floor hallway of the Green Building at MIT. There was always a ''story to be told'' by the weather maps. The story was different every day, but the overall theme never changed. The story was always about physics, dynamics, thermodynamics, and new scientific insights that could be gleaned from synthesizing these processes and applying them in real-time weather analysis and forecasting. In addition to the scientific story, there was also some psychological drama when he sauntered past the weather maps, behind students preparing their forecasts, and muttered under his breath, ''You don't suppose that . . . '' The bulk of the forecasters, reaching for their erasers, would hurriedly amend portions of their forecasts. With Fred, learning was made fun.

But the story didn't end there. Fred also taught his students the importance of transferring the scientific knowledge gained from studying the weather to operations, to the benefit of weather forecasters—and ultimately the general public. Fred used the daily weather forecasting contest at MIT to teach his students about how the atmosphere worked. At stake were a prize cigar and the potential for prospective thesis topics. Although his students worked long and hard to try to beat him during the semester-length forecasting contests, when the bell rang at the end of the semester more often than not Fred was at the top of the heap. New scientific ideas and insights about the workings of the atmosphere were continually put on the table during these map discussions, which proved to be the highlight of the day for many students. Together with his colleague, Richard Reed, Fred elevated the field of synoptic meteorology to the status of a respected science, to the benefit of the field and to generations of students. He was the recipient of many awards, and was a fellow of the AMS as well as the American Association for the Advancement of Science.

While mixing very well with students and maintaining an air of informality, Fred held them to very high standards. He constantly challenged them and made them think very deeply about scientific issues. Fred was much beloved and esteemed not only by the many students he mentored, but also by the colleagues he worked with, so much so that, in 2004, the AMS held a scientific colloquium in his honor. Most of those who today teach and do research in synoptic meteorology have profited directly from Fred's guidance. In Fred's words, ''My career was heavily weighted toward teaching, in which I enjoyed sharing the enthusiasm I felt for weather analysis and forecasting.'' That Fred's publication rate in the refereed scientific literature went up after he retired from MIT in 1984 is testimony to the considerable amount of his time that he had invested in teaching. Steve Mullen, a scientific collaborator in recent years, has noted that ''There are few people in the history of the field who have trained and mentored as many outstanding meteorologists as Fred; his legacy in terms of his offspring is just legendary.''

That many of the authors and coauthors of articles appearing in this monograph are Fred's academic ''children'' and ''grandchildren,'' and that other authors and coauthors are close Sanders ''family'' members, attests to his enduring legacy as a mentor, colleague, and educator.

Fred's first Ph.D. student, Lance Bosart, and Lance's former Ph.D. students Alicia Wasula, Eric Hoffman, and David Schultz (co-advised with Daniel Keyser); his present Ph.D. student, Tom Galarneau; and his former M.S. students Greg Hakim (Dan Keyser was Greg's Ph.D. advisor) and Keith Meier are represented in this monograph. Fred's Ph.D. student Howie Bluestein and Howie's former Ph.D. student Christopher Weiss are also represented, as are Fred's former Ph.D. students Bob Burpee, Randy Dole, John Gyakum, and Steve

Tracton, and Fred's former M.S. student Paul Roebber. Finally, Ryan Torn, who was Greg Hakim's Ph.D. student, making him Fred's academic "great grandchild," is also represented in this monograph.

At MIT, Kerry Emanuel interacted with and was influenced by Fred Sanders; Kerry's Ph.D. student, John Nielsen-Gammon, and John's Ph.D. student Dave Gold have also made contributions to this monograph. Ed Kessler, the first director of the National Severe Storms Laboratory, interacted with Fred at MIT beginning in the 1950s and continuing up until Fred's passing in October 2006.

Fred joined the MIT faculty at a time when federal funding of scientific research was ramping up rapidly in response to the challenge posed by the U.S.S.R.'s Sputnik satellite. To his great credit, Fred resisted the sea change toward research and away from teaching that affected most premier institutions of higher education, preferring to spend most of his time preparing lectures and interacting with students. Consequently, he became a greatly beloved professor and mentor, and has had a large influence on his field not just through his own research, but through the carefully nurtured talent of his students. Fred could often be found tutoring lagging students over lunch, or taking entire classes for an outing on his sailing yacht, Stillwater, bringing joy as well as knowledge to the study of weather. Fred was also beloved by staff members at MIT, including Ann Corrigan, Ed Nelson (who took care of the map room and assisted students with their data needs), and Isabel Kole (who drafted all kinds of figures for Fred and his students). A common sight on the 16th floor of the Green Building at MIT was Fred huddling with Ann, Ed, Isabel, and various students surrounded by maps, teletype paper, and figures being drafted.

In later years, Fred maintained his friendship and scientific collaboration with many of his students. He was a frequent scientific visitor at the University of Arizona, and visited Norman, Oklahoma, almost yearly to storm chase. While he never did see a tornado, he completed numerous collaborative studies with colleagues at the National Severe Storms Laboratory and the Cooperative Institute for Mesoscale Meteorological Studies while there.

Fred was a passionate sailor and participated in many ocean races, including the Newport–Bermuda and Marblehead–Halifax races. He also loved to cruise the coast of Maine and the Canadian Maritimes with his family and friends, to whom he brought much pleasure. An accomplished tenor, he sang with the MIT Choral Society and more recently with the choir of the Old North Church in Marblehead.

The spirit of Fred Sanders is well captured in this remembrance by his friend and colleague, Ed Zipser: "I don't think we will ever see his equal—not just for his scientific insight, but his outgoing nature, his helpfulness, his sometimes acerbic wit, and without fail remaining the consummate gentleman at all times."

—Adapted from Lance Bosart, Howie Bluestein, and Kerry Emanuel, obituary of Frederick Sanders, *Bull. Amer. Meteor. Soc.,* **88,** 425–427

Fred Sanders' life was commemorated in the *Boston Globe* on 27 October 2006 (the article may be found online at www.boston.com) and by the MIT News Office on the same date (the article maybe found online at web.mit.edu/newsoffice/2006/obit-sanders.html).

ACKNOWLEDGMENTS

The publication of this monograph was made possible by the collective efforts of many people. The idea to create a monograph to honor Fred Sanders' many scientific, educational, and operational contributions to the atmospheric sciences originated during the planning for the *AMS Fred Sanders Symposium* by the "Gang of Four" (Howie Bluestein, Lance Bosart, Brad Colman, and Todd Glickman). The well-attended Sanders Symposium was held in Seattle, Washington, in January 2004 in conjunction with the *84th AMS Annual Meeting*.

We thank Peter Ray, AMS meteorological monographs series editor, for giving us the green light to proceed with this monograph. We would also like to express our great appreciation to AMS Executive Director, Keith Seitter, and AMS Publications Director, Ken Heideman, for their continuing support and encouragement as the monograph moved forward from a concept to reality. Special thanks also go to Sarah Jane Shangraw at the AMS and Celeste Iovinella at the University at Albany, SUNY, for expertly managing all the details and the technical issues with a firm hand on the tiller that otherwise would have overwhelmed us.

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Special thanks also go to the generations of Fred's students (and their students) as well as his many friends and colleagues who enthusiastically supported the *Sanders Symposium* and the idea to produce a Sanders monograph. We also greatly appreciate the continuing support and interest of Fred's beloved wife, Nancy Sanders, and his children, grandchildren, and other family members as the Sanders monograph moved forward from a concept to reality.

—Lance F. Bosart and Howard B. Bluestein

CONTRIBUTORS

ANANTHA R. AIYYER
Department of Marine, Earth, and Atmospheric Sciences
North Carolina State University
2800 Faucette Dr.
Raleigh, NC 27695
E-mail: afractal@gmail.com

MICHAEL BAKER
NOAA/NWS/MDL
W/OST22
1325 East West Hwy.
Sta. 11316
Silver Springs, MD 20910
E-mail: michael.n.baker@noaa.gov

HOWARD B. BLUESTEIN
School of Meteorology
University of Oklahoma
120 David L. Boren Blvd., Suite 5900
Norman, OK 73072
E-mail: hblue@ou.edu

LANCE F. BOSART
Department of Earth and Atmospheric Sciences
University of Albany, State University of New York
1400 Washington Ave.
Albany, NY 12222
E-mail: bosart@atmos.albany.edu

ROBERT W. BURPEE[1]
Cooperative Institute for Marine and Atmospheric Studies
4600 Rickenbacker Causeway
Miami, FL 33149

RANDALL M. DOLE
NOAA/Earth System Research Laboratory
325 Broadway
Boulder, CO 80305
E-mail: randall.m.dole@noaa.gov

WALTER H. DRAG
NOAA/NWS
445 Myles Standish Blvd.
Taunton, MA 02780-1041
E-mail: wdrag111@comcast.net

[1] Deceased. See Lance F. Bosart for correspondence.

KERRY EMANUEL
Program in Atmospheres, Oceans, and Climate (PAOC)
Rm. 54-1620
Massachusetts Institute of Technology
77 Massachusetts Avenue
Cambridge, MA 02139
E-mail: emanuel@texmex.mit.edu

THOMAS J. GALARNEAU JR.
Department of Earth and Atmospheric Sciences
University at Albany, State University of New York
ES-234, 1400 Washington Ave.
Albany, NY 12222
E-mail: tomjr@atmos.albany.edu

BART GEERTS
Department of Atmospheric Sciences
University of Wyoming
P. O. Box 3038
Laramie, WY 82071-3038
E-mail: geerts@uwyo.edu

DAVID A. GOLD
Department of Atmospheric Sciences
Texas A&M University
College Station, TX 77843-3150
E-mail: dr_david_gold@earthlink.net

JOHN R. GYAKUM
Department of Atmospheric and Oceanic Sciences
McGill University
805 Sherbrooke Street West
Montreal, QC H3A 2K6, Canada
E-mail: john.gyakum@mcgill.ca

GREGORY J. HAKIM
Department of Atmospheric Sciences
Box 351640
University of Washington
Seattle, WA 98195-1640
E-mail: hakim@atmos.washington.edu

ERIC G. HOFFMAN
Department of Chemical, Earth, Atmospheric, and Physical Sciences
Plymouth State University
313 Boyd Hall
Plymouth, NH 03264
E-mail: ehoffman@plymouth.edu

EDWIN KESSLER
Department of Geography, and School of Meteorology
University of Oklahoma
Norman, OK 73072-6337
E-mail: kess3@swbell.net

ROBERT KISTLER
NOAA/NWS/NCEP
Ocean Prediction Center
5200 Auth Road
Camp Springs, MD 20746
E-mail: rek067@gmail.com

PAUL J. KOCIN
NOAA/NWS/NCEP
Hydrometeorological Prediction Center
5200 Auth Road
Camp Springs, MD 20746
E-mail: pkocin@aol.com

KEITH W. MEIER
National Weather Service
2170 Overland Ave.
Billings, MT 59102-6455
E-mail: keith.meier@noaa.gov

JOHN W. NIELSEN-GAMMON
Department of Atmospheric Sciences
Texas A&M University
3150 TAMUS
College Station, TX 77843-3150
E-mail: n-g@tamu.edu

ANDREW L. PAZMANY
ProSensing, Inc.
107 Sunderland Rd.
Amherst, MA 01002-1117
E-mail: apazmany@yahoo.com

PAUL J. ROEBBER
Atmospheric Science Group
Department of Mathematical Sciences
University of Wisconsin—Milwaukee
P. O. Box 413
Milwaukee, WI 53201
E-mail: roebber@uwm.edu

DAVID M. SCHULTZ
Finnish Meteorological Institute
Erik Palmenin Aukio 1
P. O. Box 503
FI-00101 Helsinki, Finland
E-mail: david.schultz@fmi.fi.

JOSEPH SIENKIEWICZ
NOAA/NWS/NCEP
Ocean Prediction Center
5200 Auth Road
Camp Springs, MD 20746
E-mail: joseph.sienkiewicz@noaa.gov

RYAN D. TORN
National Center for Atmospheric Research
Box 3000
Boulder, CO 80307
E-mail: torn@atmos.washington.edu

M. STEVEN TRACTON
Office of Naval Research
One Liberty Center
875 Randolph St., Suite 1425
Arlington, VA 22203
E-mail: s.tracton@hotmail.com

LOUIS W. UCCELLINI
NOAA/NWS/NCEP
5200 Auth Road
Camp Springs, MD 20726
E-mail: louis.uccellini@noaa.gov

ALICIA C. WASULA
Department of Earth and Atmospheric Sciences
University at Albany, State University of New York
1400 Washington Ave.
Albany, NY 12222
E-mail: alicia@atmos.albany.edu

CHRISTOPHER C. WEISS
Department of Geoscience
Texas Tech University
Box 42101
Lubbock, TX 79409
E-mail: chris.weiss@ttu.edu

TABLE OF CONTENTS

INTRODUCTION TO PARTS I AND II

By Howard B. Bluestein

Fred Sanders published research in many areas of meteorology. In this volume contributions from current studies and from reviews are included on the observations and theory of surface fronts and other surface boundaries, the techniques used for the analysis and diagnosis of observational and model data, weather forecasting, and climatology-related issues. The contributions in the volume by no means represent all of Fred's interests, but perhaps best showcase how his mentorship has inspired several generations of students to continue to make progress in areas in which he has made contributions. The papers presented herein can be used to augment graduate courses in synoptic and mesoscale meteorology.

In chapter 1, Howard Bluestein reviews the characteristics of surface boundaries in the Southern Plains and discusses their role in the initiation of convective storms. This paper updates the seminal work Fred did in the 1950s and continued on with applications to convective systems. Fred visited Oklahoma many times to chase storms and try to forecast them. He collaborated with scientists at the National Severe Storms Laboratory on convection-related issues. Although Fred's early interests were on fronts in the central United States, he later considered fronts along the east coast. Lance Bosart, Alicia Wasula, Walt Drag, and Keith Meier discuss the characteristics and dynamics of strong surface fronts over sloping terrain and the coastal plains. Fred had a keen interest in surface fronts that interacted with the mountains in New England and the Appalachians in the Carolinas. Kerry Emanuel has contributed a provocative essay on the strengths of the Norwegian School of cyclones and fronts. It is interesting to note how certain modes of thought are in favor, then fall out favor, and then return again. Ed Kessler discusses small-scale observations of frontal passages on his farm in Oklahoma and how they conform and don't conform to conventional ideas. Dave Schultz presents a review of Fred's work on surface cold fronts and updates his work using contemporary observations. Dave Schultz and Paul Roebber then discuss a numerical simulation using a state-of-the art mesoscale model of the front analyzed by Fred back in the mid-1950s; Fred's work has since been accepted as a classic study. It is interesting to see how significant aspects of his seminal work bear up under the scrutiny of modern model simulations.

In doing so many observational studies, Fred tackled the problems of how to assess data quality, analyze the data, and make carefully thought out inferences that are tested against alternative explanations. In Part II there are papers on analysis and diagnostic techniques. Using ensemble model forecasts to produce analyses on the synoptic scale is the subject of a paper by Greg Hakim and Ryan Torn. In this paper, a technique for improving analyses of data by using a suite of numerical simulations to produce dynamically and statistically consistent analyses on the synoptic scale is detailed. Fred long advocated using analyses of surface potential temperature rather than analyses of temperature, especially when stations are not at the same elevation. Eric Hoffman discusses the implementation of Fred's ideas. Fred Sanders taught generations of students the intricacies of quasisgeostrophic theory and carefully applied it to the analysis of many types of cyclones and anticyclones. John Nielsen-Gammon and Dave Gold propose that the analysis of Ertel's potential vorticity has significant advantages to simple quasigeostrophic diagnosis. Fred was always interested in the analysis of new types of data. Chris Weiss, Howard Bluestein, and Andrew Pazmany describe the development of a new technique for analyzing the vertical circulation across drylines using data from a mobile Doppler radar. The authors focus on data collected during IHOP (International H_2O Project) in 2002.

Part I

Fronts and Surface Boundaries

Chapter 1

Surface Boundaries of the Southern Plains: Their Role in the Initiation of Convective Storms

HOWARD B. BLUESTEIN

School of Meteorology, University of Oklahoma, Norman, Oklahoma

(Manuscript received 28 January 2004, in final form 16 June 2006)

Bluestein

Our approach is to resist the traditional appeal to ''indications'' or ''ingredients'' as described in a historical account by Schaefer (1986), however successful it has been in development of the present modest predictive skill. We rely instead on a simple physical consideration: intense convection will occur provided that large convective available potential energy (CAPE) is present in the air column and provided that the typical negative area (CIN, or convective inhibition) below the level of free convection for surface air is somehow removed or reduced to a small value that can be overcome by random cloud-scale pulses at the top of the surface boundary layer.

— Sanders and Blanchard (1993)

ABSTRACT

The nature of the different types of surface boundaries that appear in the southern plains of the United States during the convectively active season is reviewed. The following boundaries are discussed: fronts, the dryline, troughs, and outflow boundaries. The boundaries are related to their environment and to local topography. The role these boundaries might play in the initiation of convective storms is emphasized. The various types of boundary-related vertical circulations and their dynamics are discussed. In particular, quasigeostrophic and semigeostrophic dynamics, and the dynamics of solenoidal circulations, density currents, boundary layers, and gravity waves are considered.

Miscellaneous topics pertinent to convective storms and their relationship to surface boundaries such as along-the-boundary variability, boundary collisions, and the role of vertical shear are also discussed. Although some cases of storm initiation along surface boundaries have been well documented using research datasets collected during comprehensive field experiments, much of what we know is based only on empirical forecasting and nowcasting experience. It is suggested that many problems relating to convective-storm formation need to be explored in detail using real datasets with new observing systems and techniques, in conjunction with numerical simulation studies, and through climatological studies.

1. Introduction

Fred Sanders has taught his students the importance of plotting surface-observation data and analyzing surface weather maps, especially using standard data from the operational network. He has shown that much can be

Corresponding author address: Prof. Howard B. Bluestein, School of Meterology, University of Oklahoma, 100 E. Boyd, Rm. 1310, Norman, OK 73019.
E-mail: hblue@ou.edu

learned about weather forecasting and the physical mechanisms driving weather systems by examining surface weather maps and by describing what actually happens in nature. The purposes of analyzing the maps are to critically assess how well existing conceptual models are valid and to formulate newer and more accurate conceptual models of the features analyzed on the maps. In recent years, numerical forecast models that have assimilated data on both large and small scales have attempted to predict the onset of convective storms (e.g., http://www.caps.ou.edu/forecasts.htm; http://wrf-model.ogr/index.php).

I have been inspired by watching Fred Sanders analyze sequences of hourly radar summaries and other data spread out on the 16th floor of the Green Building at the Massachusetts Institute of Technology (MIT), in an attempt to find order in the evolution of a convective system. I recall the tremendous excitement he instilled in us students on 3 April 1974 as he anxiously monitored one of the largest outbreaks of severe weather ever. In addition, I remember him engaging Ed Kessler, who was at the time at MIT and on leave from the National Severe Storms Laboratory (NSSL), in conversations on severe convection. Finally, I recall how he regaled me with stories of waterspouts seen by moonlight, while he was sailing.

For more than 25 yr, this student of Fred's has spent countless hours plotting and analyzing surface weather maps and, in the past several years, output from numerical forecast models, with the goal of being able to forecast the initiation of severe convective storms in the southern plains. The ultimate goal has been even more practical: being able to position storm-intercept vehicles near tornadoes and their parent convective storms for observation and probing by various types of instruments (Bluestein 1999). Fred Sanders joined our team on many occasions. He shocked some of the student participants by meticulously plotting and analyzing surface equivalent potential temperature, while the rest of us were fixated on the sky.

Much has been learned about the conditions under which convective storms form. It is generally acknowledged that storms that are rooted in the boundary layer (i.e., those whose main, buoyant updraft contains air that originated in the boundary layer) often are initiated along or near surface ''boundaries'' (e.g., Byers and Braham 1948; Rhea 1966; Gaza and Bosart 1985; Shapiro et al. 1985; Schaefer 1986; Wilson and Schreiber 1986; Dorian et al. 1988; Lee et al. 1991; Galway 1992), especially in the southern plains during the spring season. [In other instances, convection is not triggered along surface boundaries and not rooted in the boundary layer (e.g., Martin et al. 1995).] In this paper a boundary is defined as a line of discontinuity or a narrow zone separating air having distinctly different meteorological conditions. A boundary may separate two different air masses or might mark a shift in wind direction and/or speed across which there may or may not be a change in air mass. Careful and detailed surface analyses of data are essential for recognizing and describing the boundaries on a weather map (Sanders and Doswell 1995).

The purpose of this chapter is to review what we have learned about the initiation of convective storms in the southern plains of the United States, during the convectively active season, and how initiation is related to surface boundaries. Because convective storms are observed most frequently during the spring months, from April to June, we will focus our attention only on these months. In the next section we review briefly the basic physics of storm formation. In section 3 the characteristics of the primary surface boundaries found in the southern plains are discussed. The nature of vertical circulations along the edges of these surface boundaries is discussed in section 4. The chapter ends with a list of suggested research topics.

2. Storm initiation

How is storm initiation defined? It could be when the first convective cloud becomes visible, which is a sign that the level of free convection (LFC) has been reached. The appearance of cumulus congestus on satellite images or reports of the same from spotters might be enough to convince forecasters to issue statements concerning the possibility of convective activity. However, sometimes cumulus congestus do not develop into convective storms because they grow in an environment of too much vertical shear or because they are too narrow, and the entrainment of dry, environmental air destroys their buoyancy before they can develop any precipitation. The beginning of a storm might be when precipitation aloft is first detected. In radar studies, such a definition is common (e.g., Rhea 1966; Bluestein and Jain 1985; Bluestein et al. 1987; Bluestein and Parker 1993). However, in some instances the convective cell dissipates immediately when a downdraft develops and there is no further development. In any case, the process of storm initiation is highly nonlinear: there is only a very brief intermediate stage between that of no convective clouds and that of deep convective clouds bearing precipitation (Crook 1996), just as there is no intermediate stage at all between air that is saturated and air that has condensation; air is not partially saturated and storms do not exist in a partially formed state, except perhaps for a very short length of time.

Convective storms can be initiated when air parcels are heated at the surface to their convective temperature, lifted to their LFC, or are both heated and lifted (Bluestein 1993). It is generally thought that synoptic-scale vertical motions ($\sim$1 cm s^{-1}) are not directly responsible for initiating convective clouds (because the vertical motions are so weak), but rather for preconditioning the environment (e.g., Rockwood and Maddox 1988). There are many cases in which sinking motion on the synoptic scale suppresses convective development (e.g., Richter and Bosart 2002), while rising motion can make the difference between the initiation of and the suppression of convection (Roebber et al. 2002). The reader is referred to Doswell and Bosart (2001) for further discussions on the relationship between synoptic-scale processes and convection. Mesoscale vertical motions (approximately 10 cm s^{-1}–1 m s^{-1}), on the other hand, are thought to be capable of both initiating convective clouds and modifying the local environment so that convection becomes possible or so that the type of possible convection is modified (Doswell 1987; Johnson and Mapes 2001). Mesoscale lift can decrease the convective inhibition, increase the convective available potential energy (CAPE), and moisten the air column.

Since surface boundaries are often the locations of mesoscale regions of upward motion, it is not surprising that convective storms often begin along boundaries. The precise nature of storm initiation is not understood, mainly because it is very difficult to observe clouds in the act of growing into storms, while at the same time collecting observational data on scales small enough to resolve the features associated with storm formation. While many field programs have addressed the problem of convective-storm behavior, not many have specifically addressed storm initiation. The International H_2O Project (IHOP) was conducted in the late spring and early summer of 2002 in the southern plains (Weckwerth et al. 2004). One of the goals of this project was to study storm initiation, with particular focus on the role of moisture variability. Because the results from this field experiment are still forthcoming, analyses of data from IHOP and significant findings are not available at the time of this writing for inclusion into this review paper. However, it is expected that there will be significant new findings, especially from the airborne (e.g., Murphey et al. 2003) and ground-based mobile multiple-Doppler radar analyses (e.g., Richardson et al. 2003; Ziegler et al. 2003) of the wind field, and analyses of the moisture field from dropsonde data and lidar data around boundaries, as convective storms were forming.

Because it is so difficult to use observational instruments to document all the meteorological variables during storm formation along boundaries, it is useful to employ numerical simulations. Numerical simulation studies of convective-storm evolution, however, often use unrealistic methods for triggering the storms. For example, in many idealized studies, unrealistically wide and highly buoyant thermal bubbles are introduced to initiate the storms and the environmental soundings must be moistened, especially at midlevels (e.g., Weisman and Klemp 1982). In models in which the nature of the heating and lift are explicitly modeled, the nature of the subgrid-scale turbulence parameterization must be called into question when the horizontal resolution is reduced below 1 km (Bryan et al. 2003).

3. Surface boundaries in the southern plains

The primary surface boundaries in the southern plains are fronts (cold, warm, and stationary), the dryline, troughs, and outflow boundaries. While frontal zones are usually located on the cold side of the axis of troughs, frontal zones also have a significant temperature gradient across them (Sanders 1999). Of these boundaries, the dryline is unique to the plains region. However, fronts and troughs also have characteristics unique to the plains, owing to their link to local topography. Also present, but perhaps underappreciated by the community, are discontinuities associated with surface sensible heat-flux gradients (Segal and Arritt 1992) and bores (e.g., Doviak and Ge 1984).

The characteristics of fronts and prefrontal troughs are discussed in detail elsewhere in this volume (Schultz 2008). Because convective storms often form along and just behind surface cold fronts (e.g., Crook 1987), it is important to understand how they behave. Cold fronts that frequent the southern plains are affected by the terrain, which slopes relatively gently upward to the west and then more steeply to the far west, along the Rocky Mountains. In particular, it has been hypothesized that many fronts that are zonally oriented propagate rapidly southward as either Kelvin waves or trapped density currents in the western regions of the southern plains (Bluestein 1993). Colle and Mass (1995) concluded, however, that they do not propagate as a result of rotationally trapped waves. If they propagate too rapidly, then convective cells that grow are removed from their boundary layer roots before they have had a chance to mature. On the other hand, for fronts that are meridionally oriented, extend southward from surface cyclones, and propagate toward the east, storm formation may, under some circumstances, be more likely.

The dryline marks the boundary between relatively cool, moist air of maritime origin and relatively warm, dry air of continental origin (Bluestein 1993). It may also be collocated with a trough axis (Fig. 1) (e.g., Bluestein 1993; Bluestein and Crawford 1997; Martin et al. 1995). Since convective storms often form near and just to the east of them (Rhea 1966; Ziegler and Rasmussen 1998; Ziegler et al. 1997), it is important to understand where they are located and how they move. A "quiescent" dryline is one not embedded in an environment of strong, synoptic-scale forcing. Such a dryline advances eastward during the day into the eastern Texas panhandle or western Oklahoma and retreats westward at night into the western Texas panhandle and eastern New Mexico (e.g., Ziegler et al. 1995).

When a dryline is influenced by strong synoptic-scale forcing (e.g., associated with a mobile, short-wave trough aloft), a surface cyclone can form and the dryline that extends to its south may then advance far to the east as the surface cyclone propagates away from the Rocky Mountain region (Carr and Millard 1985; Hane et al. 2001) (Fig. 2). Although the main mechanism through which a dryline propagates eastward during the day is vertical mixing, when there is strong synoptic-scale forcing, horizontal advection of dry air aloft is the

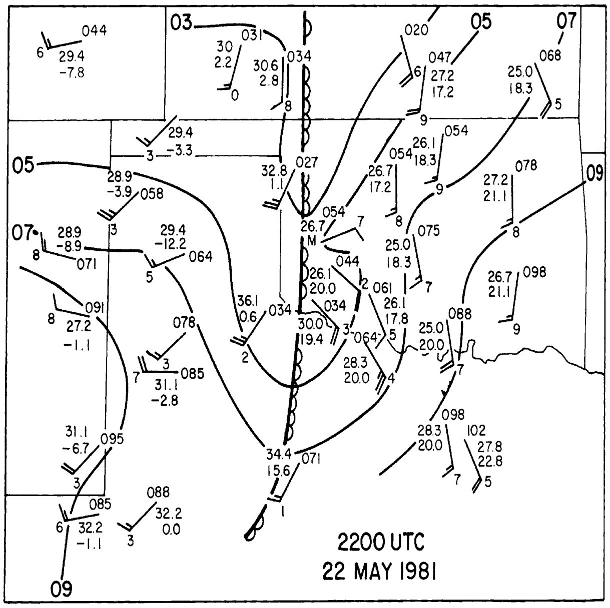

FIG. 1. The dryline, not under the influence of strong synoptic-scale forcing. The dryline, late in the afternoon, remains in far western OK. Analysis of surface pressure reduced to sea level as altimeter setting (solid lines, hPa, without the leading ''10'') around a dryline (scalloped line) at 2200 UTC 22 May 1981. Temperature and dew-point plotted in °C; whole (half) wind barbs = 5 (2.5) m s^{-1}. Tornadic supercells formed along the dryline and propagated eastward. From Bluestein (1993).

major reason why the dryline advances through vertical mixing so much farther to the east (Hane et al. 2001).

When there is a surface cyclone in the lee of the Rockies, formed in part from compressional warming in air flowing downslope and in part from synoptic-scale forcing associated with an upper-level trough, the dryline often intersects fronts at the center of the cyclone (Fig. 3). However, the dryline often intersects fronts even in the absence of strong synoptic-scale forcing; in this case, the surface cyclone is orographically forced (Bluestein and Parks 1983) (Fig. 3a). Sometimes the dryline intersects a front and there is no cyclone at the intersection point (e.g., Ziegler and Hane 1993). In other situations when there is no surface cyclone, but only a meridionally oriented trough associated with the dryline, an outflow boundary from earlier convection may intersect the dryline and behave like the intersection of a front with the dryline (e.g., Bluestein and MacGorman 1998; Bluestein and Gaddy 2001; Weiss and Bluestein 2002) (Figs. 3b and 4).

Maddox et al. (1980) have shown how the low-level vertical wind shear is enhanced just behind an outflow boundary, near its intersection with the dryline (Fig. 3d). This increase in vertical shear could be responsible for providing an environment more conducive for supercells (Weisman and Klemp 1982) and possibly for tornadoes. Even in the absence of a preexisting outflow boundary, an isolated convective storm that forms along the dryline and leaves behind an outflow boundary (as it propagates away from the dryline) could intersect the dryline to the west and set the stage for new supercells; in the absence of the outflow boundary from the preceding storm, it is possible that subsequent convection might not be as severe because the vertical shear would be weaker. In the case of low-precipitation (LP) supercells (Bluestein and Parks 1983), there would not be strong outflow because the potential for evaporative cooling is less.

Troughs not associated with fronts or the dryline [''baroclinic troughs'' (Sanders 1999)] may be classified as lee troughs when they have propagated away from the lee slopes of mountains (e.g., Karyampudi et al. 1995a) or ''prefrontal troughs'' when they are located just ahead of frontal zones (Fig. 5) (Hutchinson and Bluestein 1998), and ''inverted troughs'' (Keshishian et al. 1994), which are troughs in easterly flow, poleward of surface cyclones (Fig. 6).

Inverted troughs form in the lee of the Rocky Mountains and separate a relatively cold air mass dammed up along the eastern foothills of the Rocky Mountains from a modified (not as cold, because of a longer residence time away from its source) cold-air mass over the plains. Not much has appeared in the literature about convective-storm formation along these inverted troughs, probably because they tend to occur most frequently during the cold season and because the air to their east is not often susceptible to boundary-layer-based convection. Weisman et al. (2002) have shown how during the cold season, precipitation in general can be found on either side of the trough, but is much more common east of the trough. There are some instances in which ''inverted troughs'' are found north of the intersection of the dryline and an outflow boundary (Fig. 3a); these troughs might represent an extension of the trough found along the dryline, above the cool pool of air behind the outflow boundary.

Outflow boundaries separate evaporatively cooled air produced in convective-storm downdrafts (in which precipitation has fallen into unsaturated air) and ambient, warm air (e.g., Byers and Braham 1948; Young and Fritsch 1989; Stensrud and Fritsch 1993; Fritsch and Vislocky 1996). Outflow boundaries sometimes propagate as density currents, especially during their mature stages when they mark the leading edge of a deep cold pool. When they behave like density currents they are called gust fronts. Usually troughs are not found along outflow boundaries (Fig. 7) because air parcels do not reside along them long enough for earth's vorticity to be amplified significantly. Since the location and intensity of outflow boundaries are determined by the details of the spatial extent and intensity of prior convective storms, the location of outflow boundaries, unlike the location of fronts and the dryline, are not as easily well forecast. It is a significant challenge to predict the initiation of storms along an outflow boundary, especially before the convection producing the outflow boundary has broken out (Carbone et al. 1990). In many instances,

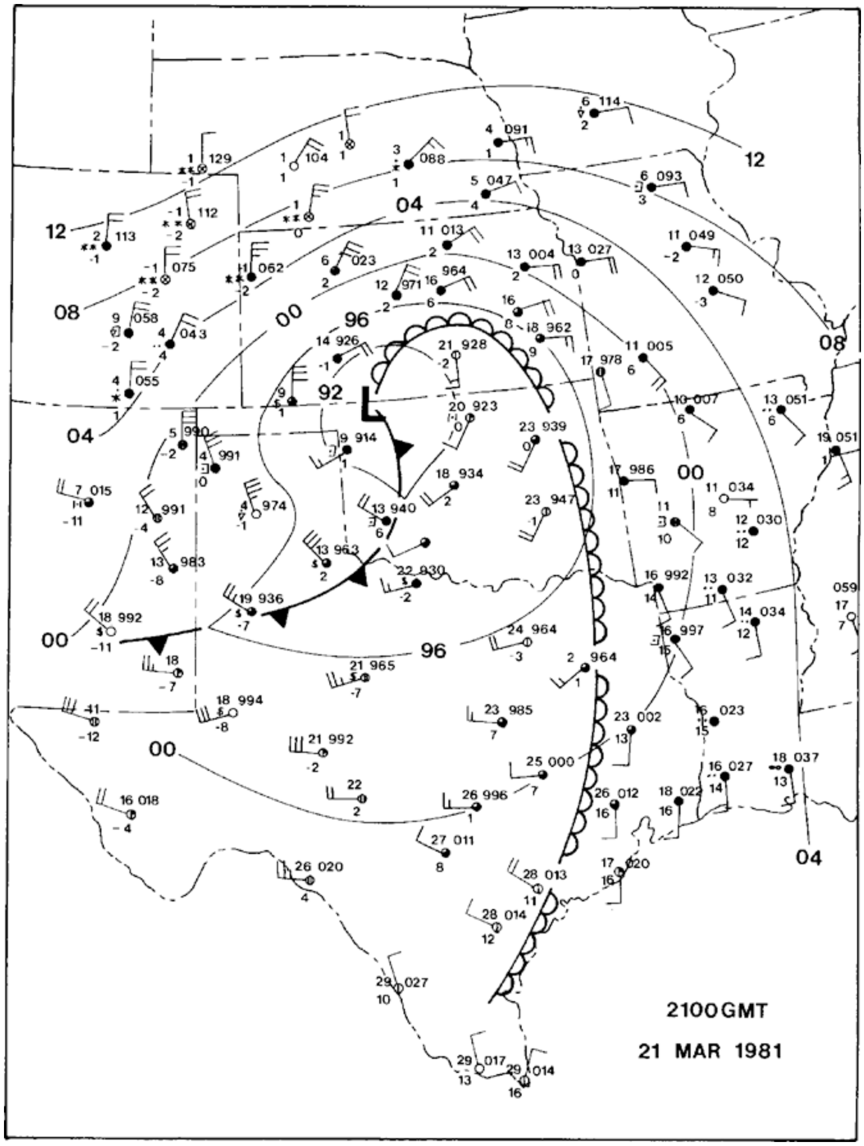

FIG. 2. The dryline, under the influence of strong synoptic-scale forcing. The dryline (scalloped line), during the afternoon, has pushed into eastern OK and TX. Analysis as in Fig. 1, but at 2100 UTC 21 Mar 1981; the reduced sea level pressure is plotted without the leading "9" or "10." Severe convection developed along the dryline and moved eastward. From Carr and Millard (1985).

convective storms have been initiated along outflow boundaries and they have gone on to produce tornadoes and other severe weather. In the absence of an outflow boundary, it is unlikely that any convection would have been triggered at all.

When outflow boundaries form in response to convective activity triggered along a front, the front may jump discontinuously ahead as a result of the cold surface air (Bryan and Fritsch 2000). The old surface front dissipates and a new one forms at the edge of the outflow boundary, as a midlevel front passes over the pool of cold air and reaches the leading edge of the cold pool.

Bores are boundaries across which the wind shifts but the temperature may or may not change. Bores are produced when a relatively dense fluid impinges on a low-level stable layer. In a bore, changes in temperature are produced through adiabatic vertical motions; no mass is transported and it is a type of a gravity wave. The passage of a bore is characterized by a wind shift that is accompanied by no drop in temperature or even an increase in temperature, while the passage of a gust front/density current is characterized by a wind shift that is accompanied by a drop in temperature. It is not, however, always easy to distinguish a bore from a density current (Simpson 1997) because there is in nature a continuum between flows that are pure bores and flows

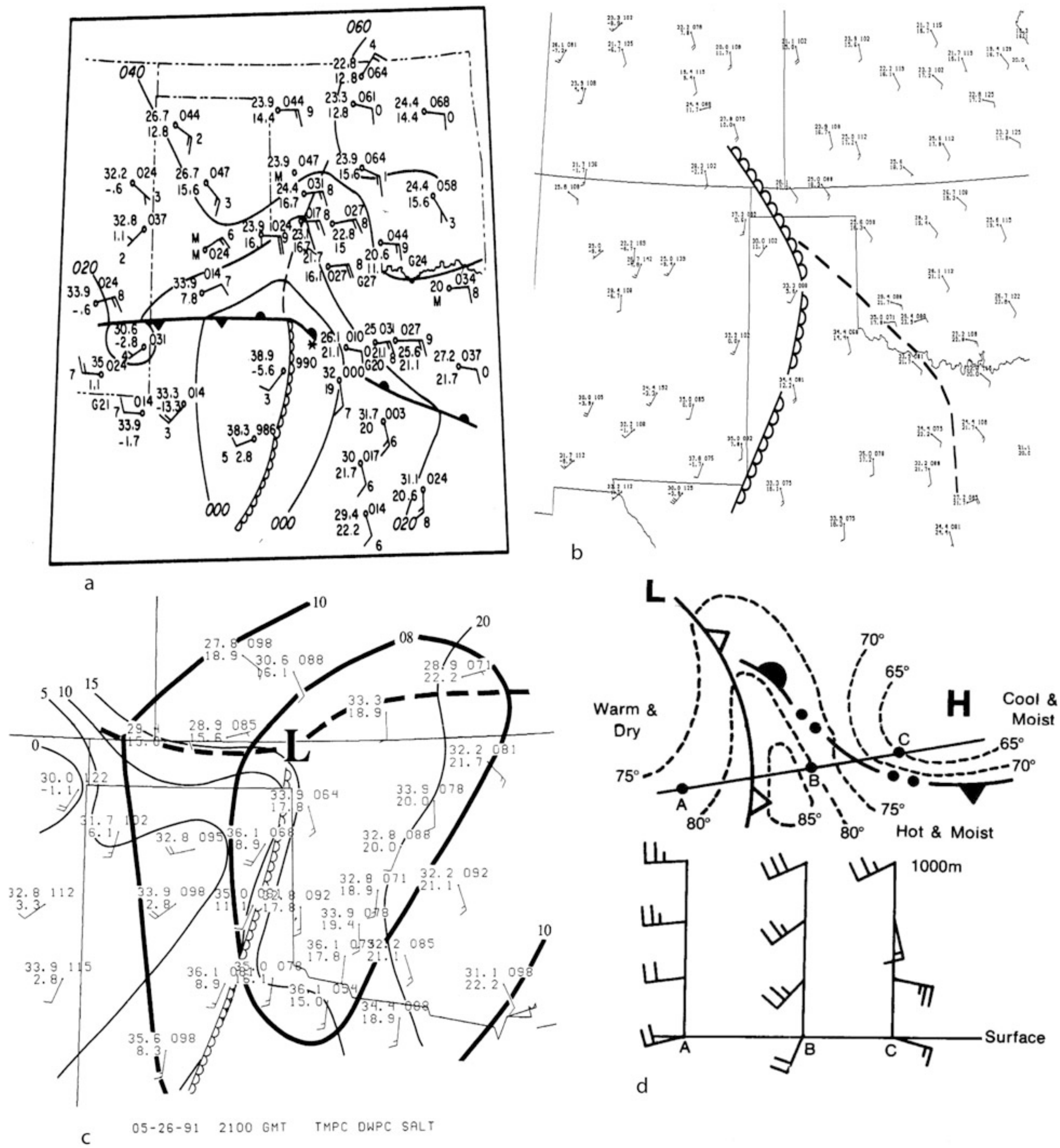

FIG. 3. Three examples of the intersection of the dryline with a front or outflow boundary, often at a surface cyclone, and an idealized depiction. In all cases, the only or the most significant convective storm was initiated near the dryline–front/outflow boundary intersection. (a) With little synoptic-scale forcing. An isolated supercell formed near the dryline–front intersection. Analysis of altimeter settings at 0000 UTC 17 May 1978. Temperature and dewpoint plotted in °C. From Bluestein and Parks (1983). (b) With little synoptic-scale forcing at 2300 UTC 31 May 1990. Series of isolated tornadic supercells formed near the dryline–outflow boundary intersection. From Bluestein and MacGorman (1998). (c) With significant synoptic-scale forcing at 2100 UTC 26 May 1991. A tornadic supercell formed near the intersection of the dryline and outflow boundary. From Hane et al. (1997). Analyses similar to those in Figs. 1 and 2. (d) Idealized depiction, including variation of vertical wind profile across the dryline (shown as a cold front symbol with open triangular barbs) and outflow boundaries. From Maddox et al. (1980).

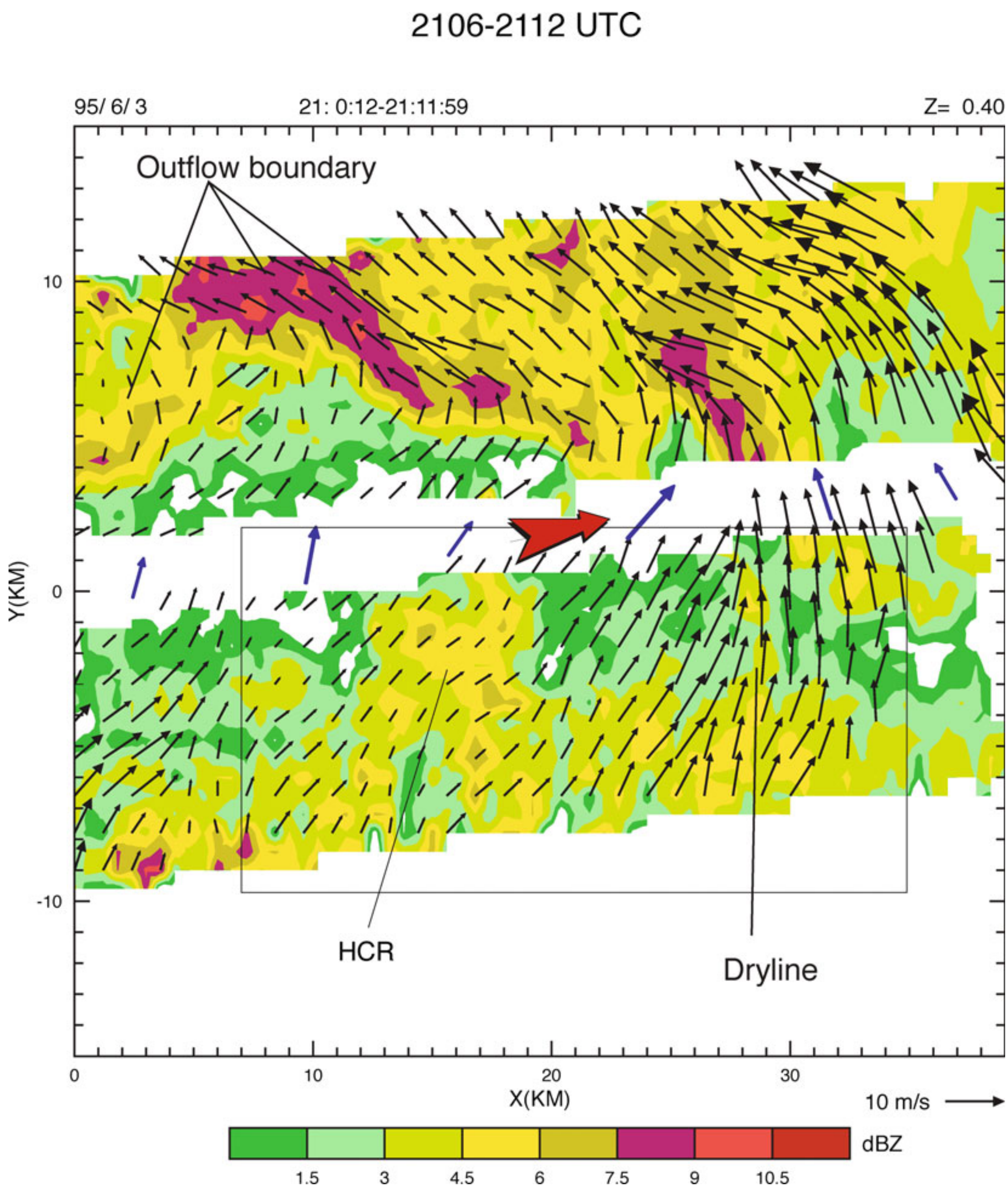

FIG. 4. Intersection of an outflow boundary with the dryline at 400 m AGL on the small scale in northwest TX, as depicted by wind (vectors) and radar reflectivity (color coded) based on data from the Electra Doppler Radar (ELDORA) from 2106 to 2122 UTC 3 Jun 1995. The red arrow depicts the direction of the Electra flight track, which coincides approximately with the data-free swath. The blue arrows along the track indicate in situ flight-level wind measurements. From Weiss and Bluestein (2002).

that are pure density currents. Haertel et al. (2001) argued that that density currents and gravity waves lie at the opposite ends of a spectrum of phenomena: bores, which are in the middle of the spectrum, are due partly to the advection of cold air that accompanies the pressure difference across a density current and partly to propagation that is associated with buoyancy as a restoring force.

4. Vertical circulations associated with surface boundaries

a. Frontal circulations

Vertical circulations are induced along fronts in response to changes in the across-front temperature gradient by deformation, convergence, and cross-frontal gradients in diabatic heating. [The reader is referred to

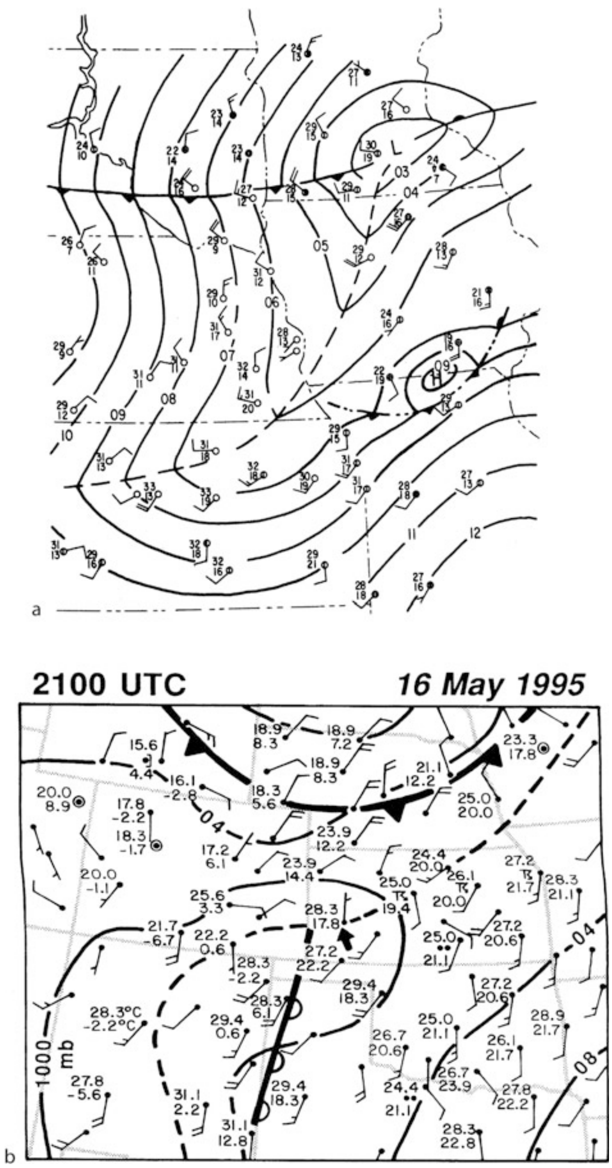

FIG. 5. Prefrontal surface troughs not collocated with a front or the dryline. (a) Surface isobars (solid lines) depicted every 1 hPa at 1900 UTC 4 Jun 1979. Temperature and dewpoint in °C. Severe convective storms formed along the trough. From Gaza and Bosart (1985). (b) Analysis of surface pressure (solid lines) at 2100 UTC 16 May 1995; temperature and dewpoint in °C. A tornadic supercell formed along the trough. From Wakimoto et al. (1998).

studies by Petterssen, Bergeron, Eliassen, and Hoskins and Bretherton, which are summarized in Bluestein (1993).] When the forcing is frontogenetical (frontolytical), a thermally direct (indirect) circulation is forced. The thermally direct circulation favors convective development because the upward branch of the circulation originates on the warm side of the front. A thermally direct vertical circulation forced adiabatically may be enhanced during the day (night) by diabatic heating when the air behind (ahead of) the front is cloudy (clear) (Koch 1984; Koch et al. 1995). In some instances, however, there is more surface moisture on the cold side of the front, especially when the surface air on the warm side of the front is of continental, not maritime origin, and the boundary layer is heated so that it is deep and surface moisture is diluted via mixing

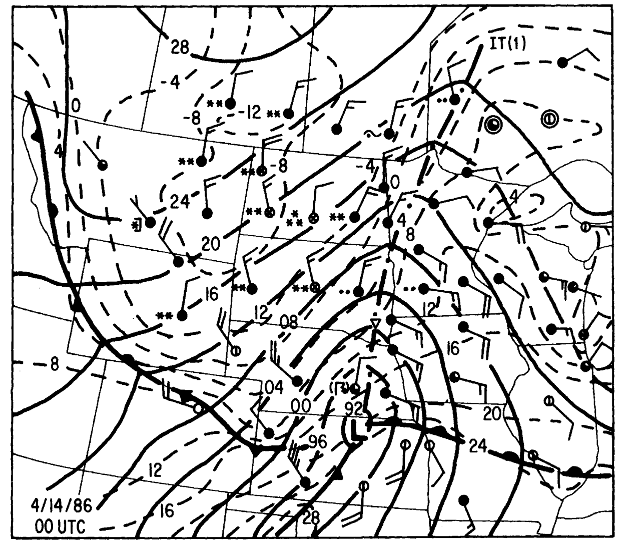

FIG. 6. Inverted trough extending northward from a surface cyclone. Analysis of sea level pressure at 4-hPa intervals at 0000 UTC 14 Apr 1986. Temperature and dewpoint plotted in °C. From Keshishian et al. (1994).

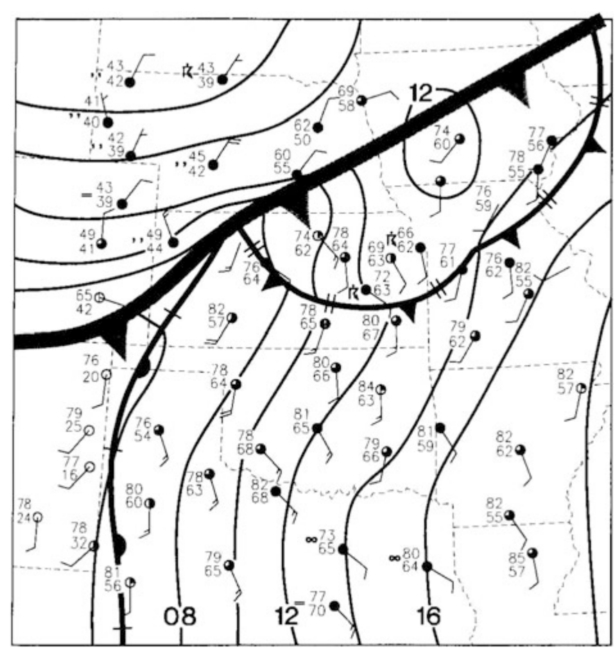

FIG. 7. Outflow boundary ahead of a cold front. Analysis of sea level pressure (hPa, solid lines) at 1800 UTC 11 May 1982. Temperature and dewpoint plotted in °F for emphasis. From Stensrud and Fritsch (1993).

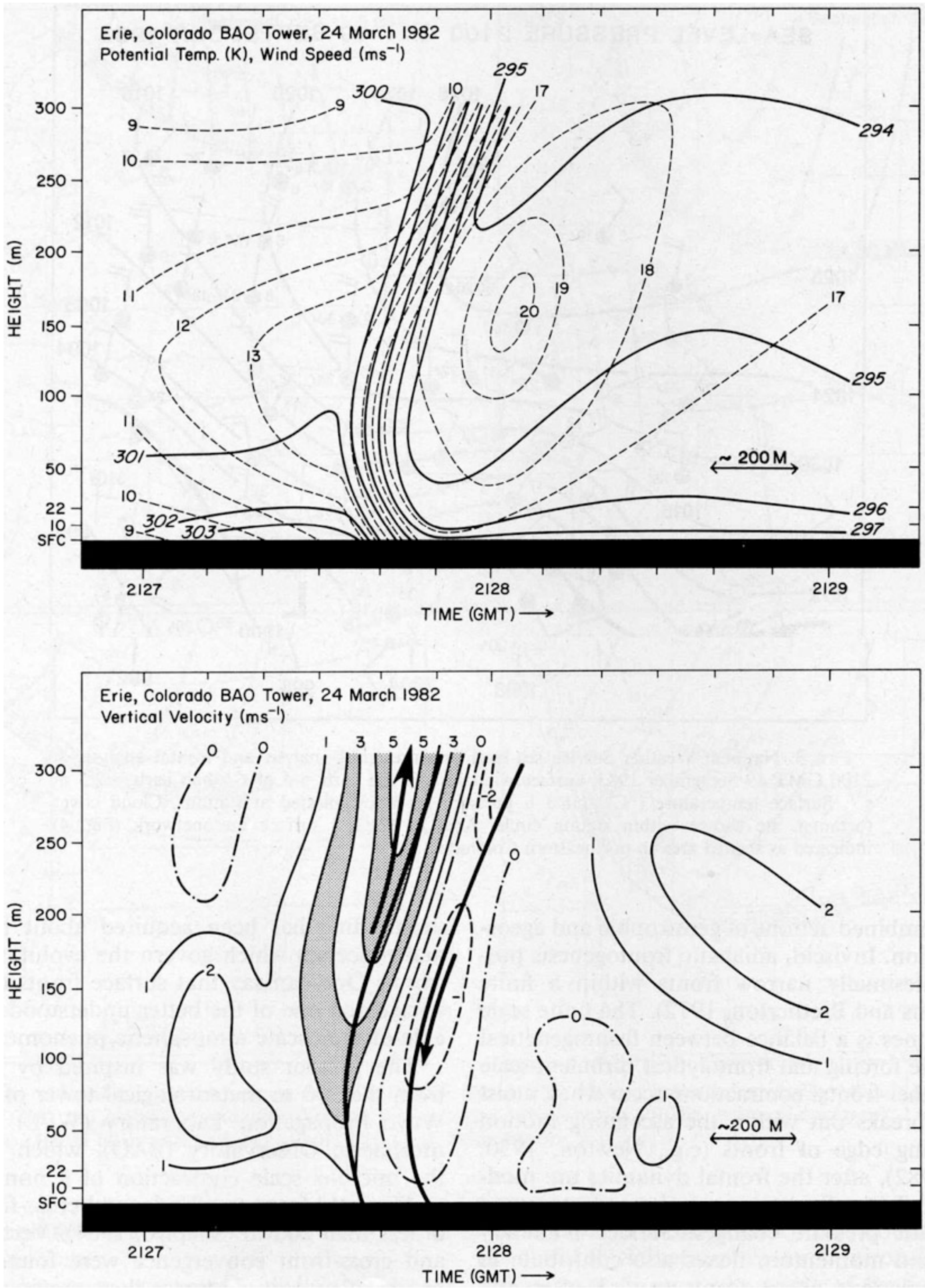

FIG. 8. Vertical cross section (via time-to-space conversion in the cross-front direction) through a front that behaved like a density current of (a) potential temperature and wind speed normal to the front and (b) vertical velocity. Data from the Boulder Atmospheric Observatory 300-m tower, 24 Mar 1982. From Shapiro et al. (1985).

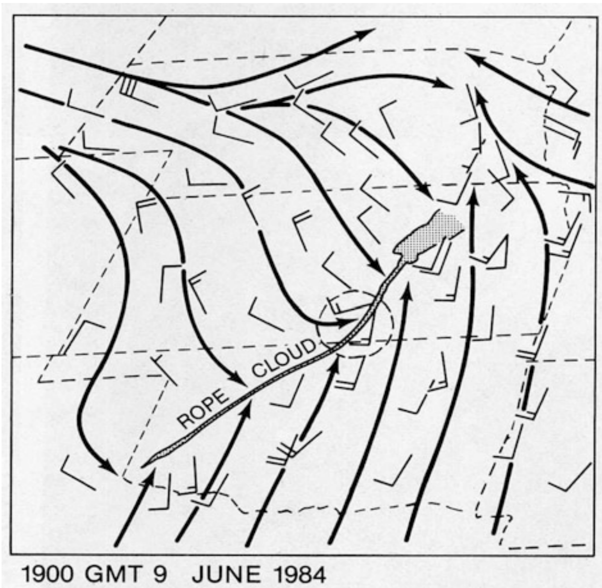

FIG. 9. Surface streamline analysis associated with a cold front and depiction of a rope cloud along it (cf. Fig. 10) where convection is being initiated at l900 UTC 9 Jun 1984. Full (half) wind barb = 5 (2.5) m s^{-1}. From Shapiro et al. (1985).

through a deep layer. In these cases, convection along the front may be suppressed.

When fronts behave like density currents (Fig. 8), the earth's rotation plays little or no role in forcing the vertical circulation at the leading edge of the front; the major forcing mechanism is the across-the-front (hydrostatic) pressure-gradient force. It is thought that fronts that are not associated with precipitation and that behave like density currents were formed through the collapse of the frontal temperature gradient through the convergent action of the ageostrophic vertical circulation (Shapiro et al. 1985). When precipitation falls on the cold side of fronts and evaporates into unsaturated air below, the density-current-like character of a front can be enhanced through differential diabatic heating (cooling on the cold side, no diabatic temperature changes on the warm side) (Browning and Pardoe 1973).

Fronts sometimes have properties of both semigeostrophic phenomena (i.e., those affected by earth's rotation such that the advection of momentum and heat by the ageostrophic components of the wind is significant and those for which their variations along the boundary can be ignored) and density currents, depending on how wide, deep, and intense the frontal zone is. Frontal zones on the order of 100 km behave semigeostrophically, while frontal zones on the order of 1–10 km behave like density currents if they are intense and deep enough. The magnitude of the lift along a density current (1–10 m s^{-1}) is greater than the lift associated with semigeostrophic processes (10 cm s^{-1}−1 m s^{-1}), and is therefore more efficient at initiating convection (Figs. 9 and 10).

Fronts propagating into a strong low-level inversion, such as that produced at night, can trigger a bore. For example, Karyampudi et al. (1995b) have discussed the role a prefrontal bore (e.g., Crook and Miller 1985) can play in triggering a squall line.

The difference in the ability of cold, warm, and stationary fronts to trigger convection is the difference in the trajectories of air parcels that are lifted along them. The front-normal relative surface wind speed and vertical motion are of most importance because they determine how long and how far air parcels are lifted. In the southern plains, it is an empirical observation (but not as yet rigorously proven through climatological analysis) that rapidly southward moving, zonally oriented cold fronts are not very efficient at initiating convection. On the other hand, zonally oriented stationary fronts are efficient at initiating convection. In the case of the former, air trajectories originating south of the front may not be lifted very much or very long; in the case of the latter, air parcels may be lifted substantially for a longer period of time.

b. Outflow boundary circulations

As air approaches an outflow boundary, it is lifted over it (e.g., Wilhelmson and Chen 1982; Bluestein 1993). The susceptibility of the air to reaching its LFC depends to a large extent on the depth of the outflow boundary and its intensity (i.e., temperature deficit). Rotunno et al. (1988), in what has come to be known as Rotunno, Klemp, and Weisman (RKW) theory, have shown how the magnitude of the vertical wind shear in the direction normal to the outflow boundary, and extending over the depth of the outflow boundary, plays a crucial role in determining how far air is lifted along a steady-state, frictionless density current of constant depth. The farther air is lifted, the more likely it will reach its LFC. When the rate of import of horizontal vorticity (associated with vertical shear) from the region ahead of the outflow boundary is counterbalanced by the baroclinic generation of horizontal vorticity at the leading edge of the outflow boundary, then it is most likely that the vertical circulation will remain erect and air parcels can be lifted to their LFC (Fig. 11a).

Xu (1992) also showed that the amount of lifting of air along an outflow boundary depends to a great extent on the magnitude of the vertical shear over the depth of the boundary layer (Fig. 11b). He demonstrated that when the shear is relatively weak, the depth of the density current head increases with shear (density-current relative wind speeds decreasing with height) and the flow is supercritical; the depth of the vertical excursion of air lifted over the boundary depends on the depth of the head. As the shear is increased, the flow may eventually become subcritical, and its depth decreases. In both Rotunno et al.'s (1988) and Xu's (1992) analyses, there is an optimal value of low-level vertical shear for which the chances for storm initiation are maximized.

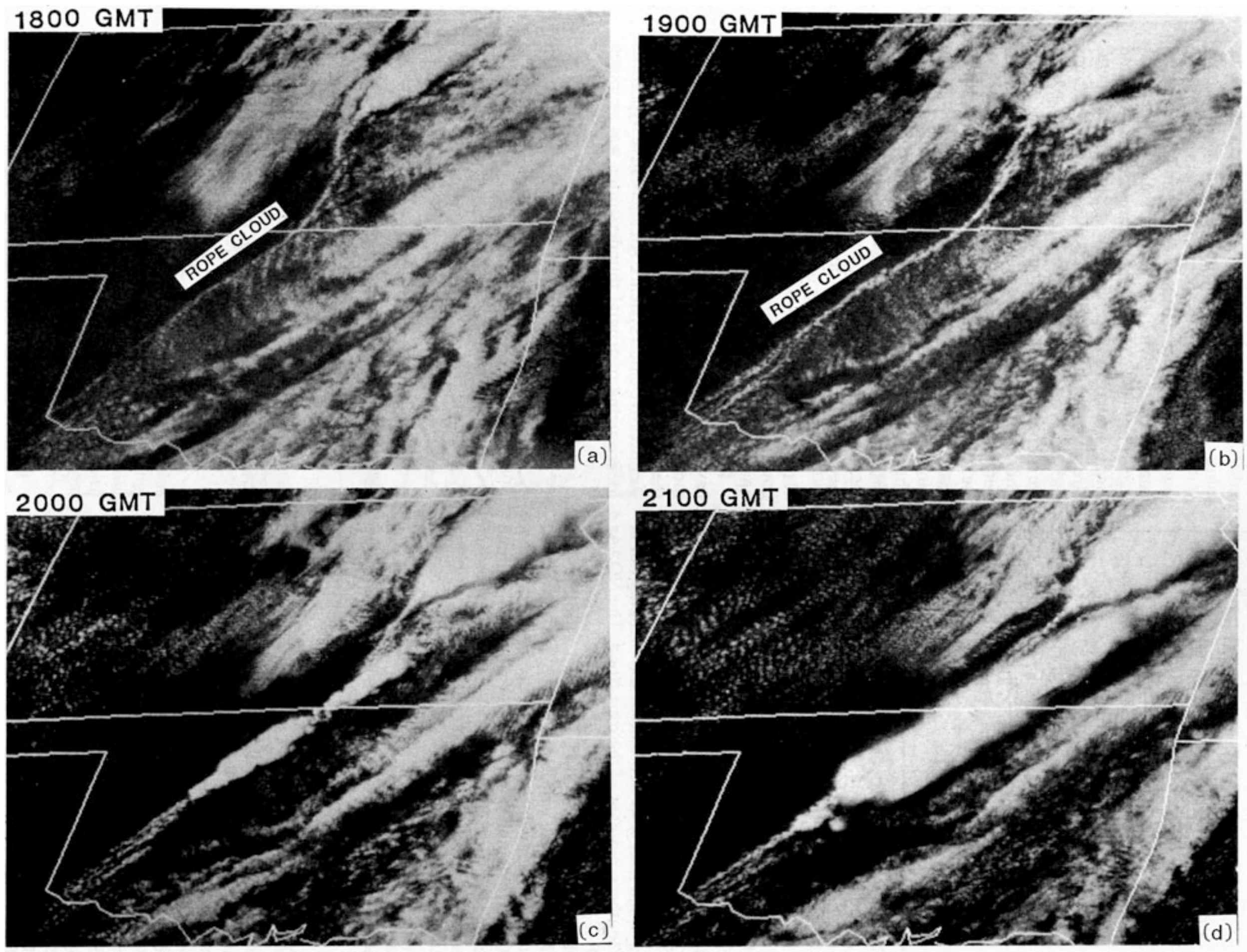

FIG. 10. Deep convection being initiated along a cold front on 9 Jun 1984 as viewed by National Oceanic and Atmospheric Administration (NOAA)/*Geostationary Operational Earth Satellite-5* (*GOES-5*) visible satellite images. From Shapiro et al. (1985).

When outflow boundaries impinge on an environment having a stable layer, a bore may be triggered (Doviak and Ge 1984; Fulton et al. 1990), especially at night when there is a nocturnal inversion. Rising motion associated with the bore may or not be able to initiate new convection. Such a process is similar to that described by Karyampudi et al. (1995b) for a front propagating into a nocturnal inversion.

c. Dryline circulations

1) INLAND SEA BREEZE

It has been proposed that the vertical circulation across the dryline is forced solenoidally by the horizontal gradient in diabatic heating across it, in the same way that a sea-breeze circulation is forced by the diabatic heating difference across a land–water interface (Sun and Ogura 1979; Sun 1987; Sun and Wu 1992; Bluestein and Crawford 1997). Such a circulation has therefore been given the oxymoronic name, the ''inland sea-breeze.'' The variation in the across-the-dryline heating may be caused by the nature of the surface vegetation and soil moisture (Grasso 2000). As convergence develops at the surface under the rising branch of the vertical circulation in response to the solenoidal forcing, both the temperature and moisture gradients will increase.

2) DENSITY-CURRENT-LIKE BEHAVIOR

The dryline may behave like a weak density current late in the day, when the difference in virtual temperature across the dryline is the greatest, which is when the virtual temperature is the highest on its west side (Parsons et al. 1991) (Fig. 12). It is possible that the inland-sea-breeze circulation, which had been acting much of the day frontogenetically to increase the surface density gradient, is the trigger that makes the density contrast at the dryline strong enough that it behaves like a density current.

The analysis of data from a scanning Doppler lidar during the Texas Frontal Experiment (TEXEX) in 1985

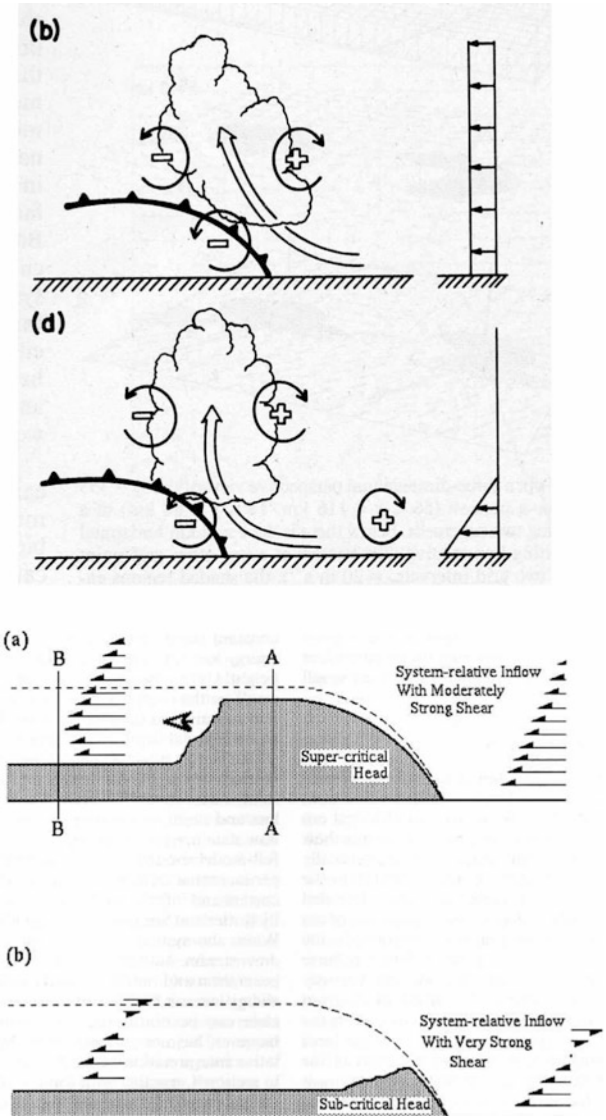

FIG. 11. Illustration of the effects of low-level vertical shear on the vertical circulation across a density current and on the shape of a density current. (top) RKW theory: density-current-relative horizontal wind depicted at the right. (top, b) When the shear is zero air is lifted at a relatively low angle with respect to the leading edge of the density current (cold-front symbol). (top, d) When there is shear directed in the same direction as the motion of the density current the air is lifted at a steeper angle. The sense of horizontal vorticity associated baroclinically with the leading edge of the density current and the edges of the buoyant cloud/updraft, and associated with the environmental low-level shear, are shown by curved arrows and plus signs (into the figure) and minus signs (out from the figure) according to the right-hand rule. From Rotunno et al. (1988). (bottom) Shapes of head of a density current when the shear is (a) moderately strong and in supercritical flow, and (b) very strong and in subcritical flow. (bottom, a) The head is deep and (bottom, b) the head is shallow. From Xu (1992).

shows air being lifted up and over the cooler, westward-retreating air on the east side of the dryline during the early evening (Fig. 13a). The lifting was as intense as 5 m s^{-1}. Atkins et al. (1998), using airborne data from

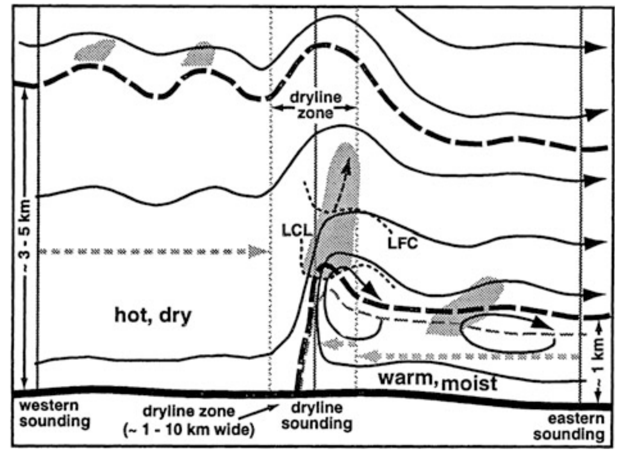

FIG. 12. Conceptual model of convection initiation along the dryline. Vertical cross section depicting streamlines and clouds; lower heavy dashed line represents the extent of the moist, convective boundary layer; the upper heavy dashed line represents the top of the deep, dry convective boundary layer west of the dryline and the top of the elevated ''residual'' layer east of the dryline (above the moist layer). The heavy dashed streamline represents a buoyantly accelerated cloudy air parcel trajectory. From Ziegler and Rasmussen (1998).

the Verification of the Origin of Rotation in Tornadoes Experiment (VORTEX) in 1995, also showed how the vertical circulation along the dryline (in Texas) can behave like that associated with a density current (Fig. 13b). More recently, the analysis of a scanning, mobile, W-band Doppler radar during IHOP in 2002 shows lift on even finer scales (Fig. 14). It is not thought that the slope of the terrain over the high plains is high enough to slow down significantly the upslope retreat of the cool, moist air mass (Parsons et al. 1991). A significant tornado, which struck Lubbock, Texas, on 11 May 1970, was spawned from a storm initiated along a retreating dryline (Fujita 1970).

When a density current impinges on a stable layer, such as a nocturnal inversion, a bore may be triggered. Wakimoto and Kingsmill (1995) described a case in which a sea-breeze front collided with a gust front and generated a bore. The sea-breeze current undercut the gust front and the bore propagated against the ambient flow in the stable layer associated with the cold pool from the sea-breeze air mass. It is therefore possible that a dryline, which behaves like a density current, could trigger a bore if it collided with a gust front.

3) GRAVITY WAVE MOMENTUM MIXED DOWNWARD BEHIND THE DRYLINE

Koch and McCarthy (1982) have presented evidence of waves along the dryline and shown how they might be associated with convective development. Sanders and Blanchard (1993) found periodic fluctuations in the dryline (Fig. 15a) during Oklahoma–Kansas Preliminary Regional Experiment for Storm-scale Operational and

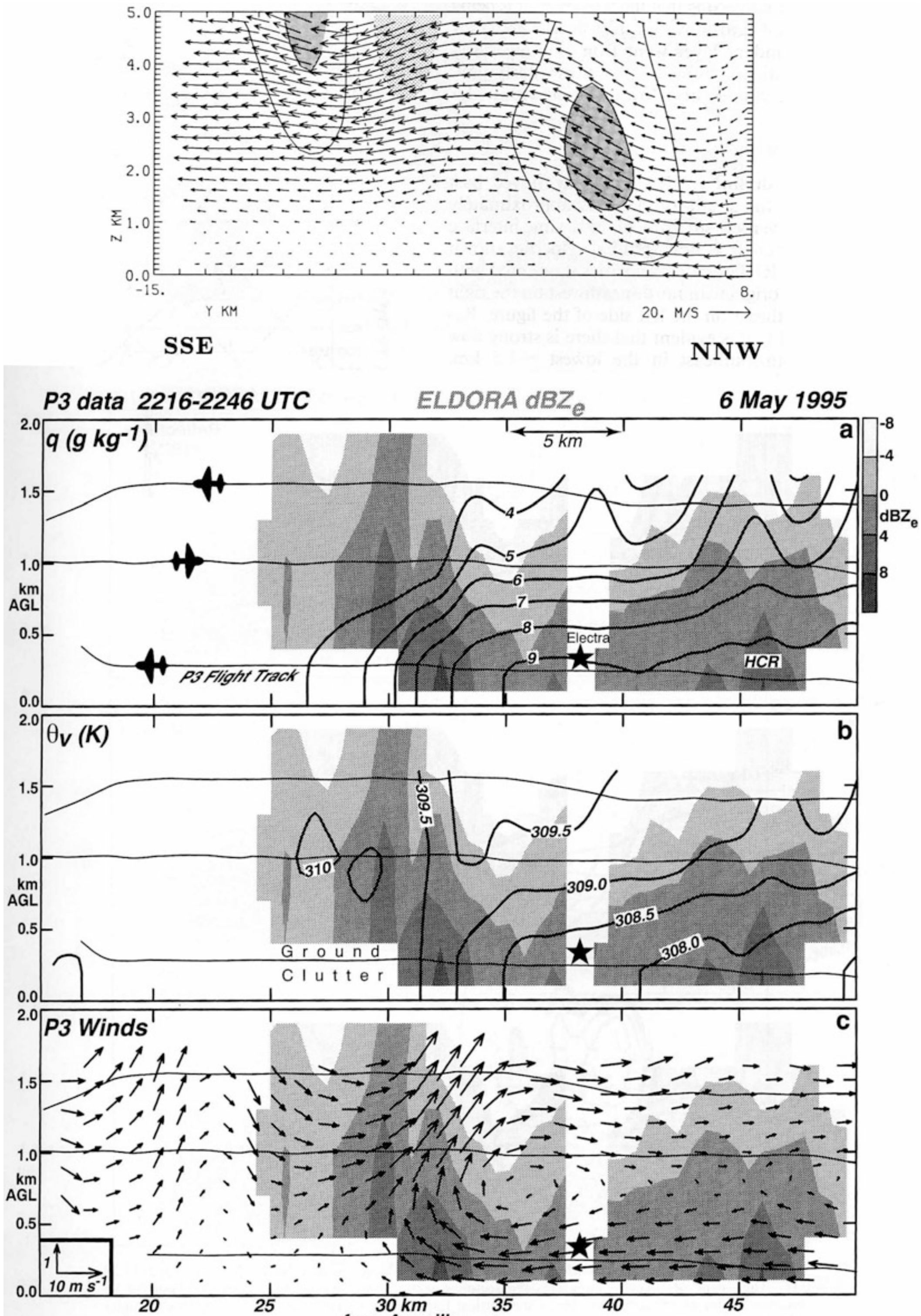

FIG. 13. Density-current-like vertical circulations at the edge of the dryline as shown in vertical cross sections of wind. (top) Dryline-relative wind vectors and contours of vertical motion based on data from a scanning Doppler lidar. The solid and dashed lines indicate vertical motions (upward and downward, respectively) greater than 1 m s^{-1}. The shading indicates vertical motions in excess of 4 m s^{-1} and the stippling indicates vertical motions less than -4 m s^{-1}. Analysis for 0100 UTC 22 Apr 1985, at Midland, TX. From Parsons et al. (1991). (bottom panels) Analysis of (top) water vapor mixing ratio, (middle) virtual potential temperature, and (bottom) winds from a NOAA P-3 aircraft from 2216 to 2246 UTC 6 May 1995 in west TX. Shaded regions represent radar reflectivity field from ELDORA. The thin black line marks the P-3 flight track and the star indicates the position of the Electra aircraft. From Atkins et al. (1998).

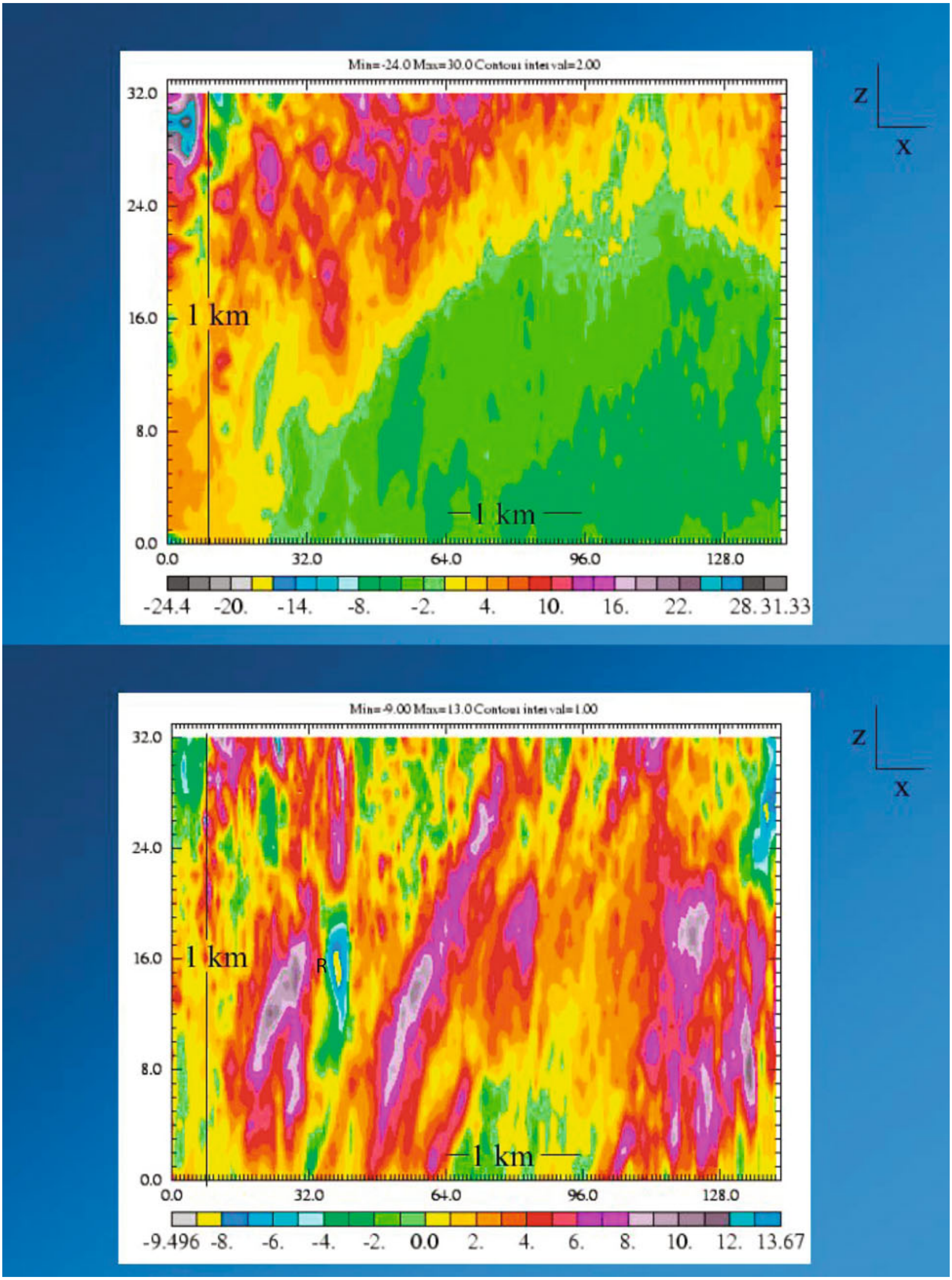

FIG. 14. Analysis of vertical cross section of the (top) ground-relative wind component normal to the dryline [m s^{-1}; positive (negative) speeds denote a westerly (easterly) wind component] and (bottom) vertical velocity (m s^{-1}) at 0007–0036 UTC 23 May 2002 in the Oklahoma Panhandle. The wedged-shaped dryline boundary is located approximately along the yellow–green interface. The spacing between each numbered tick mark along the abscissa and ordinate represents 30 m. The ''R'' denotes the center of a rotor circulation. Based on data collected by a truck-mounted, W-band Doppler radar (Weiss et al. 2003). Courtesy of C. Weiss.

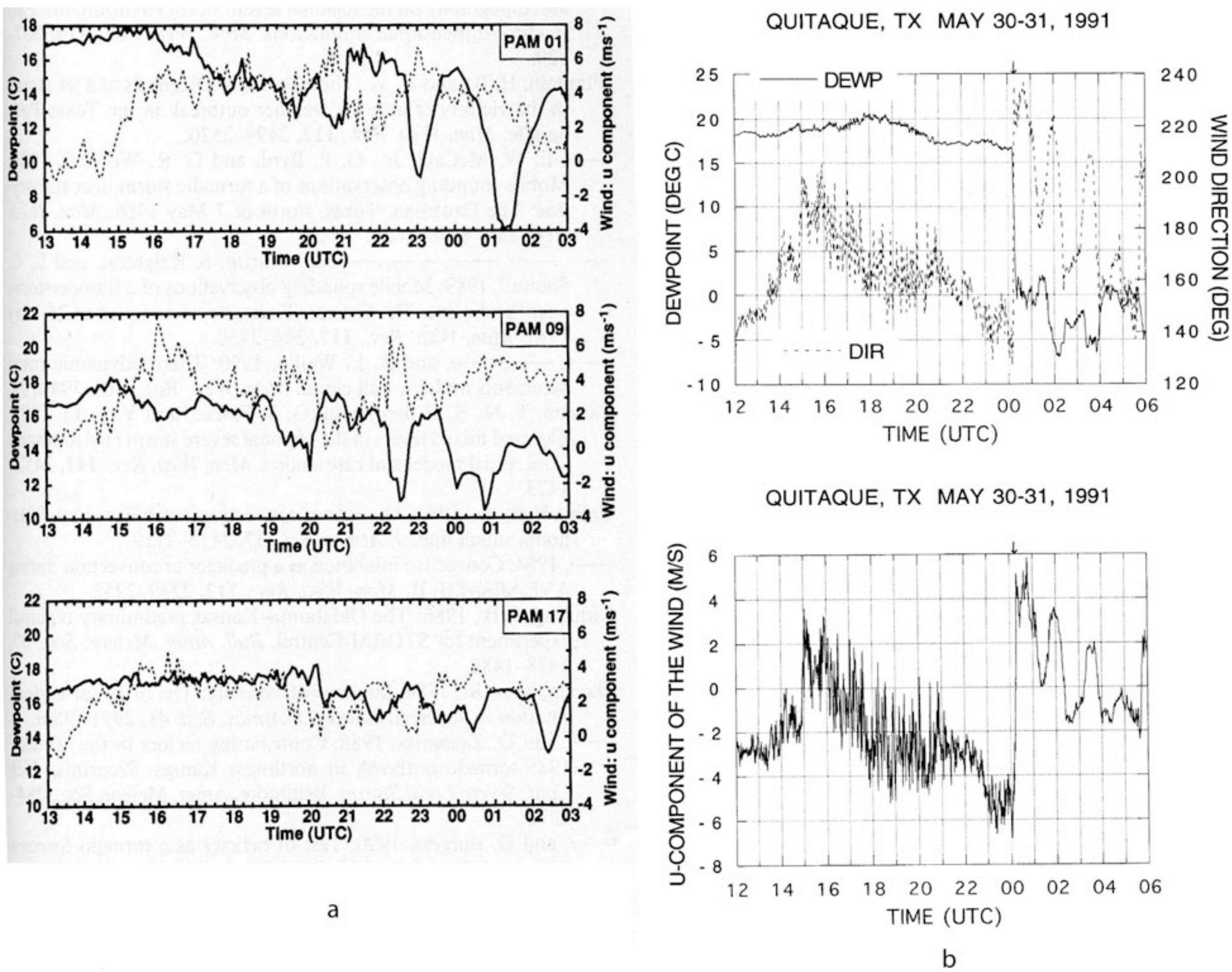

FIG. 15. Oscillations in the dryline-normal wind component and the dewpoint near the dryline. (a) Zonal wind component (dashed line) and dewpoint (solid line) at surface mesonet stations as a function of time on 10–11 May 1985. Note how the dewpoint in general rises (drops) when the zonal wind component decreases (increases) with a periodicity of around 2–3 h. From Sanders and Blanchard (1993). (b) Wind direction (dashed line) and dewpoint (solid line) are shown in the top panel and the zonal component of the wind is shown in the bottom panel. Note also how zonal wind speed and changes in wind direction are correlated with changes in the dewpoint. From Crawford and Bluestein (1997).

Research Meteorology (O–K PRESTORM) in 1985, which were associated with convective development. The fluctuations were associated with mesoscale waves having a wavelength of about 200 km, and were thought to be forced in the exit region of a jet streak. Crawford and Bluestein (1997), during Cooperative Oklahoma Profiler Studies (COPS-91), also documented similar periodic fluctuations along the dryline, though they were not necessarily associated with convective development. The wind periodically backed and the dewpoint rose, while later the wind veered and the dewpoint dropped, and so on, with a period of a few hours (Fig. 15b). It was hypothesized the waves were caused by gravity waves generated in the upper troposphere and their momentum mixed down to the surface in the deep dry-adiabatic layer to the west of the dryline.

4) "SIX-O'CLOCK MAGIC"

Storm chasers have noted that the initiation of convection along the dryline in the southern plains of the United States is often delayed until about 6 P.M. local time. (There is anecdotal evidence that such a delay is observed elsewhere, also.) When storms have not been initiated by then, it is not likely that they will form later that day or early evening. This empirical behavior is colloquially known as "6-o'clock magic." It has been shown, using a mixed-layer model, that behavior like the six-o'clock magic phenomenon may be associated with a local maximum in the height of the inversion that caps the moist air east of the dryline around dusk (Jones and Bannon 2002), when the daytime eastward movement of the dryline has ceased and its westward movement begins. A "spike" in inversion height (Fig.