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**A New Theory for Diabatically-Induced Along-Stream Jet/Front
Formation and its Role in Severe Weather**

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I. Overall Research Summary

During the course of this contract, a great deal of analysis, synthesis, and writing was undertaken in an effort to construct a general theory of how along-stream frontogenetical/jetogenesis processes create an environment conducive to severe convection. After performing numerous mesoscale simulation experiments for three different case studies, i. e., the 27-29 March 1984, 11-12 July 1981, and 27-28 March 1994 case studies the patterns are coalescing which are apparent in all three case studies. These patterns indicate how mesoscale mutual mass/momentum adjustment processes organize along-stream jet/front systems and how said systems produce the vertical wind shear and instability necessary for severe convection. These patterns can be employed to construct a paradigm of how a hydrostatic environment conducive to severe weather eventually evolves over the central and eastern U. S. when synoptic scale jet streaks are juxtaposed over the Rocky Mountain west particularly, but not exclusively, during the spring and summer months.

It is important to realize that these frontogenetical mechanisms are inherently ageostrophic. This differs from most classical studies of frontogenesis where the total wind is similar to the geostrophic wind in magnitude and direction. During geostrophic frontogenesis, confluence and tilting mechanisms are controlled by the rotational rather than the divergent wind. Furthermore, frontogenesis is favored in the entrance region of a straight jet stream rather than its exit region. Therefore, the orientation of the mid-upper tropospheric front is primarily parallel to the jet stream. This is because the long period motion of air parcels is controlled by the Coriolis force and the confluence and tilting motions which produce geostrophic frontogenesis have long time periods over which to operate which is conducive to highly rotational trajectories analogous to the motions in the rotational jet streams. We will be simulating frontogenetical processes where the ageostrophic, and hence, highly accelerative wind dominates at the mesoscale and where air parcels are rapidly stretched rather than rotated producing temperature variations in both the along and cross stream directions. Therefore, the orientation of the fronts are primarily orthogonal to, as opposed to across, the jet streams. Furthermore, since the accelerative flow is within the exit region of the preexisting synoptic scale jet stream, the along-stream circulations which develop are unbalanced, in the sense that the jet is intensifying in magnitude in the exit region rather than decelerating which is typical for a balanced cross-stream oriented jet/front system.

II. Case Studies and Fundamental Methodology

We will emphasize the three aforementioned case studies in our analyses. The first is the 27-29 March 1984 "Carolina" tornado outbreak case study (Gyakum and Barker 1988; Kuo et al. 1995; Gyakum et al. 1995; Rozumalski et al. 1998). This case study is famous for both severe weather and multiple explosive subsynoptic scale cyclogenesis events. The second case study is the well-known sequence of observed gravity wave episodes accompanying the CCOPE experiment in Montana during July 11-12, 1981 (Koch and Golus 1988; Koch et al. 1988; Koch and Dorian 1988; Koch et al. 1993; Kaplan et al. 1997). Not only were there several gravity waves observed on these days but also a massive mesoscale convective system developed which produced severe weather. The third case study occurs on the day of the devastating Palm Sunday tornado outbreak in Alabama and Georgia, i.e., 27 March 1994 (Hamilton et al. 1998; Kaplan et al. 1998). These three (primary) case studies comprise the bulk of the research performed over the three year time period. In addition to these three case studies, the aforementioned analyses were compared to previous research performed on three (secondary) case studies, i. e., (1) the 14-15 December 1987 intense midwest cyclone/gravity wave case study, (2) the 27-28 November 1988 Raleigh tornado outbreak case study, and (3) the 3-4 January 1994 Atlantic coast cyclone/gravity wave case study. The fundamental research methodology involved performing a literature review on the three primary case studies followed by additional indepth diagnostic analyses of synoptic and mesoscale observational datasets which had not, heretofore, been analysed in the published literature. Following this, several mesoscale numerical simulation sensitivity studies were performed varying grid resolution, initial conditions, and physics sensitivity experiments. The numerical models which were employed for these experiments included: (1) the Mesoscale Atmospheric Simulation System (MASS) (Kaplan et al. 1997), (2) the North Carolina State University Geophysical Fluid Dynamics Model (NCSUGFDM) (Lin and Wang 1996; Weglarz, 1994), and (3) the Penn State-NCAR MM5 model (Dudhia 1993). MASS and MM5 were initialized with the most comprehensive three-dimensional data sets available, which were derived from NWS LFM and NCAR Reanalysis Data Set gridded analyses, rawinsonde data, and surface data. The NCSUGFDM model was employed for the simulation of and analyses of idealized adjustment processes and, hence was initialized with more idealized initial conditions.

III. Synopsis of the New Theory/Paradigm for Diabatically-Induced Along-Stream Jet/Front Formation and its Role in Severe Weather

(1) Basic Synoptic Scale Environment

The precursor environment typically requires two jet streams in proximity to the Front Range of the Rocky Mountains. As can be seen in Figure 1, when the exit region of one jet stream, typically the subtropical jet stream, and the entrance region of another jet stream, typically the polar jet stream, are closely aligned, the low-level return branch circulations transport air masses of very different origin in proximity to one another, i. e., hot continental air and cold polar air, respectively by the subtropical jet and the polar jet. When this occurs in proximity to the Rocky Mountains, the blocking action of the terrain interrupts the downstream propagation of a jet streak most dramatically at midtropospheric levels. Thus, the wind and mass field in the mid-upper troposphere become differentially decoupled from the low-level return branch circulations under the jet streaks and quasi-geostrophic balance is interrupted. Furthermore, the low-level mass field is perturbed by the mountains as cold polar air cannot be advected eastward by the synoptic scale flow and is constrained to plunge southward along the immediate edge of the high terrain. The Rocky Mountains act to accentuate the surface sensible and compressional heating in the continental air due to the elevated nature of the high terrain and the effects of downslope flow. This further decouples the jet streak wind field over and near the mountains from its supporting lower tropospheric mass field. Thus, cold polar air, blocked in its eastward movement, flows southward parallel to the mountains rather than eastward and a reservoir of hot continental air is pooled as it flows down the Front Range of the Rockies in proximity to the southward-flowing polar air. Since the jet streaks are restricted in their eastward motion by the terrain barrier, there are numerous likely imbalances created between the pressure and wind fields throughout the lower-middle troposphere. This imbalanced flow results in rapid adjustment between the mass and momentum field. The stronger the background jet streams, the more intense the adjustments. All of these processes act in consort to disrupt quasi-geostrophic balance, forcing the jet streak exit region to lie above a mass field which is inconsistent with the perturbed wind field. Along-stream jet/front systems are the byproducts of these misphased wind and pressure systems wherein quasi-geostrophic balance is restored by very complex circulations.

(2) Geostrophic Adjustment Producing an Along-Stream Jet/Front System - Fundamental Adjustment Mechanism #1

The first, in a sequence of along-stream jet/front systems, forms as the mass field adjusts to the wind field over the lee slopes of the elevated terrain. The lee slope of the elevated plateau is a place where the mass field is changing from the low levels upward forcing an inconsistency with the southeastward propagation of the synoptic scale jet as it propagates over the mountains. Since the upper-tropospheric jet stream is less restricted in

its progress over the mountains than it is at midlevels and since a pool of hot continental air forms at midlevels to the lee of the mountains which is most pronounced in spring and summer, vertical wind shear develops to the lee of the mountains above a very warm, unstable, and hydrostatically thick column. The thickness perturbation reflecting the deep hot continental air pool is formed by elevated surface sensible heating and downslope compressional flow above the arid terrain. As the upper-tropospheric jet propagates downstream over the leeside of the elevated plateau, downward momentum transport occurs due to sinking motions within the jet's exit region. This downward transport of horizontal momentum enhances the horizontal wind shear within the exit region of the jet streak. This is caused by the rapid advection of high kinetic energy air parcels away from and to the right of the geostrophic wind maximum over the mountains. This produces the inertial-advective transport of kinetic energy into a region where a thickness perturbation exists above the hot air within the elevated leeside boundary layer resulting in a mass field which is no longer in geostrophic balance with the wind field, i.e., a mass field which contains a positive thickness perturbation. *In effect, the total wind exit region of the synoptic scale jet and geostrophic entrance of the mesoscale jet accompanying the mass perturbation phase producing a thermally-direct unbalanced circulation with rising motions in the right exit region of the large scale jet and sinking motions to its right flank* (note Figures 3 and 4). The result is the development of mass flux divergence in the region in between the mass and momentum perturbations where the jet exit region has been advected away from its upstream balanced pressure gradient. The ensuing velocity divergence and convergence fields create mesoscale ascent and descent maxima within the jet's exit region. This represents an internal adjustment within the atmosphere to produce geostrophic equilibrium between the renegade wind and perturbed pressure fields. The adiabatic cooling and warming aloft are acting to modify the thickness fields and pressure distribution, thus restoring thermal wind and quasi-geostrophic balance. The result of these adjustments is a jet/front system aligned primarily along the stream as can be seen in Figures 2 and 3 for the 27-29 March 1984 and 11-12 July 1981 case studies, respectively. This mesoscale front is the result of unbalanced adjustments wherein the advection of geostrophic momentum and the advection of total momentum are misphased resulting in a thermal wind imbalance at subRossby radius of deformation length scales. As can be seen in Figure 4, unlike quasi-geostrophic frontogenesis, tilting and ageostrophic confluence dominate as the front forms in the exit region of the jet stream rather than its entrance region. Furthermore, it is important to note that numerical sensitivity studies have shown that in the absence of the leeside surface sensible heating perturbation, said jet/front system never develops. Hence, there is a critical role for boundary layer diabatic heating in this

process because said surface sensible heating enhances the exit region mass perturbation. Additionally, during this type of frontogenesis, a fold (note Figure 5), analogous to the tropopause ozone fold rich in potential vorticity, can occur downstream within the new jetlet's exit region in proximity to moist convectively unstable air rather than above dry stable air upstream under the jetlet's entrance region, thus enhancing the environment for the development of severe convection.

(3) Geostrophic Adjustment Producing an Along-Stream Jet/Front System - Fundamental Adjustment Mechanism #2

The development of the aforementioned along-stream jet/front system #1 represented a mass adjustment to the perturbation of the wind field. Consistent with this is the necessity of the wind field to somewhat less rapidly adjust to this new mass perturbation. However, this adjustment is very strongly forced by a variety of processes triggered during (2), above. When the midtropospheric mesoscale unbalanced front forms it triggers a sequence of lower tropospheric compensating adjustments. Most notable is the development of a mesoscale surface low pressure area and a lower tropospheric wind maximum within the hot pool of air which forms along the lee slope of the topography. In effect, underneath the mesoscale unbalanced front, falling pressures accelerate a low-level southwesterly jet. In an effort to restore thermal wind balance, the low-level mass and momentum fields are adjusting to the mid-upper tropospheric wind and pressure changes. As the hot air pool is advected downstream by the new low-level jet, the decreasing surface pressure causes the leeside polar cold pool to accelerate southward as a low-level northerly jet forms. The net effect of these adjustments is to increase the cross-stream temperature gradient within the lower troposphere and enhance the surface cold front. This results in an enhanced cross-stream thickness gradient and an enhanced leftward-directed lower-middle tropospheric pressure gradient force. As air parcels within the region of increasing cross-stream pressure gradient, accelerate in a leftward direction across the stream, a new midtropospheric wind maximum forms to the north of the low-level hot continental pool of air and to the south of the polar air. In essence, a new jet streak is forming east of the mountains to compensate for the leeside mass perturbations. The mountain-plains solenoid formed along the lee slope is being transported downstream away from the mountains. The sequence of jet formation can be seen depicted in Figure 6 for the 27-29 March 1984 case study. The generation of midtropospheric kinetic energy as the wind adjusts to the modified mass field is so rapid that the new jet is comprised of ageostrophic divergent kinetic energy. Accompanying said kinetic energy is highly confluent flow which acts to induce a new along-stream front as the warmer air is converging ahead of the intensifying jet. This

new jet/front system also has a significant along-stream component as a result of the ageostrophic confluent flow within its new exit region. Again, the highly ageostrophic confluent nature of the flow enhances the jetlet's exit rather than entrance region frontogenesis. Furthermore, tilting occurs within the new jetlet's exit region producing a rightward-shifted cold pool of air above the warm low-level continental air mass (note Figure 7). This cold pool of air is available to destabilize the warm moist air which it encounters in its downstream transport therefore enhancing the likelihood of convection.

(4) Geostrophic Adjustment Producing an Along-Stream Jet/Front System - Fundamental Adjustment Mechanism #3

As the wind adjusts to the mass field during jetogenesis, the advection of total momentum and the advection of geostrophic momentum are not perfectly superimposed. This results in an unbalanced exit region circulation where cooling due to adiabatic expansion occurs on the right front side of the new jet streak. This enhances the along-stream temperature gradient and also acts to destabilize the region where the hot dry continental air is advected over the air of Gulf of Mexico origin within the boundary layer. Figure 8 depicts model-simulated trajectories for the preconvective period of the 27-29 March 1994 Palm Sunday tornado outbreak. In this figure one can see potentially very warm air originating from the elevated Mexican Plateau at 700 mb being transported over potentially cooler air at lower levels originating from the Gulf of Mexico. This warm continental air cools abruptly as it is lifted more rapidly than the wetter air underneath it as the continental air ascends to 500 mb over the southern Gulf coast states. The lifting mechanism is the unbalanced ascent accompanying a midtropospheric along-stream jet/front system resulting from the processes described in (2) and (3), above. The mesoscale jet streak accompanying the mountain-plains solenoid is overriding air from the Gulf of Mexico which is being transported by the low-level inflowing jet within the boundary layer. In time, the observed radar depicted in Figure 9 for this case study indicates the development of a massive mesoscale convective system which occurs where these trajectories from the southwest and south converge over northeastern Mississippi. Once precipitation processes are triggered, the latent heating acts to organize a third along-stream jet/front system which involves geostrophic adjustment processes wherein the mass field adjusts to the wind field but at a shorter length scale. The warming from the latent heat release accompanying mesoscale convective systems produces positive hydrostatic thickness tendencies which increase the pressure aloft and decrease the pressure at low levels. Air converges into the region of lower pressure producing ascending flow and cooling ahead of the latent heat release. As can be seen depicted in Figures 10-11, ascent within the right front quadrant of

the accelerating mesoscale jetlet, induces cooling ahead of the warm bubble of air resulting from latent heat release. The constant adjustment of the wind field to the diabatic mass perturbations sustains the jetlet and its along-stream temperature gradient. The mass perturbations are regenerated by latent heat release induced by the destabilizing effects of the right flank cold pool accompanying each mesoscale jetlet. If the convection is strong enough, the scale of the wind field becomes more controlled by the nonlinear advective terms in the equations of motion as opposed to the Coriolis force. This results in the contraction of scale of the jetlet into a propagating gravity wave. This scale contraction process can be achieved by terrain-induced heating accompanying a mountain wave and/or local elevated mountain/plains solenoid circulation as is most evident in the 11-12 July 1981 CCOPE case study. The finer the scale of the heating perturbation the more dominant the nonlinear advective terms and hence, the more dominant ageostrophic confluence is in producing an along-stream frontal system.

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V. List of Figures

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- Fig. 7: Simulated 600 mb temperatures (C, gray shaded dashed lines) and (a) total frontogenetical forcing, (b) frontogenetical forcing due to tilting, (c) frontogenetical forcing due to confluence deformation, and (d) frontogenetical forcing due to shearing deformation ($\times 10^{-9} \text{ km}^{-1} \text{ s}^{-1}$) over eastern Texas and valid for 0300 UTC 28 March 1984.
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- Fig. 11: Simulated 500 mb temperature (C) and 500 mb isotachs valid at (a) 1200 UTC, (b) 1500 UTC, (c) 1700 UTC, and (d) 1800 UTC 27 March 1994. UJRFCP is the unbalanced jetlet's right flank cold pool.

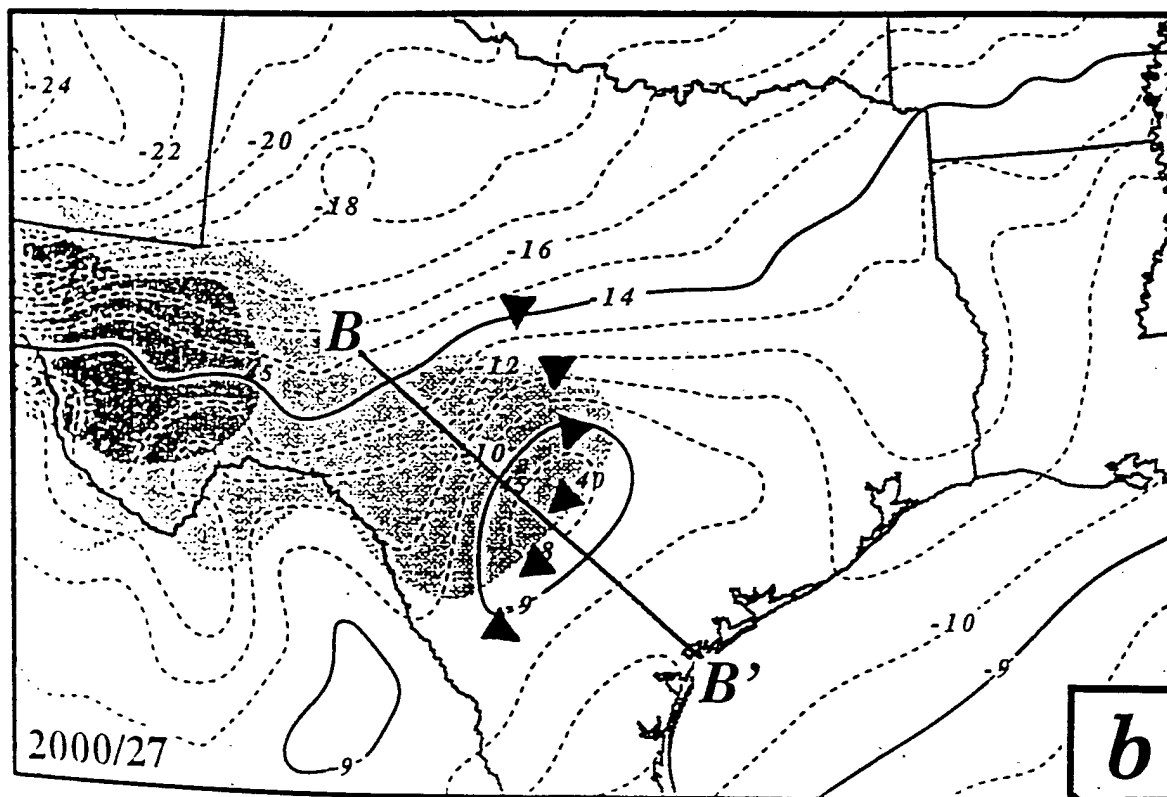
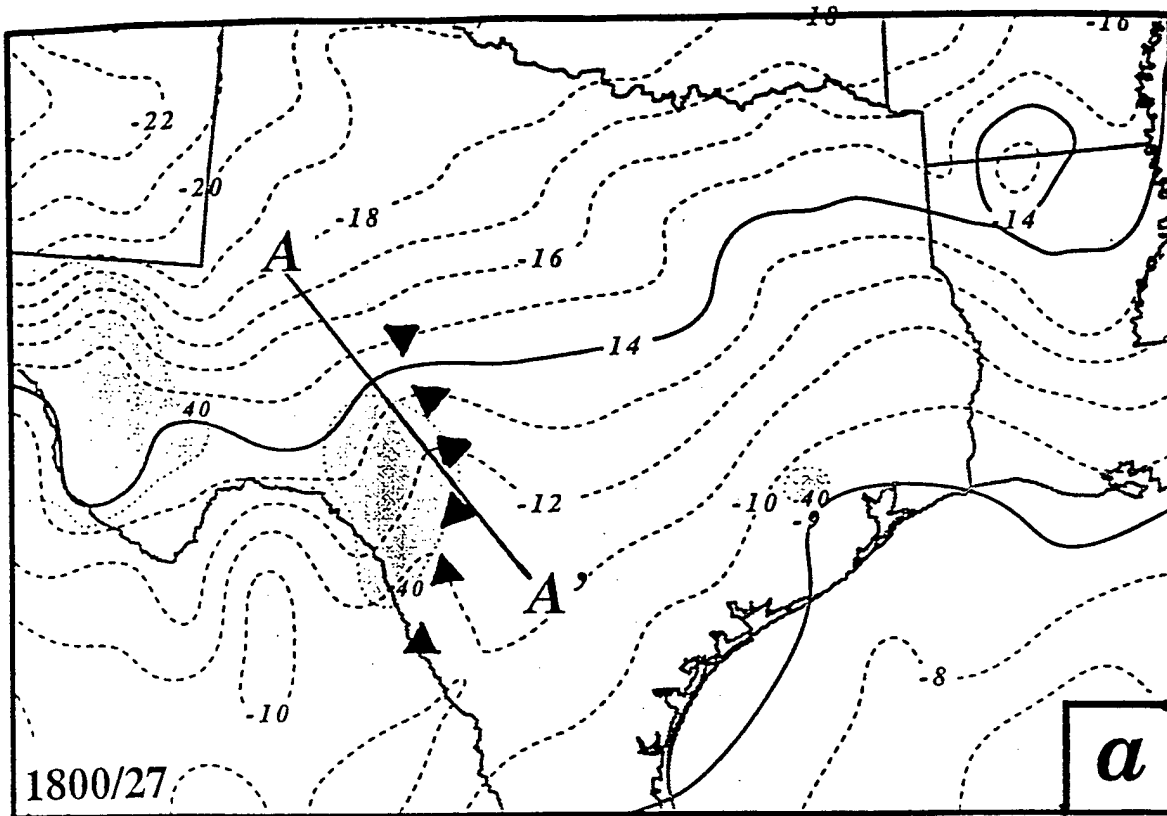


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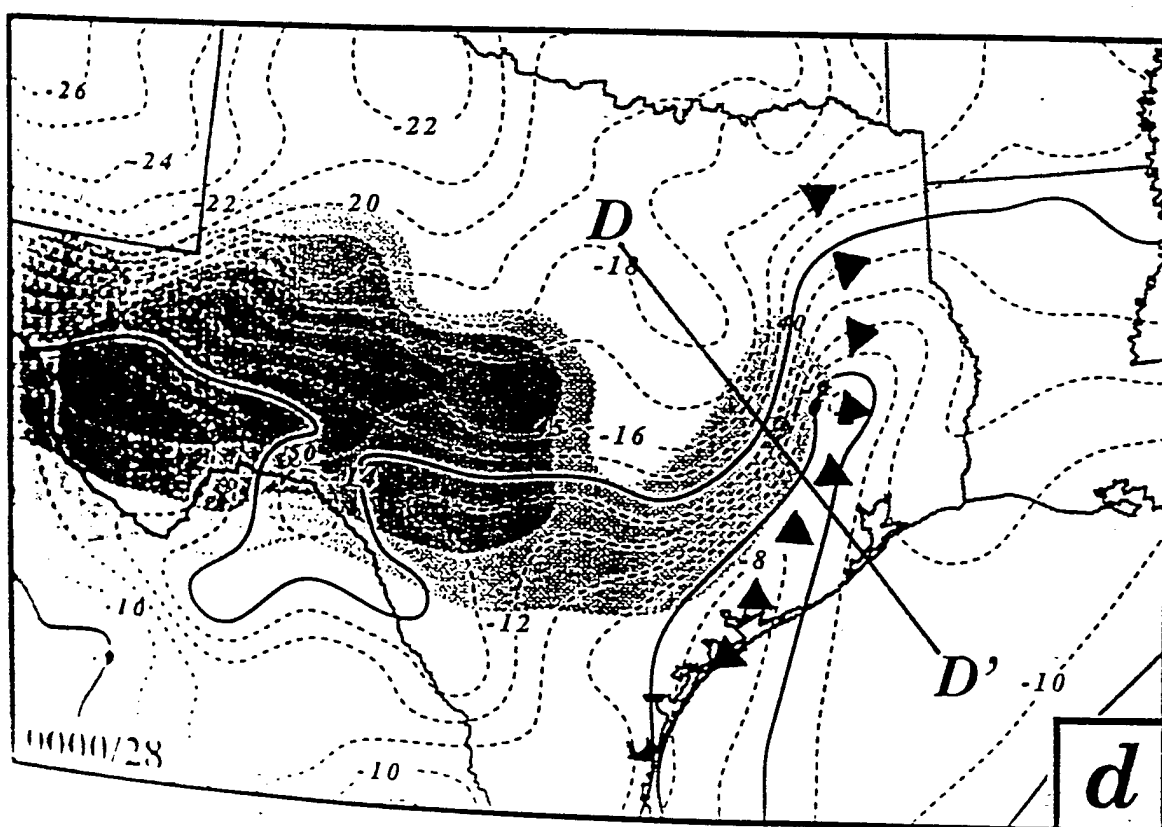
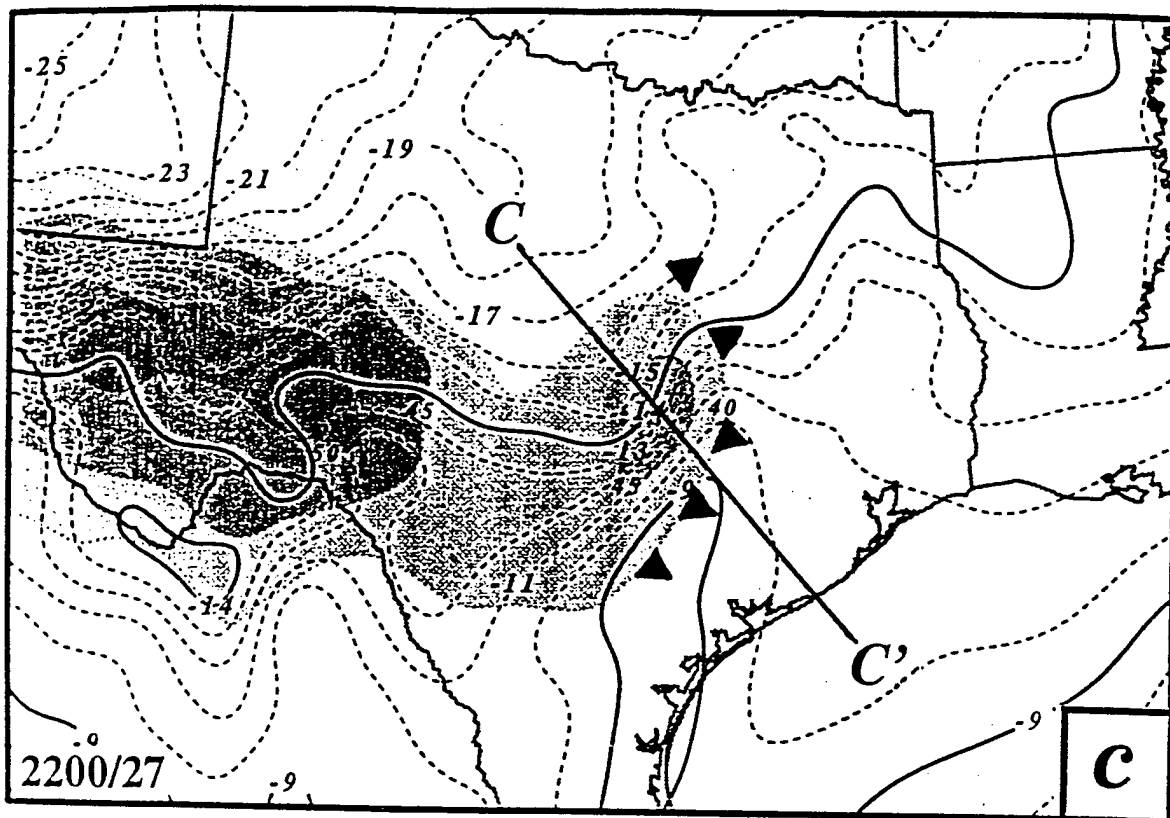


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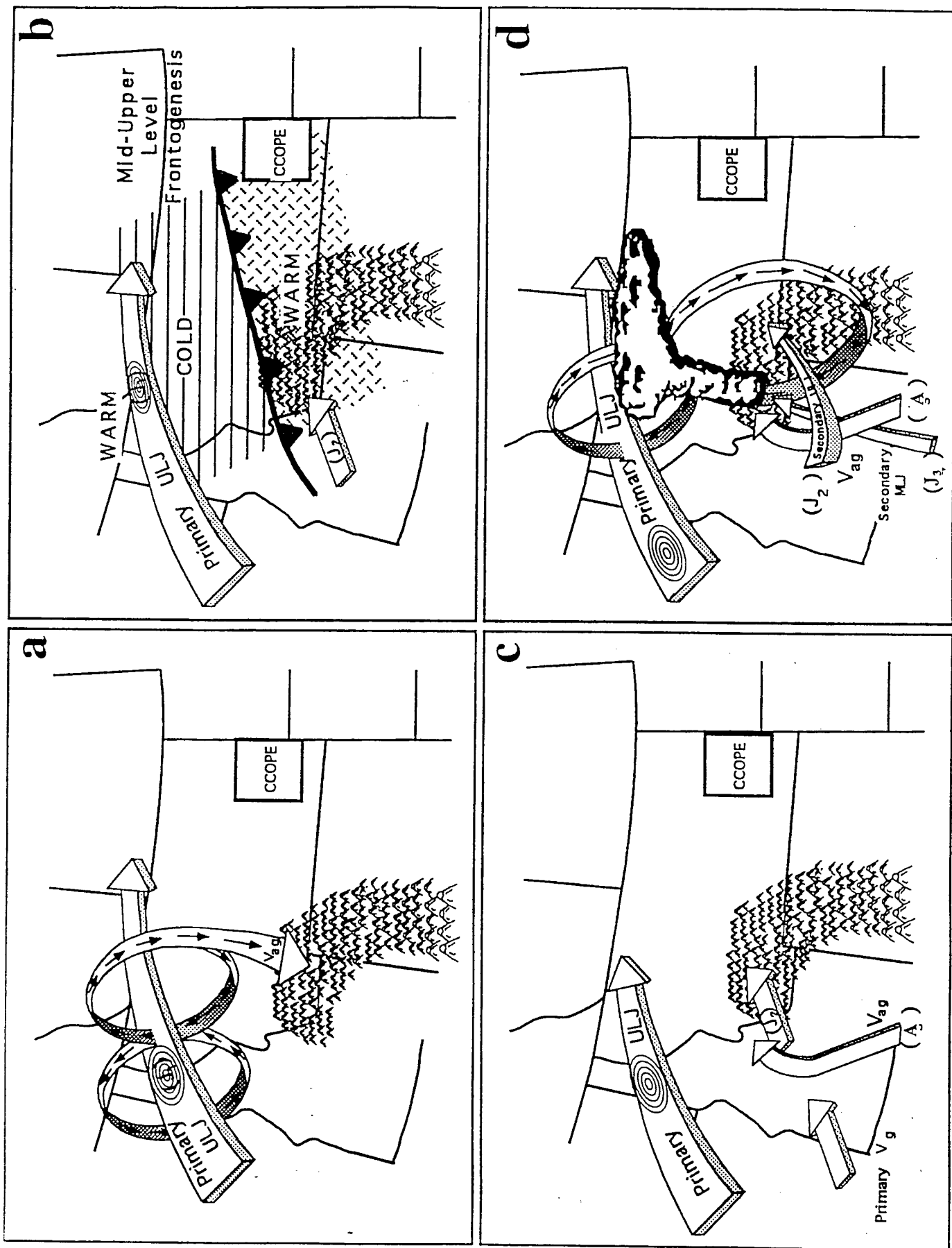


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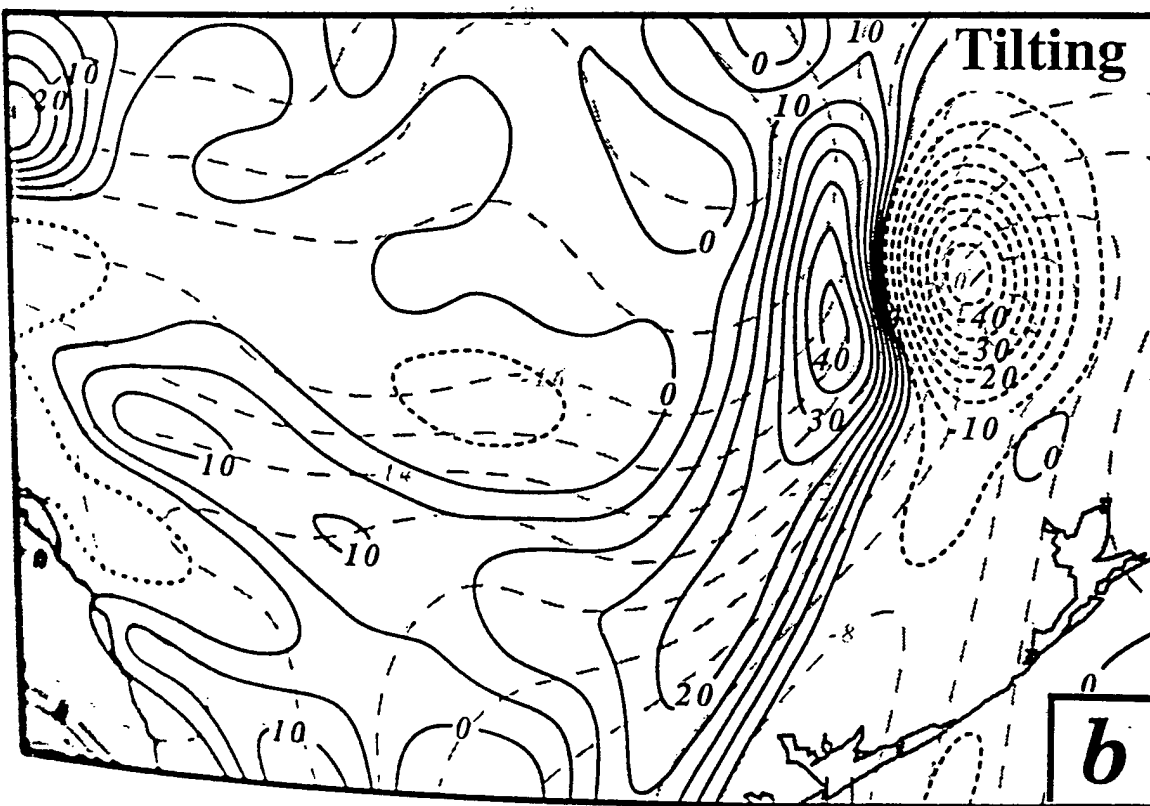
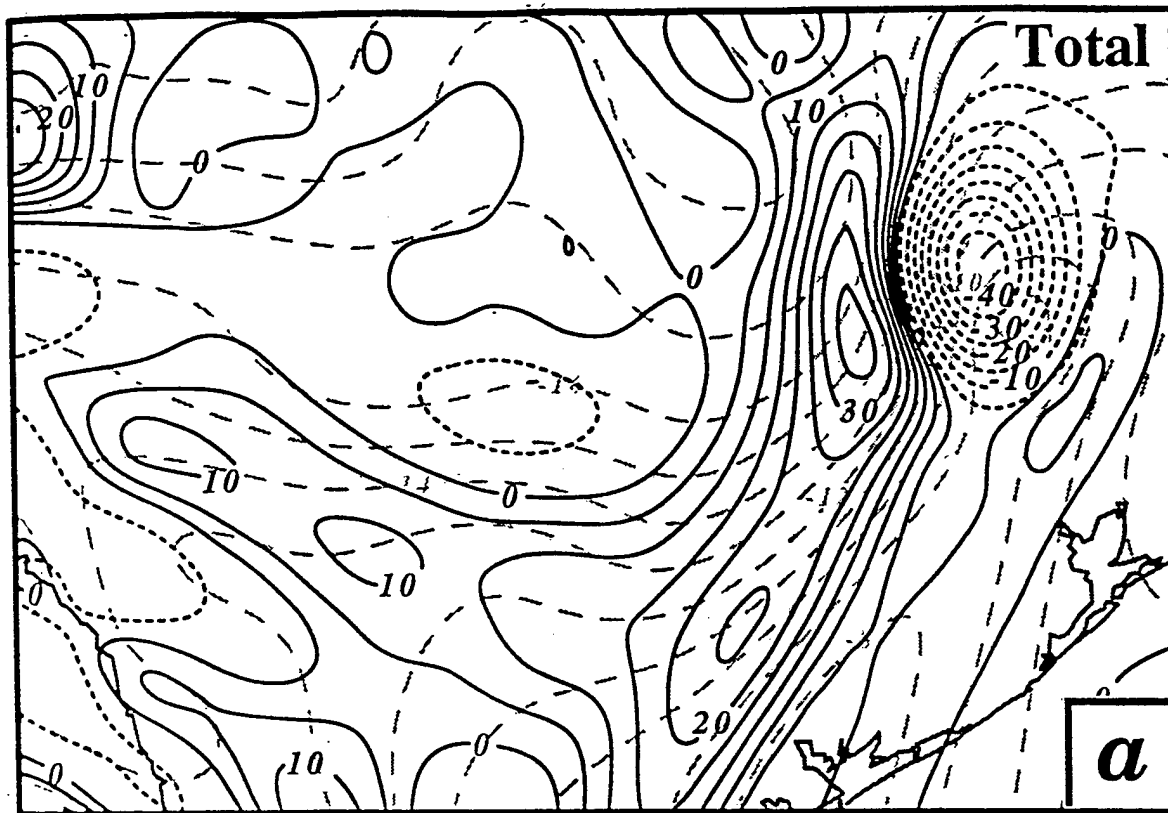


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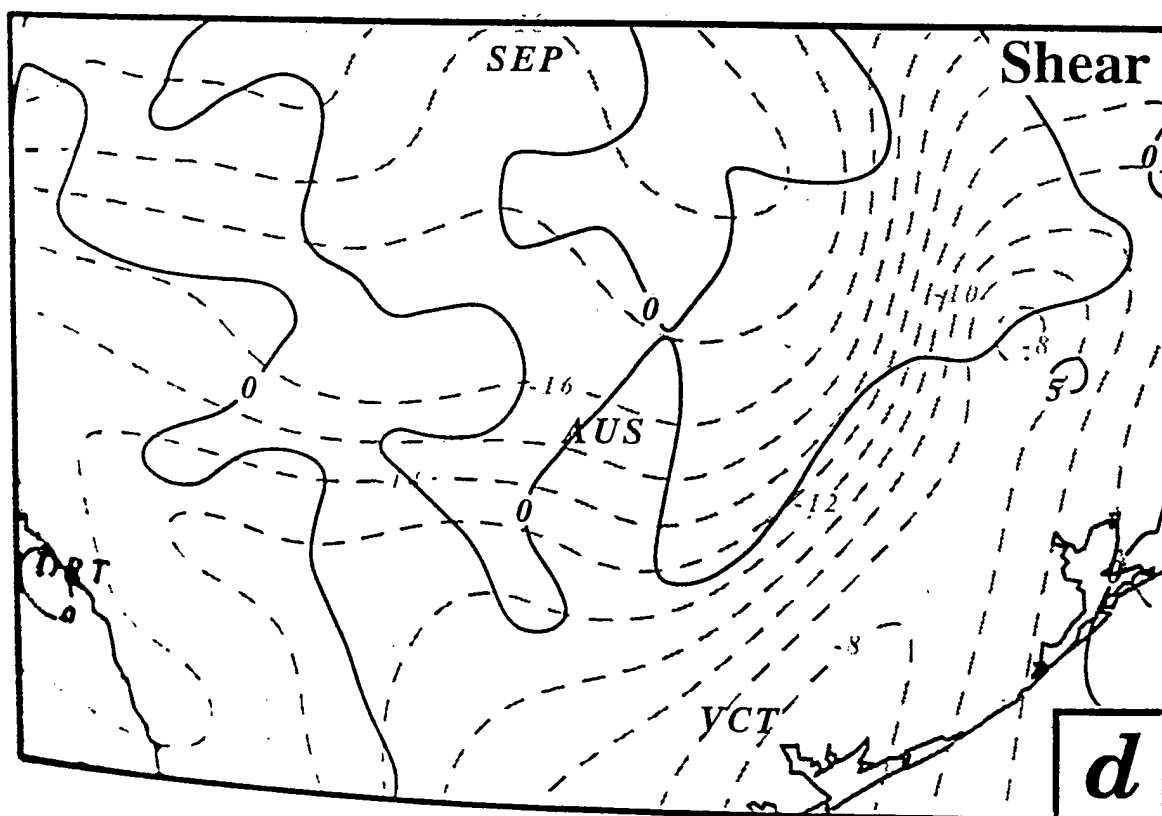
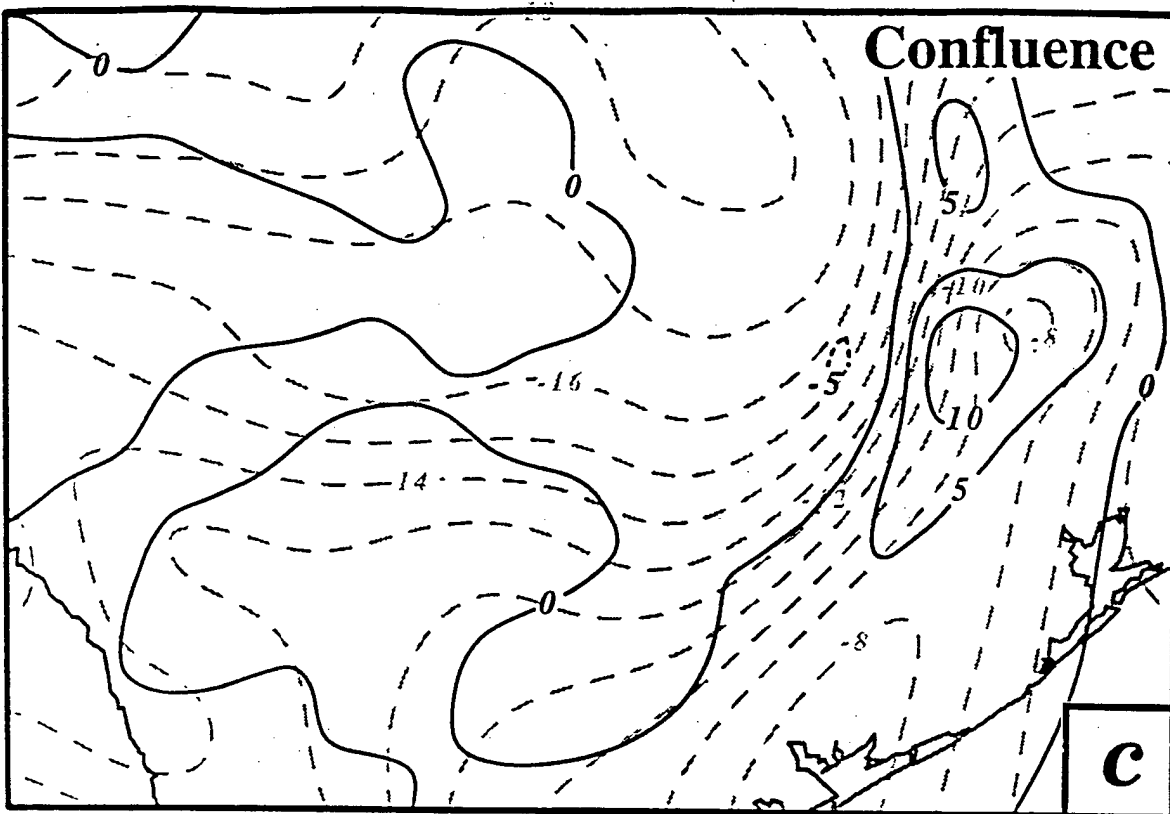


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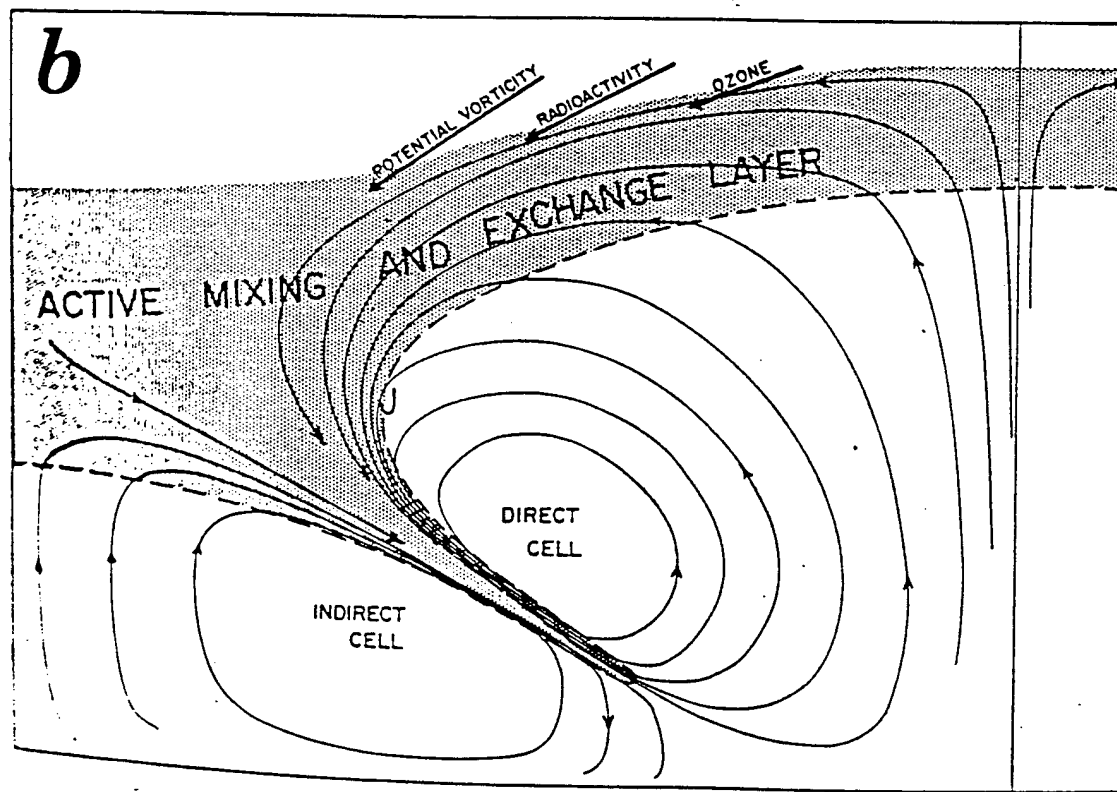
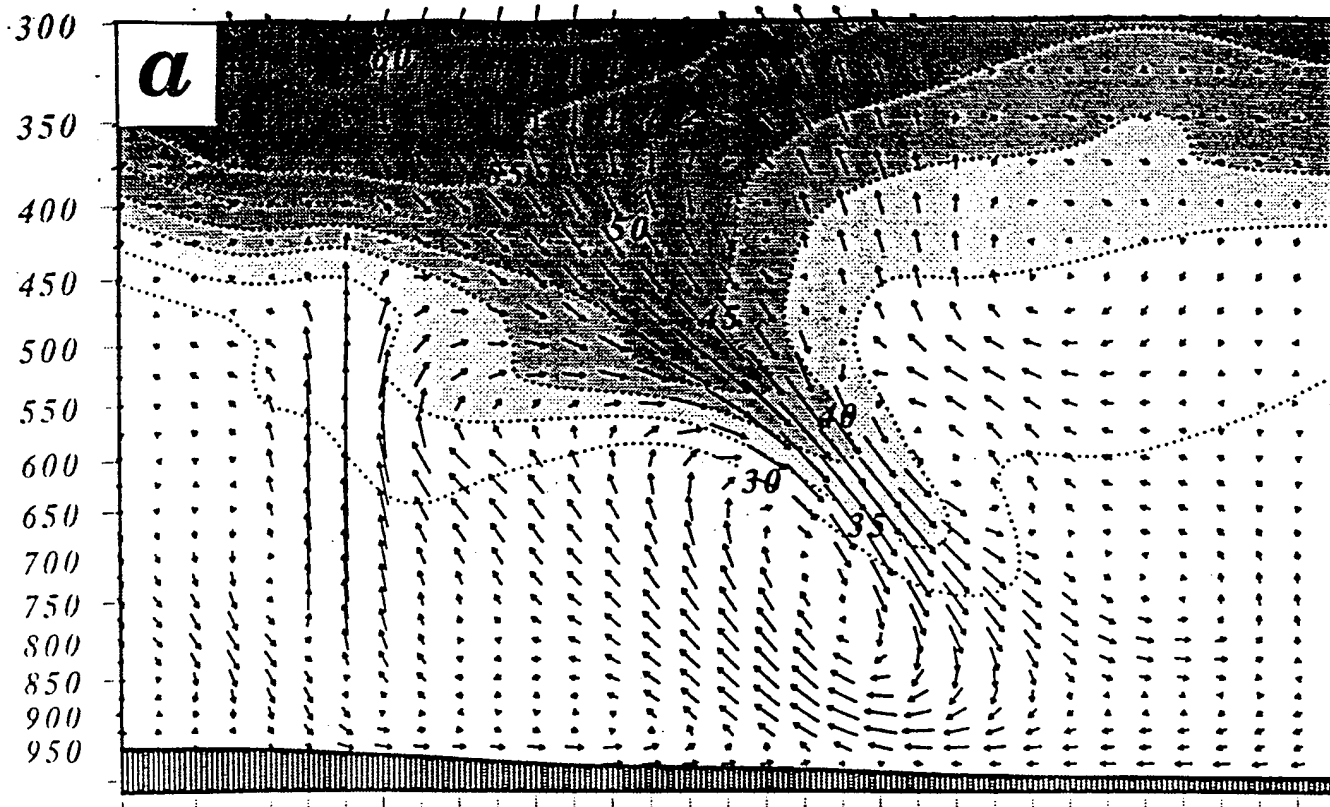


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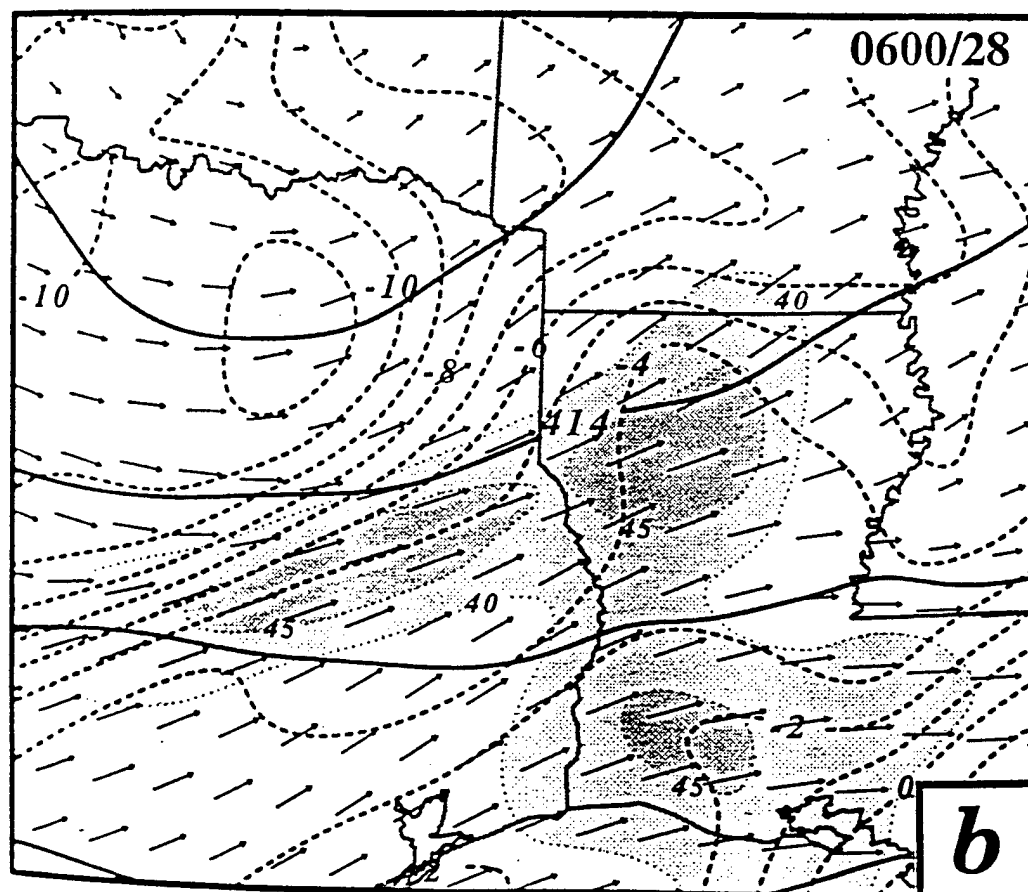
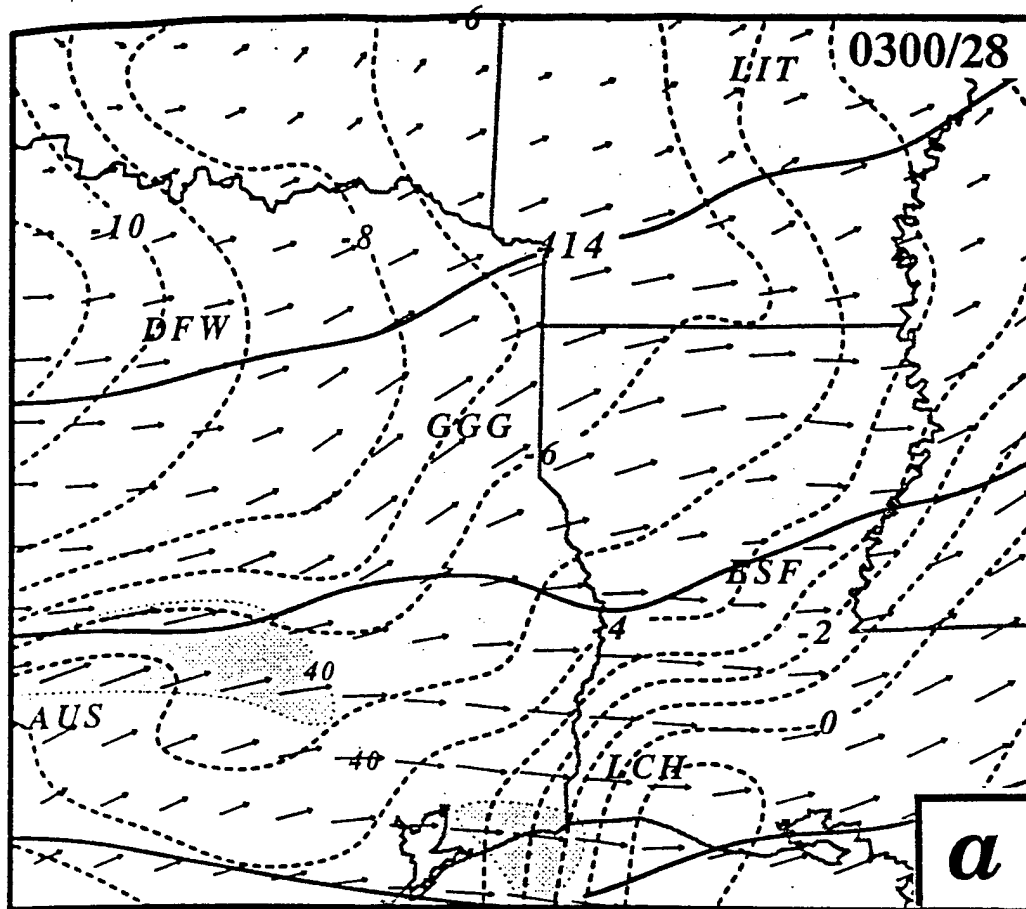


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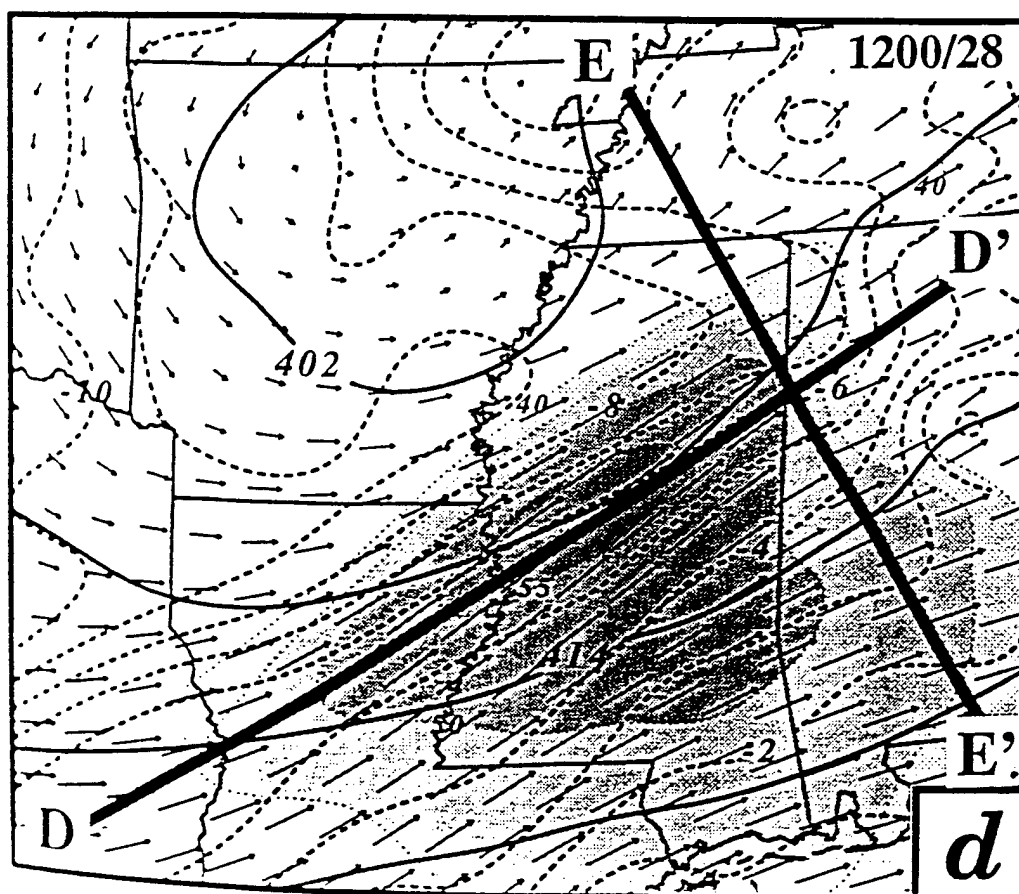
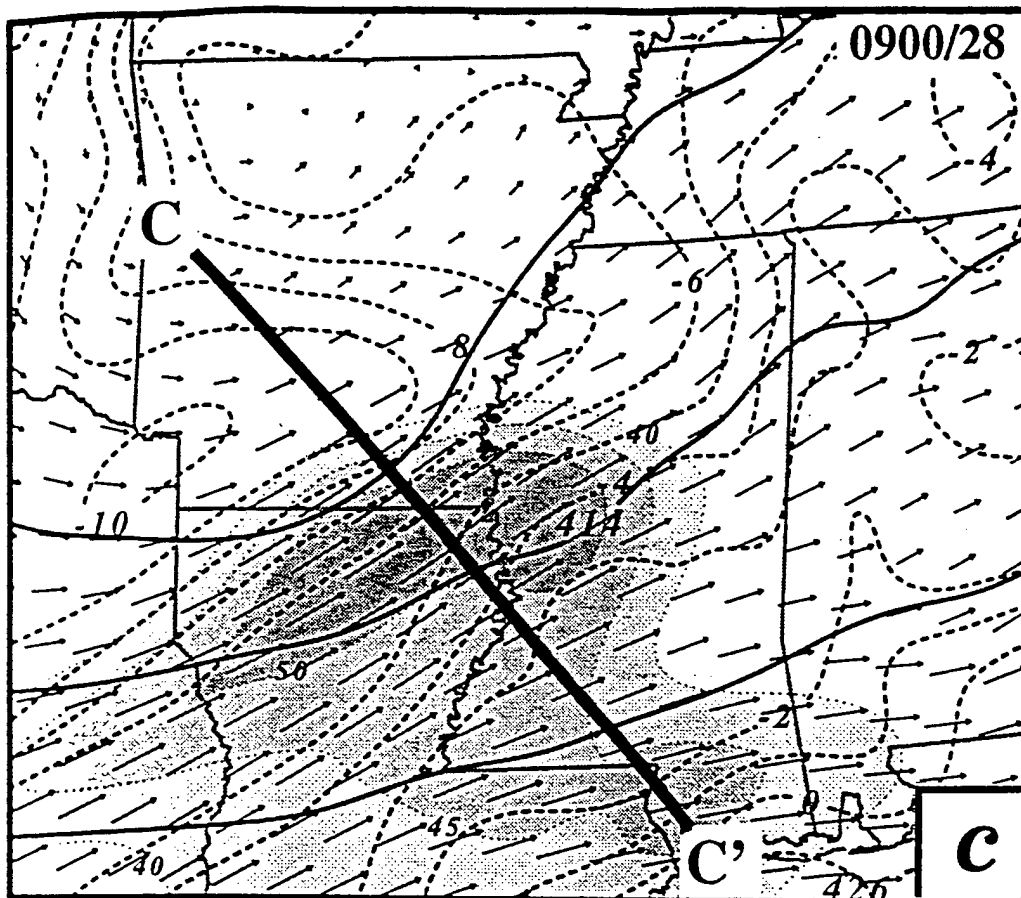


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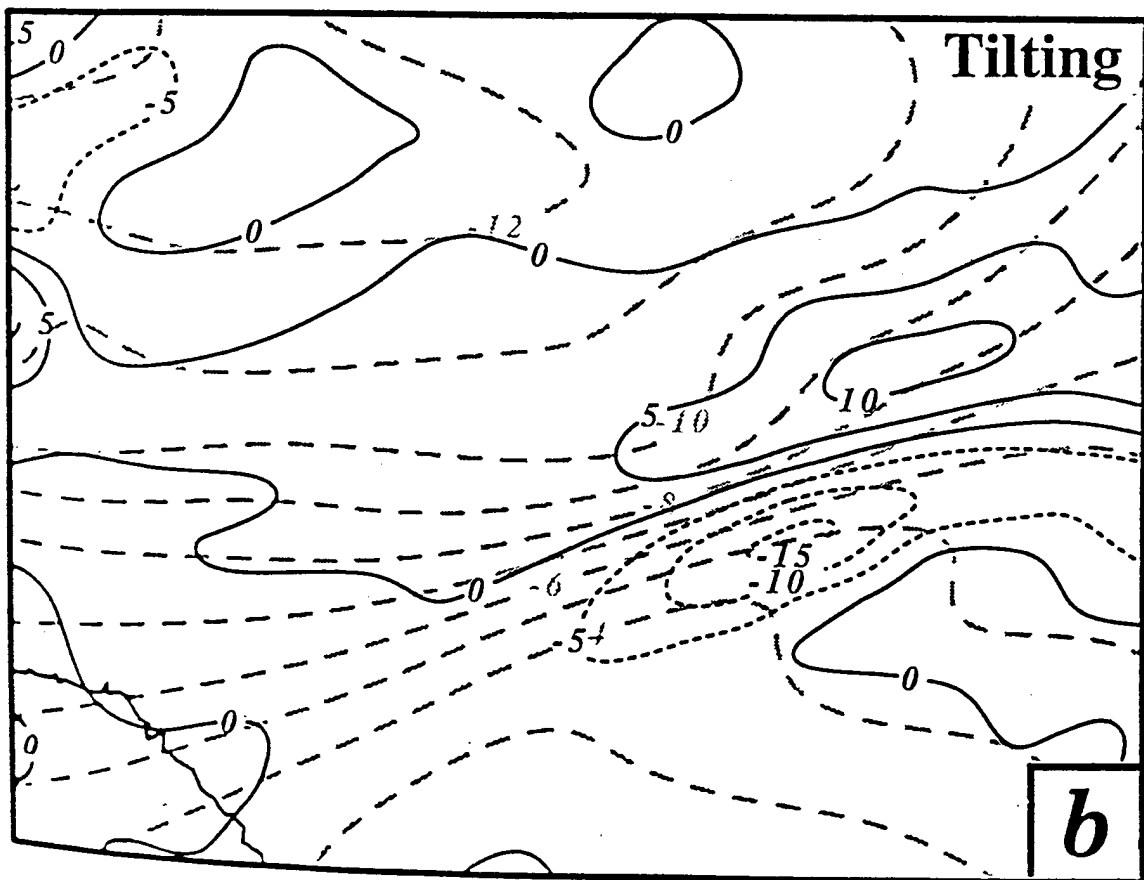
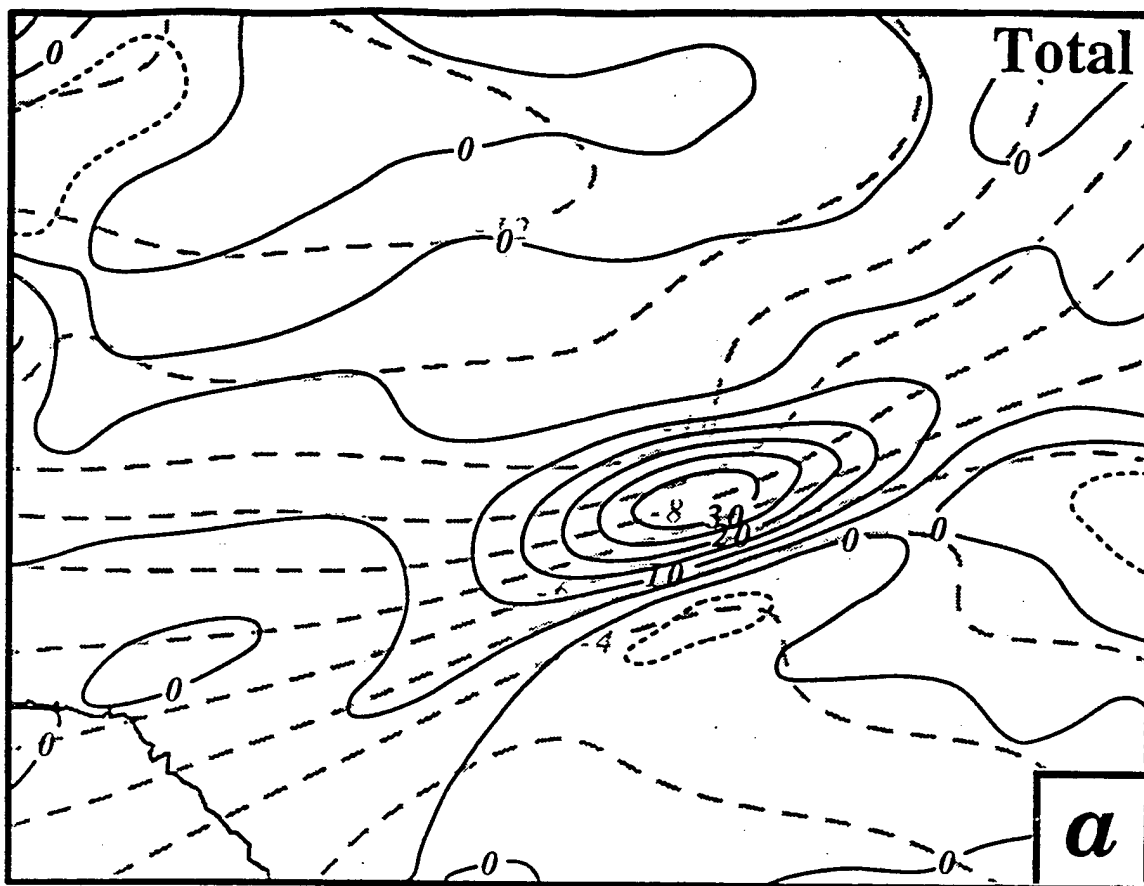


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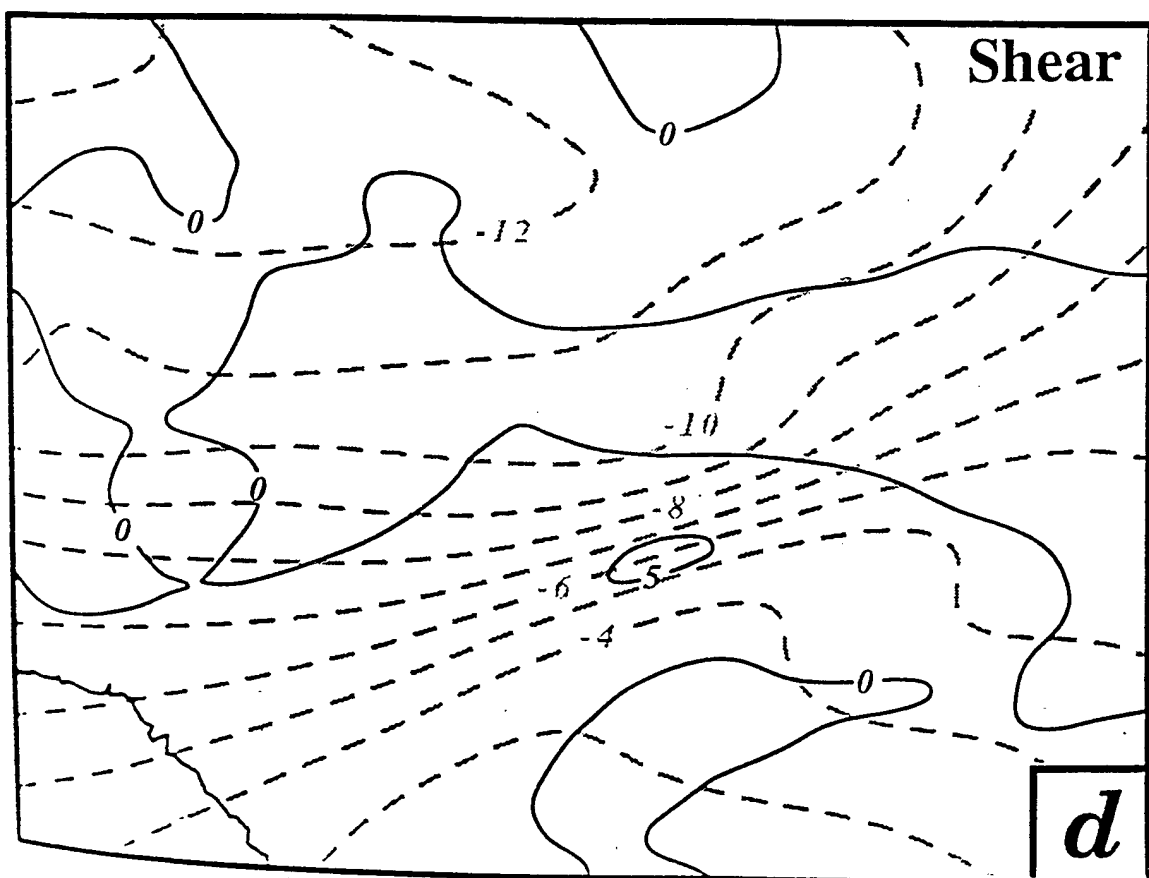
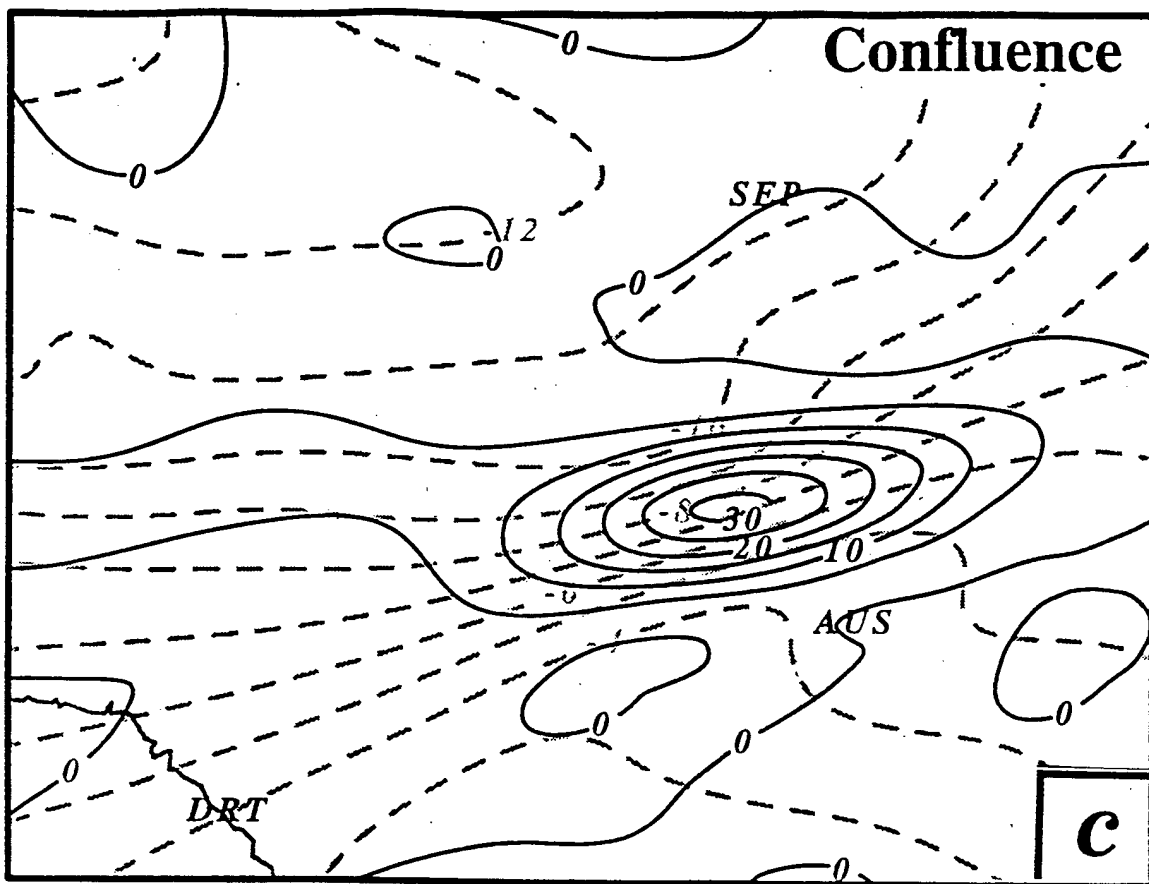


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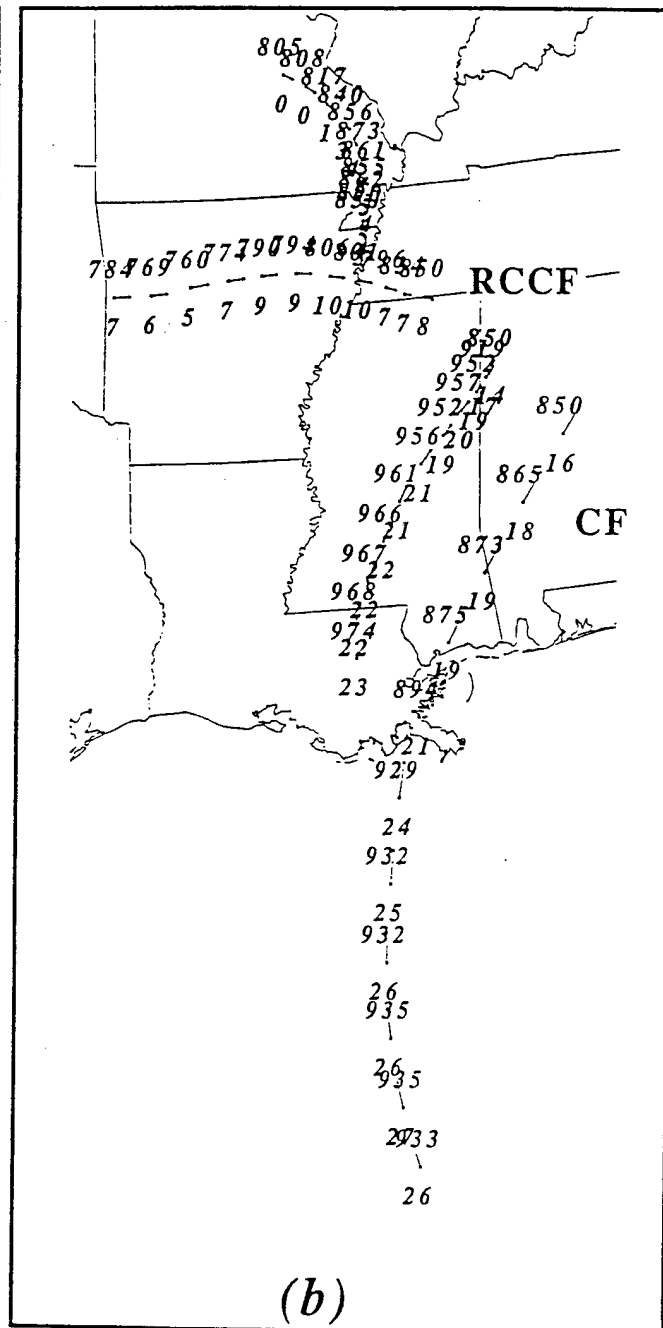
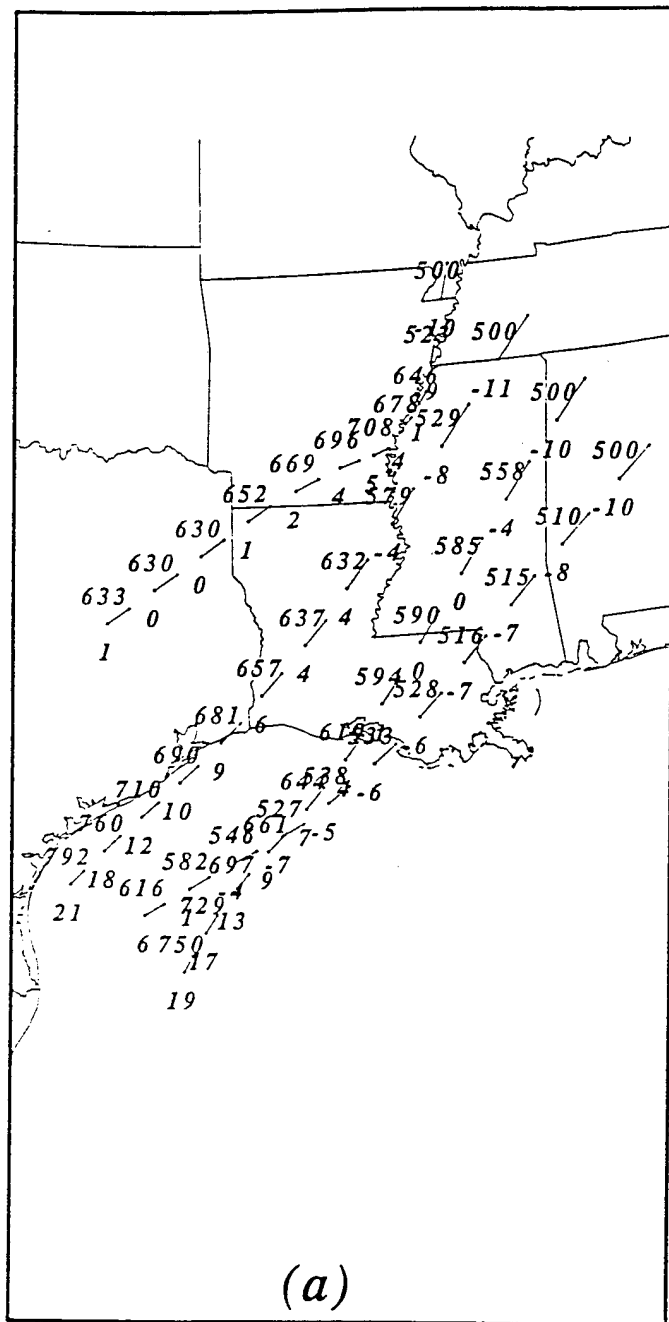


Figure 8

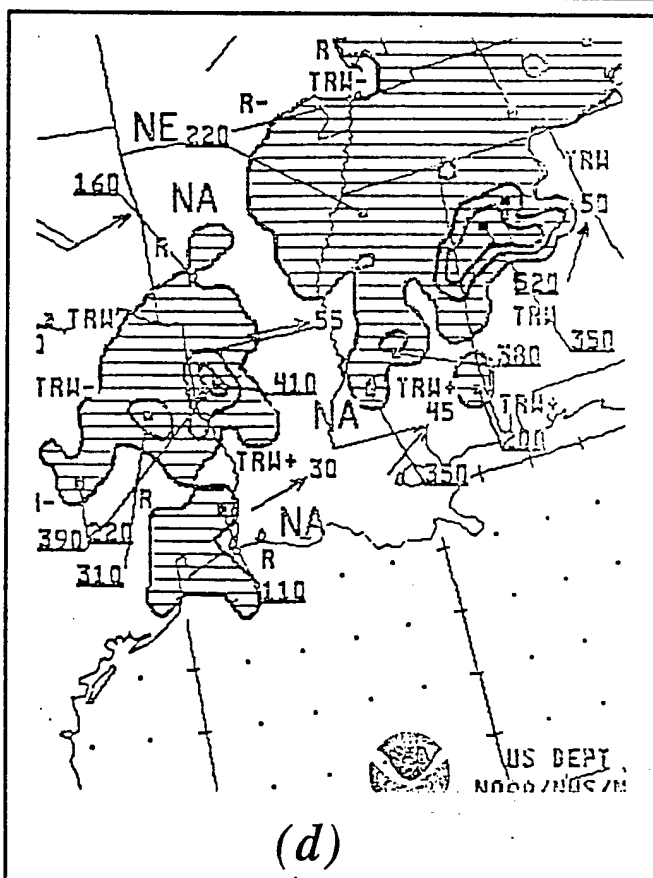
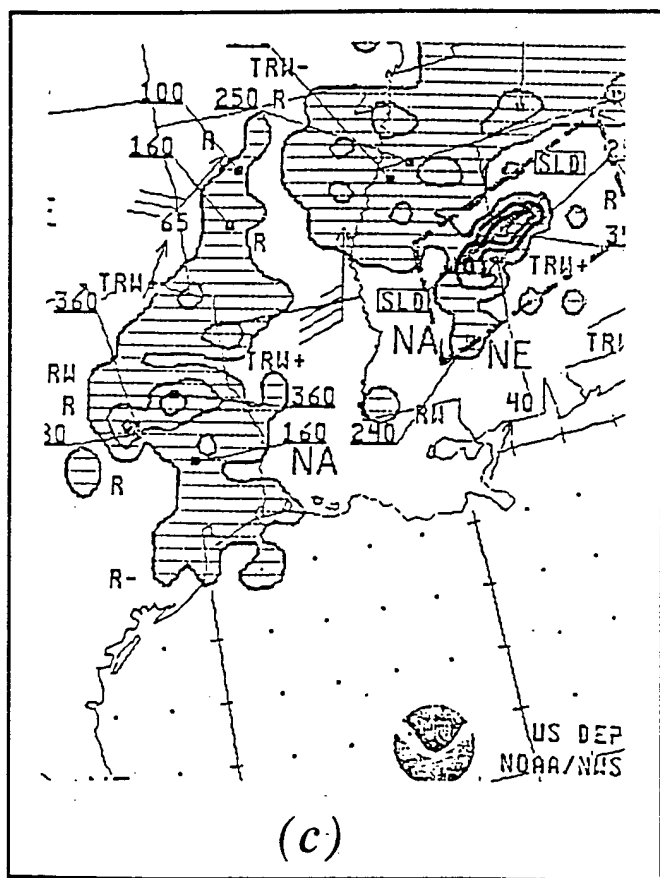
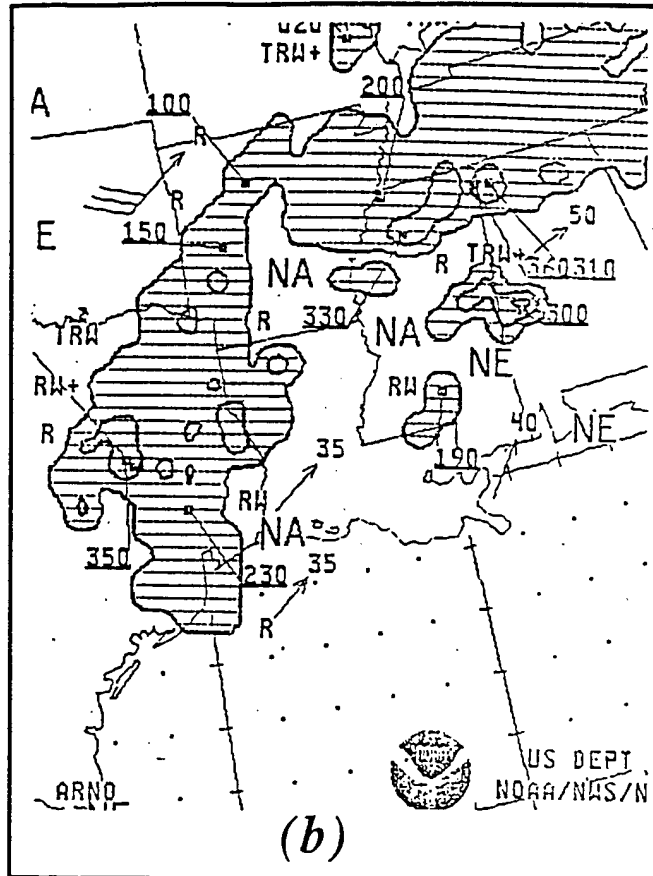
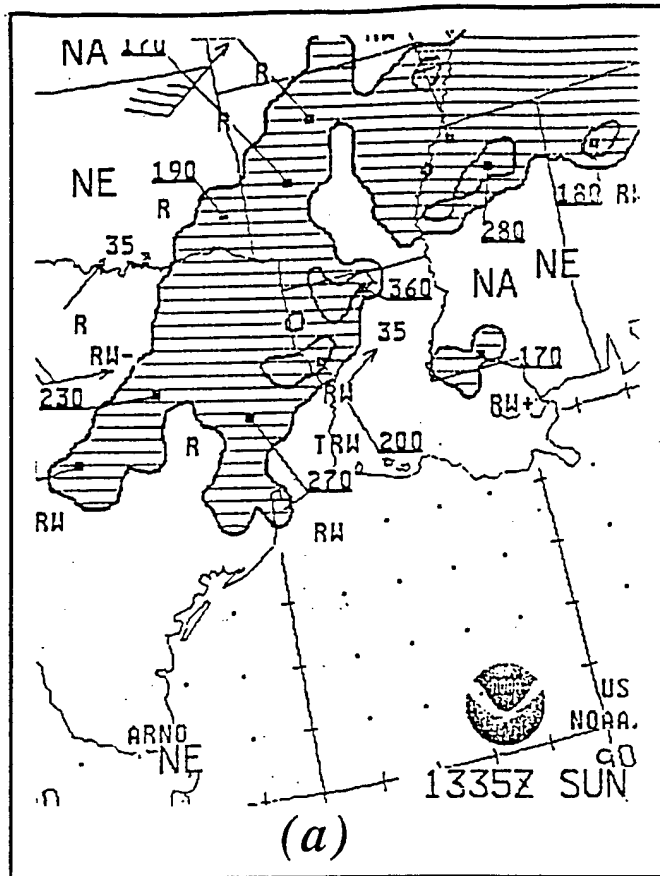


Figure 9

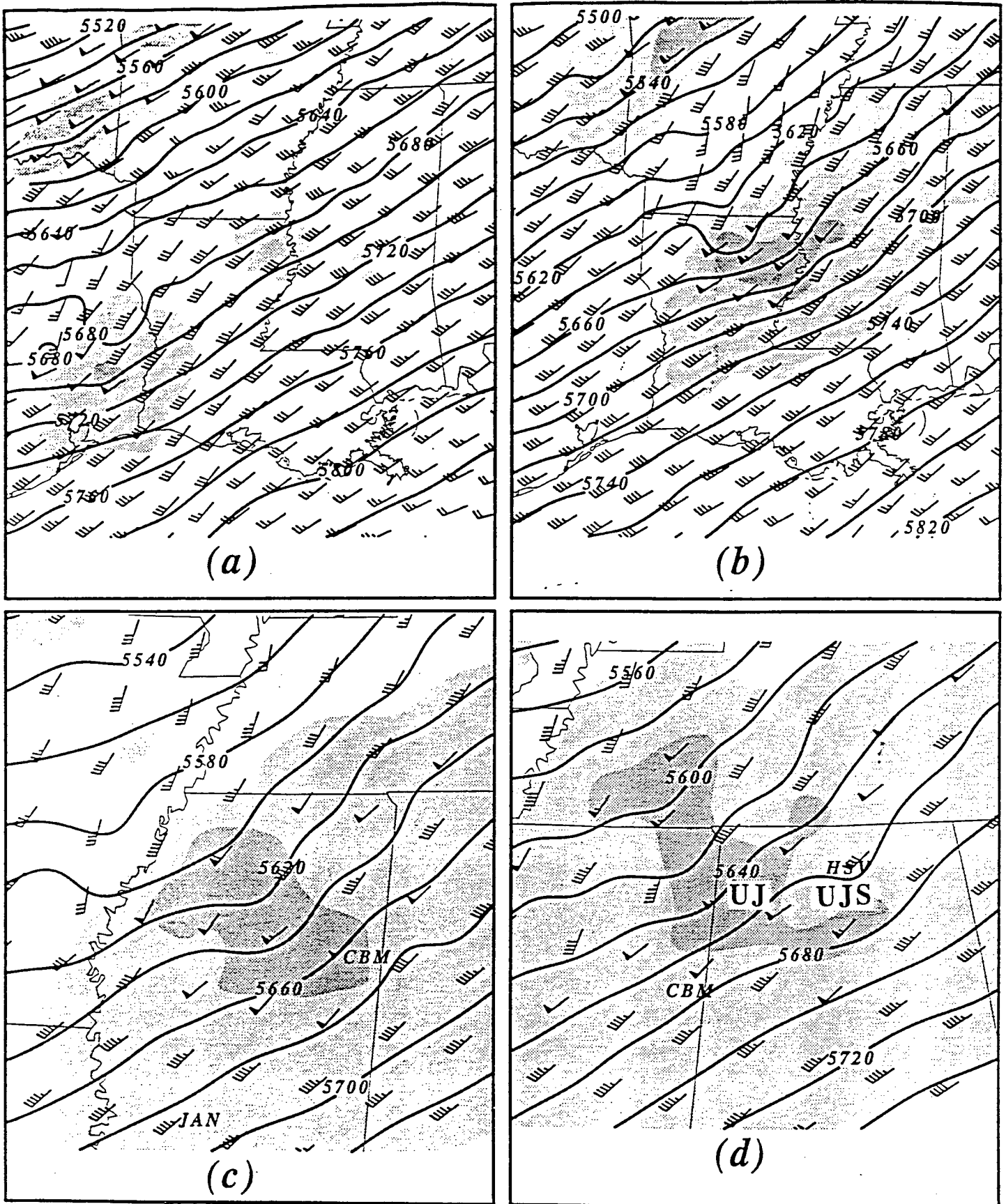


Figure 10

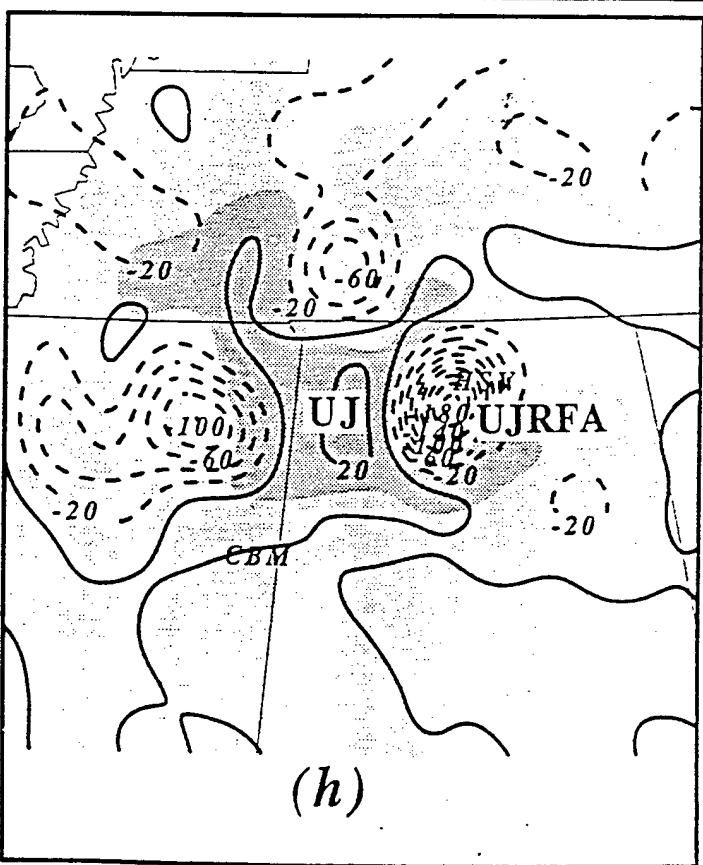
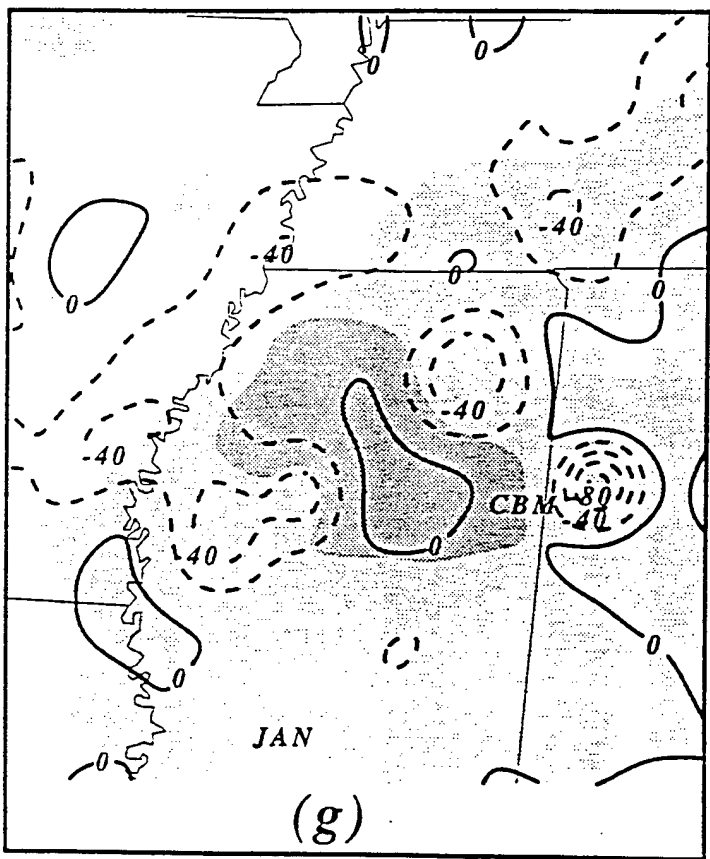
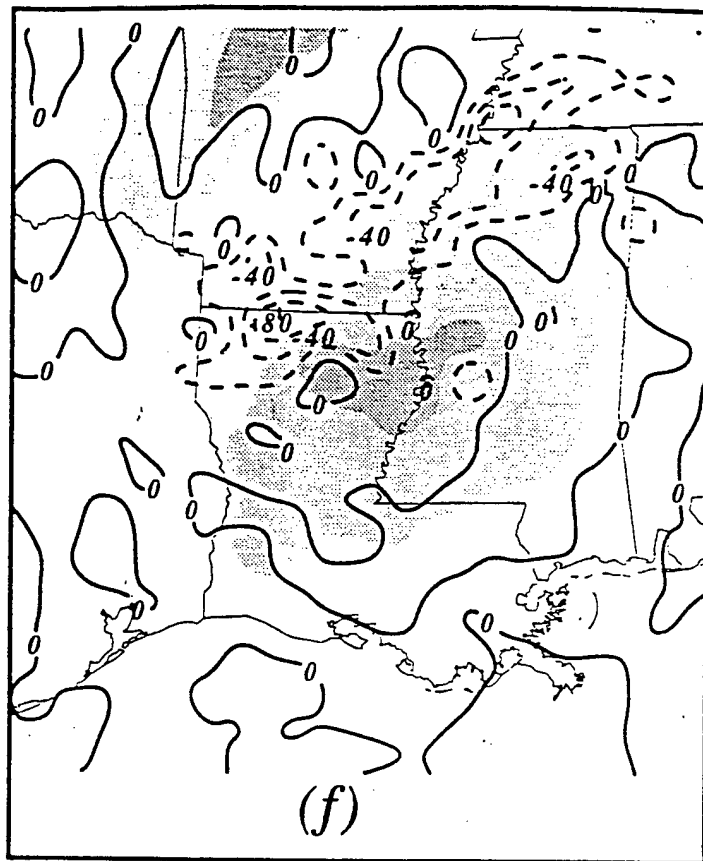


Figure 10

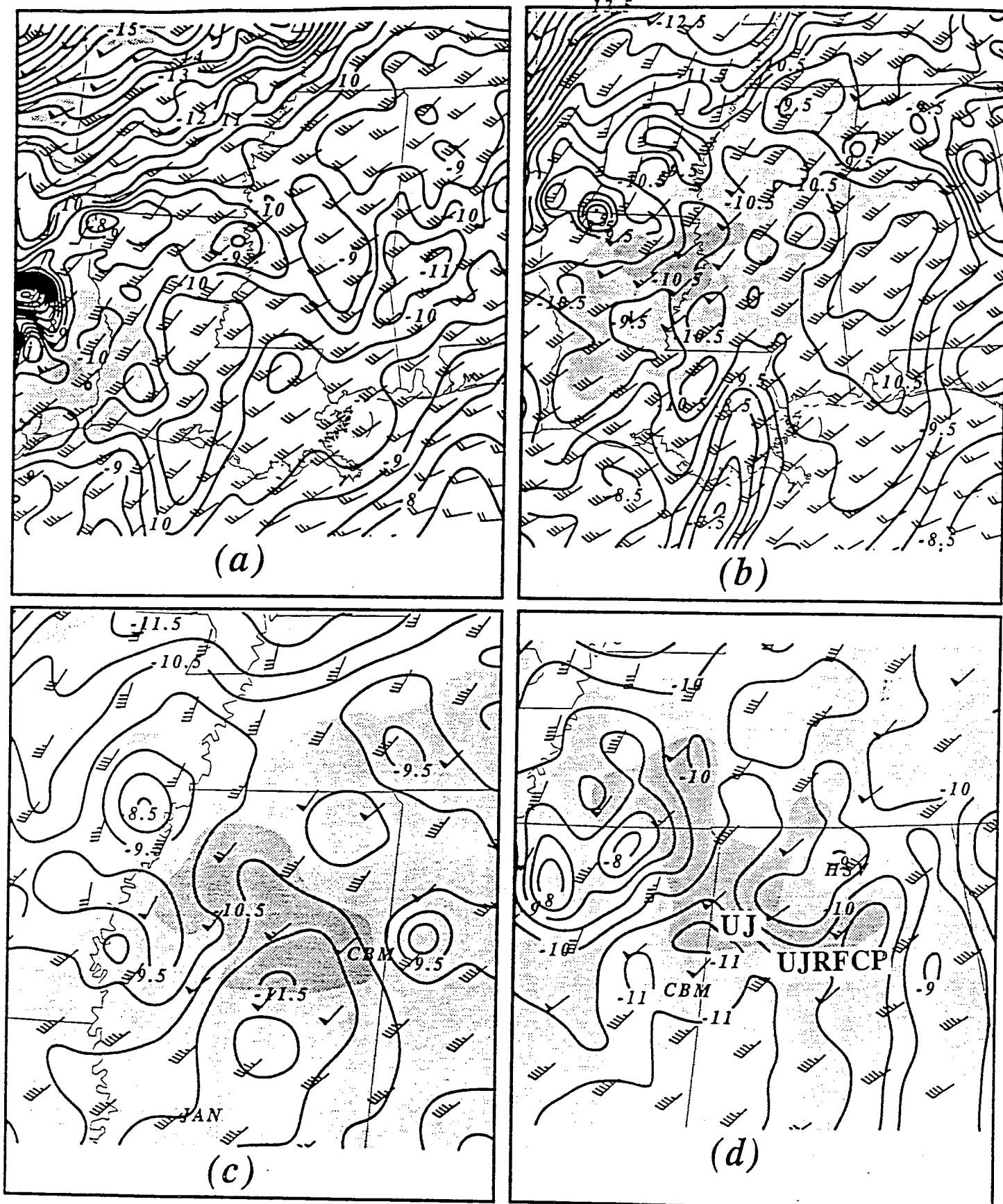


Figure 11

VI. Publications

(a) Refereed Journal Papers

- Kaplan, M. L., S. E. Koch, Y.-L. Lin, R. P. Weglarz, and R. A. Rozumalski, 1997: Numerical simulations of a gravity wave event over CCOPE. Part I: The role of geostrophic adjustment in mesoscale jetlet formation. *Mon. Wea. Rev.*, 125, 1185-1211.
- Weglarz, R. P., and Y.-L. Lin, 1997: A linear theory for jet streak formation due to zonal momentum forcing in a stably stratified atmosphere. *J. Atmos. Sci.*, 54, 908-932.
- Hamilton, D. W., Y.-L. Lin, M. L. Kaplan, and R. A. Rozumalski, 1998: Antecedent jetlet formation prior to the Palm Sunday 1994 tornado outbreak in Alabama and Georgia. In press, August 1998, *Mon. Wea. Rev.*
- Kaplan, M. L., Y.-L. Lin, D. W. Hamilton, and R. A. Rozumalski, 1998: The numerical simulation of an unbalanced jetlet and its role in the Palm Sunday 1994 tornado outbreak in Alabama and Georgia. In press, August 1998, *Mon. Wea. Rev.*
- Lin, Y.-L., R. L. Deal, and M. S. Kulie, 1998: Mechanisms of cell regeneration, development, and propagation within a two-dimensional multicell thunderstorm. *J. Atmos. Sci.*, in press.
- Koch, S. E., D. W. Hamilton, D. Kramer, and A. Langmaid, 1998: Mesoscale dynamics of the Palm Sunday tornado outbreak. In press, August 1998, *Mon. Wea. Rev.*
- Rozumalski, R. A., M. L. Kaplan, Y.-L. Lin, and S. E. Koch, 1998: The evolution of a mid-tropospheric unbalanced front forced by a continental planetary boundary layer. Conditionally accepted, *Mon. Wea. Rev.*
- Weglarz, R. P., and Y.-L. Lin, 1998: Nonlinear adjustment of a rotating homogeneous atmosphere to zonal momentum forcing. Accepted by *Tellus* for publication.
- , Y.-L. Lin, S. E. Koch, and R. P. Weglarz, 1998: Numerical simulations of a gravity wave event over CCOPE. Part II: The role of terrain-induced mass perturbations in wave genesis. Submitted, *Mon. Wea. Rev.*

(b) Conference preprints

- Koch, S. E., Y.-L. Lin, M. L. Kaplan, M. Vescio, A. Langmaid, D. Hamilton, D. Kramer, and M. Black, 1996: Frontal mesoscale dynamics in the Palm Sunday tornado outbreak. Preprints, 18th Conference on Severe Local Storms, Amer. Meteor. Soc., 19-23 February 1996, San Francisco, CA, 47-51.
- DeCroix, D. S., Y.-L. Lin, and R. A. Rozumalski, 1996: Cloud modeling of a squall line formed in the 1984 North Carolina tornado outbreak. Preprints, 18th Conference on

- Severe Local Storms, Amer. Meteor. Soc., 19-23 February 1996, San Francisco, CA, 190-194.
- Kaplan, M. L., Y.-L. Lin, D. W. Hamilton, and R. A. Rozumalski, 1996: The numerical simulation of an unbalanced jetlet and its role in the Palm Sunday 1994 tornado outbreak in Alabama and Georgia. Preprints, 18th Conference on Severe Local Storms, Amer. Meteor. Soc., 19-23 February 1996, San Francisco, CA, 240-244.
- Deal, R. L., Y.-L. Lin, M. S. Kulie, and D. S. DeCroix, 1996: Observations and simulations of a long-lived tornadic storm: the 27 March 1994 Cherokee County, Alabama supercell. Preprints, 18th Conference on Severe Local Storms, Amer. Meteor. Soc., 19-23 February 1996, San Francisco, CA, 245-249.
- Kulie, M. S., Y.-L. Lin, R. L. Deal, and D. S. DeCroix, 1996: A cloud scale numerical simulation of the 28 November 1988 Raleigh tornadic thunderstorm. Preprints, 18th Conference on Severe Local Storms, Amer. Meteor. Soc., 19-23 February 1996, San Francisco, CA, 283-287.
- Hamilton, D. A., Y.-L. Lin, M. L. Kaplan, and R. A. Rozumalski, 1996: Antecedent jetlet formation prior to the Palm Sunday 1994 tornado outbreak in Alabama and Georgia. Preprints, 18th Conference on Severe Local Storms, Amer. Meteor. Soc., 19-23 February 1996, San Francisco, CA, 288-291.
- Kaplan, M. L., J. W. Zack, Y.-L. Lin, and R. P. Weglarz, 1996: The numerical simulation of the organizing dynamics and evolution of a large amplitude gravity wave in a major Atlantic Coast cyclone. Preprints, 11th Conference on Numerical Weather Prediction, Amer. Meteor. Soc., 19-23 August 1996, Norfolk, VA, 311-315.
- Rozumalski, R. A., Y.-L. Lin, M. L. Kaplan, and S. E. Koch, 1996: Numerical simulations of secondary cold frontogenesis aloft accompanying jetogenesis and multiple secondary cyclogenesis. Preprints, 11th Conference on Numerical Weather Prediction, Amer. Meteor. Soc., 19-23 August 1996, Norfolk, VA, 316-318.
- Kaplan, M. L., R. P. Weglarz, R. A. Rozumalski, D. W. Hamilton, and Y.-L. Lin, 1997: The role of diabatically-induced jetogenesis in the formation of the mesoscale waves in the midwest cyclone of 15 December 1987. Preprints, 11th Conference on Atmospheric and Oceanic Fluid Dynamics, Amer. Meteor. Soc., 23-27 June 1997, Tacoma, WA, 111-115.
- Kaplan, M. L., J. M. Egentowich, Y.-L. Lin, A. J. Riordan, and R. A. Rozumalski, 1998: Observations and numerical simulations of the generation and transport of a Central American air mass into the Southeastern U. S. prior to a tornado outbreak. Preprints, 16th Conference on Weather Analysis and Forecasting, Amer. Meteor. Soc., 11-16 January 1998, Phoenix, AZ, 314-319.

- Koch, S. E., 1998: Mesoanalysis and modeling of the forcing for mesoconvective systems in the Palm Sunday tornado outbreak. Preprints, Joint Session, 16th Conference on Weather Analysis and Forecasting and 12th Conference on Numerical Weather Prediction, Amer. Meteor. Soc., 11-16 January 1998, Phoenix, AZ, J91-J94.
- Zhang, F., and S. Koch, 1998: Predictability study using a mesoscale model of a gravity wave event observed during CCOPE. Preprints, 12th Conference on Numerical Weather Prediction, Amer. Meteor. Soc., 11-16 January 1998, Phoenix, AZ, 201-204.

VII. Awards

None.

VI. Technology Transitions

Over the past 3 years we have been developing a paradigm/forecasting algorithm which could be applied to the problem of forecasting severe weather in the southeastern U. S. The knowledge gained from our AFOSR project has been applied to enhancing the development and refinement of this forecasting algorithm. Said algorithm has essentially been developed under AFOSR and NOAA contracts. The National Weather Service operational forecasters at the Raleigh, North Carolina office employ said algorithm regularly as part of a checklist which aids them in the operational forecasting of severe weather in the Raleigh, North Carolina regional area.