Scientific Goals and Hypothesis Testing Procedures for the Convection Initiation Component of IHOP

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(updated on 5-30-01)

The scientific objectives related to convection initiation are grouped into three categories: kinematic controls, moisture controls, and dynamical effects. Note that the kinematic controls deal with moisture transport and lifting, while dynamical effects of virtual temperature are influenced by water vapor content. Thus, the subjective categorizations are adopted only for convenience of presentation, and all hypotheses have a first-order relationship to atmospheric water vapor content and its effects.

The current document overviews these scientific objectives in greater detail than presented in the IHOP Science Overview document (available at http://www.atd.ucar.edu/dir_off/projects/2002/IHOP.html), casting each in the form of testable hypotheses. Specific experimental designs have been conceptualized for each hypothesis, and the assembled designs have been condensed to form an overarching field operations plan. The supporting document "IHOP.mobile_sampling.pdf" describes the various mobile platforms and proposes how they would be deployed and coordinated during IHOP. The required aircraft flight patterns and alternative mobile radar arrangements, the relative locations for the ground-based mobile facilities, and the operational domain for the IHOP Convective Initiation study are presented in "IHOP_CI.plan_outer_box.pdf", "IHOP_CI.plan_outer_tform.pdf", "IHOP_CI.plan_inner.pdf", and "IHOP_mobile.land.pdf" respectively.

Whereas all of the scientific objectives listed here have very specific data collection requirements, they should not be considered mutually exclusive. The CI field operations plan has been carefully crafted so that data requirements for most objectives should be met at the same time. Furthermore, it should be remembered that data collected in support of one objective may be useful in the interpretation of other data sets. As one example, UAV or Mobile Mesonet data collected in support of CI objectives will also be very useful for detailed in-situ validation of DIAL water vapor mixing ratio measurements -- a high IHOP priority -- as well as for sensor intercomparisons. As another example, we believe that mobile ground-based observations may contribute to the scientific objectives of the ABL group in IHOP. Such synergies should be exploited during IHOP to achieve a more efficient use of the data. In all about 15 missions are planned to achieve convective initiation objectives. The ABL and CI groups are jointly considering an additional 5 missions (approximately) in support of common objectives.

A common set of measurement requirements have been identified by the convection initiation group (refer to "IHOP.mobile_sampling.pdf"). Any special measurement needs for a given hypothesis are noted with the description of that hypothesis.

Scientific Hypotheses of the Convection Initiation group

(NOTE: Individual testable hypotheses are subject to debate by IHOP PIs and some are likely to be revised and updated prior to the IHOP field phase. The present hypothesis versions are current as of 5/23/01.)

Kinematic Controls on Convection Initiation (K)

OBJECTIVE K1: Dryline/outflow boundary dynamics effect on convective initiation (Bluestein)

- PROCESS TO BE STUDIED: Recent research (Weiss 2000) has revealed that an elevated dryline circulation may extend north from the dryline over an outflow boundary. It is thought that this elevated circulation may be responsible for triggering deep convection.

- HYPOTHESIS: Elevated drylines north of dryline-outflow intersections promote convective initiation.

- TEST: Sample clear-air motions with ELDORA and determine moisture structure with DIAL. Use satellite and radar to locate new deep convection.

- REFUTE: Convective initiation is not observed near elevated dryline circulations, and intensity of secondary circulation is insufficient to lift air to LFC.

OBJECTIVE K2: Effect of secondary circulation-induced dryline subsidence on convective inhibition (Bluestein)

- PROCESS TO BE STUDIED: Recent research has revealed evidence of strong subsidence east of the dryline, which was inactive. The vertical circulation about the dryline may prevent convective initiation while possibly also promoting dryline motion.

- HYPOTHESIS: Secondary circulation-induced subsidence east of drylines prevents convective initiation.

- TEST: Sample clear-air motions with ELDORA and determine moisture structure with DIAL. Use satellite and radar to locate new deep convection.

- REFUTE: Convective initiation is observed within areas of subsidence in secondary dryline circulations.

OBJECTIVE K3: Role of undular bores or solitary waves for convective initiation (Geerts)

- PROCESS TO BE STUDIED: A link between undular bores and the initiation of organized convection has been clearly established (Ferretti et al 1988, Carbone et al 1990, Karyampudi et al

1995, Koch and Clark 1999), although the causal connection has been hypothesized rather than firmly demonstrated. Undular bores or solitary waves occur at or ahead of propagating density currents (cold fronts, thunderstorm outflows), being described in Australia (e.g. “morning glory”) and also in the Great Plains region of the U.S. (e.g. Haase and Smith 1984, Koch et al 1991, Kruse and Johnson 1995, Locatelli et al 1998). In some cases such linear features have triggered or organized deep convection. The depth of the bore or gravity current (GC) circulation, and the moisture convergence associated with it, are essential in the yet unanswered question whether, and how, bores/GCs trigger organized deep convection. There is some evidence that moisture convergence, yielding a deep layer of moist air, reaching to the LCL or higher, is more important to CI and intensity than the kinetic energy of the updraft associated with the convergence (Ziegler and Rasmussen 1998, Koch and Clark 1999): deep CI and CAPE values are very sensitive to small-scale variability in PBL precipitable water (Weckwerth et al 1996).

- HYPOTHESIS: Both undular bores and solitary waves may initiate convection ahead of boundaries behaving as a parent gravity current.

- TEST: Detect the presence of pre-frontal undular bores with airborne measurements from downward (nadir)-looking WCR, nadir- and possibly side-looking modes of Leandre II DIAL, and nadir-looking HRDL Doppler lidar and DLR DIAL. Map in vertical cross-section the flow pattern, convergence, and water vapor mixing ratio fields through bores, assess whether solitary waves are present, and document the parent GC. Determine occurrence of convective initiation from satellite imagery, WSR-88D surveillance radar, ELDORA, and WCR data

- REFUTE: Convection is not initiated from undular bores or solitary waves; or neither undular bores nor solitary waves are observed in conjunction with convective initiation.

- SPECIAL MEASUREMENT REQUIREMENTS: Leandre II may be more suitable for detecting undular bores in nadir-looking mode. If available, measurements from NASA LASE would also be useful in nadir-looking mode.

OBJECTIVE K4: Effect of boundary inflections on convective initiation and role of mesoscale circulations to modulate minima and maxima of water vapor mixing ratio and cloud spacing (Kingsmill, Wakimoto)

- PROCESS TO BE STUDIED: Horizontal wave patterns or shearing instabilities have been observed along many boundary layer convergence lines (e.g., McCarthy and Koch 1982; Carbone 1982,1983; Mueller and Carbone 1987; Wakimoto and Wilson 1989; Kingsmill 1995). They usually manifest themselves as a series of small scale vertical vorticity maxima (i.e., misocyclones) spaced at regular intervals along a boundary. These phenomena produce sign changes of boundary curvature (i.e. “inflections”) and have most often been used in the explanation of non-supercell tornadogenesis. However, in the more recent literature, there has been speculation that inflections play a role in convective initiation (Kingsmill 1995; Lee and Wilhelmson 1997). These studies have focused on the convergence and vertical velocity maxima that form adjacent to each of the vertical vorticity maxima. If the convergence and vertical velocity maxima are persistent, enhanced lifting of air parcels and convective development at these locations may result. Mesoscale circulations concentrate convergence at intersections of boundaries with horizontal convective rolls, also having expected consequences of locally increasing water vapor mixing ratio and depth of the moist layer and promoting convective initiation.

- HYPOTHESIS: Horizontal inflections in boundary layer convergence zones in a thermodynamically unstable environment are preferred areas of convective development due to enhanced lifting of air parcels at these locations. Locally convergent mesoscale circulations along boundaries are regions that create pockets of high water vapor content.

- TEST: Prior to the development of deep convection, sample the kinematic structure of the boundary within the full-depth of the boundary layer with clear-air Doppler radar (WSR-88D, mobile ground-based, ELDORA) to identify a boundary layer convergence line with inflection(s) and/or vortices. Sample the thermodynamic structure of the boundary within the full depth of the boundary layer with M-CLASS, mobile surface mesonet and airborne in-situ sensors, ground-based and airborne DIAL water vapor lidar, and mobile ground-based water vapor radiometer. Monitor for the development of deep convection with radars, satellite, and video photogrammetry. Doppler analysis determines mesoscale circulations. Airborne DIAL, profiler, and in-situ humidity measurements map water vapor distribution. Examine temporal-spatial correlations between locally convergent circulations and positive humidity anomalies. Compare remote and in-situ measurements with thermodynamic fields retrieved from dual-Doppler wind syntheses.

- REFUTE: In a thermodynamically unstable environment, convection does not preferentially form in the region of an inflection or vortex. No correlation exists between locally convergent mesoscale circulations, vortices, and moist pockets.

OBJECTIVE K5: Effect of vortices on vertical motion, absolute humidity, virtual temperature, and convective initiation (Rasmussen, Ziegler)

- PROCESS TO BE STUDIED: High-resolution surface data recently have been obtained from a mobile mesonet that shows that vortices exist on the Denver Convergence Zone and drylines with scales of 100-1000 m. Our observations of the deformation of water vapor mixing ratio gradients by embedded vortices suggest that these vortices transport near-ground water vapor horizontally. Visual observations show there may be an association between cumulus growth and the existence of a vortex, suggesting that vortices also lift water vapor. If enhanced convergence results from vortex interaction with the boundary, lifting of air parcels in vortices may result in locally increasing the water vapor mixing ratio, the depth of the moist layer, and the probability of convective initiation.

- HYPOTHESIS: Vortices along boundaries are associated with local maxima in vertical velocity, absolute humidity, virtual temperature, and frequency of convective initiation, have similar structure aloft as at the ground, and are connected to the boundary through its depth.

- TEST: Prior to the development of deep convection, sample the kinematic structure of the boundary within the full depth of the boundary layer with clear-air Doppler radar (WSR-88D, mobile ground-based, ELDORA) to identify a boundary layer convergence line with vortices. Sample the thermodynamic structure of the boundary within the full depth of the boundary layer with M-CLASS, surface Mobile Mesonet and airborne UAV in-situ sensors, ground-based and airborne DIAL water vapor lidar, and mobile ground-based water vapor radiometer. Monitor for the development of deep convection with radars, satellite, and video photogrammetry. Doppler analysis determines mesoscale circulations. Airborne DIAL, profiler, and in-situ humidity measurements map water vapor distribution. Examine temporal-spatial correlations between vortices, convergence and mesoscale updrafts, and positive humidity anomalies. Compare remote and in-situ measurements with thermodynamic fields retrieved from dual-Doppler wind syntheses.

- REFUTE: Convection does not preferentially form in vortices. No correlation exists between locally convergent mesoscale circulations, vortices, and moist pockets. Ground-detected vortices weaken/disappear with height below the boundary top/inversion. Virtual temperature perturbations aloft are not correlated with the existence of ground-detected vortices.

OBJECTIVE K6: Effect of variation of lift along mesoscale boundaries on spacing of convective initiation (Wakimoto)

- PROCESS TO BE STUDIED: Past observational and modeling studies have noted that cumulus clouds may develop at locations with enhanced boundary layer lifting along mesoscale boundaries given sufficient ambient moisture.

- HYPOTHESIS: The separation between individual convective cells along a boundary are controlled by locally convergent mesoscale circulations.

- TEST: Use mobile ground-based and airborne pseudo-dual Doppler radar clear air measurements to estimate 4-D mesoscale airflow circulations and air parcel trajectories in the CBL. Estimate surface-based and boundary layer parcel LCL and LFC using fixed and mobile surface observations, RPV traverses, and M-CLASS soundings. Measure cloud location and cloud top height using airborne cloud-sensing radar. Use visible imagery to locate clouds horizontally.

- REFUTE: Convective cells develop in regions not associated with locally convergent mesoscale circulations.

OBJECTIVE K7: Effect of lift and parcel instability along mesoscale boundaries on convective initiation (Ziegler)

- PROCESS TO BE STUDIED: A modeling study of dryline convective initiation determined that deep convective clouds may develop along the boundary at locations with strong, deep mesoscale updrafts given sufficient ambient water vapor (Ziegler et al. 1997). The predominant scale of lifting in those studies is mesoscale (~ 1-10 km length scale), that is, greater than the short length scales commonly associated with turbulent mixing. A study by Ziegler and Rasmussen (1998) demonstrated that cumulus cloud development is favored if the depth of the convergent inflow to the mesoscale updraft (i.e. level of non-divergence or maximum updraft) exceeds the Level of Free Convection (LFC). ZR also demonstrated that the height of the maximum updraft could be equated to the BL depth for scaling purposes. ZR suggested an analogous relationship between the depth of lifting, the Lifted Condensation Level (LCL), and the development of shallow cumulus clouds. ZR noted that any small-scale turbulent detrainment of moisture from the mesoscale updraft would be offset by the convergent motions below the level of non-divergence -- rendering the maximum updraft height a robust scaling parameter even in the presence of mixing. The likelihood of convective initiation may be generalized by a simple combination of local boundary layer parameters representing the length and time scales and the magnitudes of lift and water vapor content along the mesoscale boundary (Ziegler and Rasmussen 1998).

- HYPOTHESIS: Convective initiation requires deep mesoscale boundary layer convergence, subject to the constraints that updraft width exceeds the maximum local advective length scale and updraft depth exceeds the local Lifting Condensation Level (LCL) and Level of Free Convection (LFC). This hypothesis may be expressed by the following joint conditions on the dimensionless ratios of the latter length and depth scales: (1) For SHALLOW cumulus convection, R(LCL) = H/LCL > 1 and R*(LCL) = WxL/UxLCL > 1; (2) For DEEP cumulus convection, R(LFC) = H/LFC > 1 and R*(LFC) = WxL/UxLFC > 1; where by definition U = flow speed across updraft, W = peak updraft speed, L = updraft width, and H = height of peak updraft.

- TEST: Use mobile ground-based and airborne pseudo-dual Doppler radar clear air measurements to estimate 4-D mesoscale airflow circulations in the CBL. Estimate surface-based and boundary layer parcel LCL and LFC using observations from fixed and mobile mesonet, UAV traverse, dropsonde, mobile sounding, mobile profiler, and aircraft traverse. Measure cloud location and cloud base height with digital ground-based stereo and airborne cloud photogrammetry, visible satellite imagery, and airborne WCR data. Use cloud/mesoscale retrieval and data assimilation to blend above observations with high-resolution DIAL water vapor measurements, to estimate the 3-D virtual temperature and absolute humidity field and compute spatially variable LCL and LFC. Determine parameters U, W, L, H, LCL, and LFC at location of mesoscale updraft cores. Results will be stratified by boundary type, stability, and shear to evaluate predictability in a range of environments. Stratify cases with or without shallow/deep convection by respective R and R* values.

- REFUTE: **Shallow cumulus**: occurs with R(LCL) < 1, or R*(LCL) < 1, or both; or does not occur despite R(LCL) > 1 and R*(LCL) > 1. **Deep convection**: occurs with R(LFC) < 1, or R*(LFC) < 1, or both; or does not occur despite R(LFC) > 1 and R*(LFC) > 1.

OBJECTIVE K8: Location of CI relative to slope of baroclinic boundaries (Markowski)

- PROCESS TO BE STUDIED: This objective addresses the displacement of the location of convective initiation relative to the surface boundaries as a function of the slope of the kinematic or thermal boundary.

- HYPOTHESIS: The distance between the surface location of a thermal boundary and the location of CI on its cold side increases with decreasing boundary slope. Therefore, if slope decreases with increasing baroclinity, then convection initiated by boundaries associated with large density gradients will first develop on the cold side of the boundary, with the distance into the cold air increasing as the baroclinity associated with the boundary increases.

- TEST: Determine the baroclinity using mobile mesonet, UAV traverse, dropsonde, mobile sounding, mobile profiler, and aircraft traverse observations, and thermodynamic retrievals from Doppler wind synthesis. The baroclinity associated with thermal boundaries indicates a positive correlation between the baroclinity strength and the distance from the boundary location at the surface to the location of CI.

- REFUTE: Analyses of baroclinity strength and the distance from the boundary location at the surface to the location of convective initiation are uncorrelated or negatively correlated.

Moisture Controls on Convection Initiation (M)

OBJECTIVE M1: Moisture pooling along mesoscale boundaries and convective initiation (Kingsmill, Wakimoto, Weckwerth)

- PROCESS TO BE STUDIED: Recent simulations have highlighted the sensitivity of thunderstorm initiation to changes in the moisture and temperature profiles of the order of 1 g/kg and 1-3 deg C, respectively (e.g., Lee et al. 1991, Mueller et al. 1993, Crook 1996). Measurements from CLASS soundings provide relatively accurate profiles at point locations, however, results have shown that if horizontal convective rolls are present within the convective boundary layer, temperature and mixing ratio variations on the order of 0.5 K and 1.5-2.5 g/kg can be expected depending on the location of the sounding site relative to the rolls. Furthermore it was shown that the water vapor variations had the greatest effect on the variations in CAPE and CIN (Weckwerth et al. 1996). Stationary convergence lines have been shown to locally increase the magnitude and depth of the water vapor in their immediate vicinity (Wilson et al. 1992). Weckwerth (2000) deduced that if soundings were modified with maximum moisture amounts observed from cross-roll aircraft tracks, then they were effective in predicting thunderstorm formation. Other mesoscale features could cause similar deviations (e.g., variations in soil moisture). The modeling and observational studies collectively suggest a need for accurate and detailed measurements of the spatial and temporal variations of water vapor in the boundary layer.

- HYPOTHESIS: The initiation of deep convection is preferred at locations of maxima in magnitude and depth of water vapor along convergence zones. Horizontal moisture variability occurs across horizontal convective rolls and creates variations in stability. Local maxima in water vapor occur at the intersections between convergence zones, some of which may include horizontal convective rolls.

- TEST: Use ground-based mobile radars, ELDORA, and WSR-88Ds to identify the location(s) of the convergence zone(s). Dual- and pseudo-dual-Doppler analyses would provide the three-dimensional wind fields (including convective rolls) and locations of thunderstorm initiation. Airborne DIAL, profiler, and in-situ humidity measurements map water vapor distribution. An instrumented aircraft would be required to validate the water vapor remote sensor fields, as well as the along-line vertical velocity field. Two vertical pointing, mobile water vapor DIAL systems would be stationed along the zone to measure the profiles of water vapor at different locations along the line. Mobile CLASS soundings would also be launched at various locations along the line, including at the DIAL sites, to examine the along-line variations in CIN and CAPE. A scanning water vapor DIAL system would be located within the dual-Doppler lobe of the ground-based mobile radars and would measure the horizontal water vapor field along the convergence zone. It is also possible that we could use an airborne downward- or sideways-pointing DIAL system to map out the water vapor field along various flight tracks. The DRI mobile radiometer would make across- and along-line measurements of the vertically integrated water vapor. Mobile ground-based and airborne mesonets would provide useful information on the surface and boundary layer moisture distribution. Examine temporal-spatial correlations between convergence zones, rolls and cloud initiation.

- REFUTE: Thunderstorm initiation occurs at regions along a convergence zone which do not exhibit moisture maxima. Observe no moisture variations in the cross-roll direction, observe that the variations are of an insignificant magnitude so as not to influence CI, or observe significant moisture variations in absence of rolls. Making observations on a clear sunny day when there are no apparent rolls or boundaries, observe no significant variations in CBL moisture. Intersections of convergence zones do not have local maxima in water vapor.

- SPECIAL MEASUREMENT REQUIREMENTS: The ground-based mobile radiometer should sample both across and along the length of boundaries as feasible given available roads. The mobile radiometer should be deployed in cloudier regions to offset the DIAL lidar limitations in those areas. On occasion, the mobile radiometer should be co-located with the ground based DIAL and Raman system for intercomparisons. Downward pointing DIAL data from the Falcon, and (if available) from NASA LASE, with 30-50-km legs, would assist in filling in the vertical structure. Monitor moisture variability from fixed ground stations with scanning Raman lidar and vertically pointing DIAL. Obtain continuous profiles of temperature and water vapor with ground-based AERI and passive profiling radiometers from Radiometrics. Observe wave motions atop the CBL with wind profilers. Assess the low-level moisture variations with radar refractivity measurements from S-Pol.

OBJECTIVE M2: Origins of moist plume structures along boundaries and impact of water vapor plumes from dissipated cumuliform clouds on convective initiation (Knupp, Wakimoto)

- PROCESS TO BE STUDIED: There is some evidence that moist plume structures along boundaries results from transport by mesoscale circulations, and water vapor plumes from dissipated cumuliform clouds (ie. moist convection) may impact subsequent convective initiation. This hypothesis seeks to understand the role of moist plumes, including the dissipation of moist convection and the subsequent transport of enhanced water vapor fields over boundary layer convergence zones. Under high shear conditions, plumes will quickly become deformed, while under low shear conditions, a deeper layer of residual enhanced water vapor is expected. This hypothesis also implies that significant dynamic entrainment within accelerating updrafts of new Cu is most substantial within the several km deep layer above the BL (consistent with observations), and that this entrainment is detrimental to the development of Cu, particularly when the layer above the BL is very dry. Therefore, high water vapor density within this layer of dynamic entrainment will increase the survivability and intensity of growing Cu. The associated time scale is less than or of order 1 h for dissipated swelling or towering Cu and small Cb clouds.

- HYPOTHESIS: Moist plumes are advected to the highest elevations in regions characterized by deep mesoscale circulations. Plumes of residual vapor from dissipated moist convection will increase the probability of convective initiation (or enhance the convective initiation process) as these plumes are advected over active BL convergence zones downstream. While these plumes may rapidly become deformed by the vertical wind shear, the residual plume several km above the BL (e.g., (850 to 700 mb or so) is hypothesized to be the most important level, since it is within this level where “dynamic entrainment” of growing Cu is large. The efficiency of this mechanism is inversely proportional to a combination of (a) the diameter of the deep convective phenomenon, and (b) the vertical wind shear within a several km deep layer above the BL summit.

- TEST: Doppler analysis determines mesoscale circulations, while airborne DIAL, profiler, and in-situ humidity measurements map the water vapor distribution. Examine temporal-spatial correlations between locally convergent circulations and moist plumes. Measurements of the BL depth, and of wind profiles above the BL are required to understand water vapor transport above the BL. Estimate the transport and diffusion of the plume with a particle dispersion model with profiler data, either alone or in conjunction with a high-resolution mesoscale model. Measurements of water vapor profiles are needed at various locations and times "downstream" from regions where deep convection dissipates. Airborne DIAL would accomplish this, perhaps in combination with measurements of vertical water vapor profiles from a mobile ground-based system. Such measurements would document the evolution of the residual water vapor plume, by defining how it becomes deformed by the vertical shear.

- REFUTE: No correlation exists between moist plumes and circulations. Either convective initiation is not statistically favored in regions where elevated plumes of enhanced water vapor advance over active convergence zones, or plumes are observed to become so highly deformed or diffused that this mechanism cannot act.

- SPECIAL MEASUREMENT REQUIREMENTS: The Falcon flies along the boundary and the lidar looks downward in an attempt to sample the along-frontal variation in the vertical. Vertical profiles or 3-D distributions of water vapor and wind near and within the regions of dissipating cumuliform clouds are required.

Dynamical Effects Related to Convection Initiation (D)

OBJECTIVE D1: Depth of lifting at a convergence line (Crook)

- PROCESS TO BE STUDIED: The depth that boundary layer air is lifted at a convergence line may depend on local stratification and wind shear. Analytical relations between the depth of lifting and these parameters have been developed for an idealized convergence line (Crook and Klemp 2000).

- HYPOTHESIS: The depth that boundary layer air is lifted at a convergence line depends, among other things, on 3 parameters; the strength of convergence, the stability above the boundary layer and the flow above the convergence line.

- TEST: Identify a boundary layer convergence line before moist convection has developed along it. Find variations in the three parameters for the same convergence line. An individual line should exhibit variations in low-level convergence along it. The stability aloft should decrease as the boundary layer heats up, and the flow across the convergence line will vary if the orientation of the line varies. Hence an individual line should exhibit variations in the three parameters, which we have hypothesized will be correlated with changes in the depth of lifting.

- REFUTE: The depth of lifting either shows no dependence on the three parameters or shows a different dependence than predicted.

OBJECTIVE D2: Generation of convergent secondary circulations near mesoscale boundaries (Knupp, Wakimoto)

- PROCESS TO BE STUDIED: Increases in boundary layer convergence may occur during the transition from a convective boundary layer to an incipient stable boundary layer during the afternoon-evening period. Winds may increase during the latter transition period (e.g., Mahrt 1981), with two primary factors influencing the transition process: 1) the magnitude of the geostrophic wind (e.g., shear generated turbulence which offsets radiative cooling at the surface); 2) clouds and integrated water vapor which influence net longwave radiation from the surface. A combination of solenoidal and frontogenetic forcing may increase horizontal thermal gradients and vertical wind shear along boundaries. This evolution leads to increased moisture convergence to assist vertical moisture transport, convective initiation, and modulation of the early character of convection (e.g. increased updraft rotation). This enhanced convergence can possibly produce deeper water vapor perturbations and enhance the probability of convective initiation.

- HYPOTHESIS: During the late afternoon to early evening transition period from convective boundary layer to stable boundary layer conditions, the magnitude of convergence within existing convergence zones is increased as a consequence of increased winds from frictional decoupling above the surface. Increased convergence in turn produces a deeper zone of enhanced water vapor, and hence may increase the probability of convective initiation. Locally convergent mesoscale circulations are caused by the interaction of the boundary with horizontal convective rolls.

- TEST: Doppler analysis would determine morphology and evolution of secondary circulations and convective rolls. Analyze boundary layer profiler and sodar data to correlate temporal changes of the magnitudes of wind shear and solenoidal components normal to the boundary changes (increases) during the well-mixed afternoon and afternoon-evening transition conditions.

- REFUTE: Locally convergent mesoscale circulations are present in the absence of convective rolls, or shearing instability better predicts the spacing of the circulations. Increases in deep layer convergence and corresponding water vapor depth are not observed within the convergence zone during the transition period.

- SPECIAL MEASUREMENT REQUIREMENTS: Dropsondes are deployed with minimum spacing in a direction perpendicular to the boundary.

OBJECTIVE D3: Generation of secondary circulations near mesoscale boundaries (Ziegler, Markowski)

- PROCESS TO BE STUDIED: Frontal zones are regions of baroclinity by definition, but baroclinity is also commonly observed along drylines and outflow boundaries (e.g., Goff 1976; Mueller and Carbone 1987; Ziegler and Hane 1993; Ziegler and Rasmussen 1998; Atkins et al. 1998). Mesoscale modeling studies have documented the presence of horizontal virtual potential temperature gradients in the vicinity of drylines (eg. Ziegler et al. 1995; Ziegler et al. 1997). These horizontal virtual density gradients may be present at sunrise, and are modified by horizontal transport and surface heating patterns during the daytime. A combination of solenoidal and frontogenetic forcing may increase horizontal thermal gradients and vertical wind shear along boundaries. Increases in boundary layer convergence may persist during the transition from a convective boundary layer to an incipient stable boundary layer during the afternoon-evening period, as a result of persisting horizontal thermal gradients and solenoids. This evolution leads to increased moisture convergence, assisting vertical moisture transport and increasing the probability of convective initiation.

- HYPOTHESIS: Vertical wind shear normal to (ie. horizontal vorticity parallel to) and within the cool side of a mesoscale baroclinic boundary increases during the afternoon and evening from the action of a thermal solenoid, which induces a thermally direct secondary circulation. The secondary circulation leads to augmented moisture convergence and moisture depth, which may promote CI.

- TEST: Evaluate the horizontal vorticity component parallel to the mesoscale thermal boundary with ground-based mobile multiple-Doppler and airborne pseudo-dual Doppler analysis of the 3-D boundary layer airflow. Blend dynamically retrieved virtual temperature with mobile mesonet, UAV traverse, dropsonde, mobile sounding, mobile profiler, aircraft traverse, and high-resolution ground-based and airborne DIAL water vapor measurements to determine the solenoid field in the boundary layer. Evaluate correlation of changes in the horizontal vorticity component parallel to the boundary and the magnitude of the horizontal buoyancy gradient normal to the boundary.

- REFUTE: Locally increasing horizontal vorticity cannot be correlated with strength of baroclinity via the horizontal vorticity equation.

OBJECTIVE D4: Generation of buoyancy forcing along boundaries (Ziegler)

- PROCESS TO BE STUDIED: Observational studies of drylines have suggested that local maxima of virtual temperature may develop from the surface through the lowest 100-200 m of the CBL in a region of strong horizontal convergence (Ziegler and Hane 1993; Atkins et al, 1998; Ziegler and Rasmussen 1998). Modeling studies of drylines and their colocated mesoscale updrafts have documented the presence of enhanced horizontal vorticity solenoidal forcing on the updraft flank in the lower CBL (Ziegler et al. 1995) and virtual potential temperature plumes in the updraft cores (Ziegler et al. 1997). This effect may provide a source of thermal buoyancy for invigorating the mesoscale updraft.

- HYPOTHESIS: The unstable low-level stratification in the CBL is tilted into the horizontal by convergent circulations associated with mesoscale updrafts and boundaries, deforming and locally deepening the unstable layer.

- TEST: Evaluate the 3-D airflow across a mesoscale boundary in the CBL with ground-based mobile multiple-Doppler and airborne ELDORA and WCR pseudo-dual Doppler analysis. Blend dynamically retrieved and measured virtual potential temperature from mobile mesonet, UAV traverse, dropsonde, mobile sounding, mobile profiler, and aircraft traverse observations. Compute kinematic frontogenesis terms, and use a kinematic continuity retrieval model with an insulated lower boundary to compute the virtual potential temperature field across the low-level mesoscale updraft. Compare kinematically modeled and observed virtual potential temperature fields with kinematic frontogenesis terms.

- REFUTE: Neither a deepening of the unstable stratification nor a local maximum of virtual potential temperature are observed in low-levels of mesoscale updrafts in the CBL. Equivalently, kinematically modeled tilting frontogenesis does not produce either a deepening of the unstable stratification or a local maximum of virtual potential temperature in low-levels of mesoscale updrafts in the CBL.

OBJECTIVE D5: Dissipation rate of horizontal vorticity near boundaries (Markowski)

- PROCESS TO BE STUDIED: This objective addresses the longevity of secondary circulations near boundaries as influenced by turbulent dissipation. Horizontal vorticity generated by horizontal density gradients "outlives" the density gradients by a time scale dictated by the turbulent dissipation of the vorticity. For example, an outflow boundary initially may be associated with a large thermal gradient, which baroclinically generates primarily horizontal vorticity. Over time, the thermal gradient associated with the outflow boundary tends to weaken owing to modification of the cold air mass; however, there is some evidence that the dissipation of the baroclinic horizontal vorticity (Dutton 1986) has a time scale of a few hours (Markowski et al. 1998). Thus, the effects of solenoids may be important to CI even after the solenoids themselves have diminished. The vorticity dissipation rate (for the total horizontal vorticity, which includes both the baroclinic horizontal vorticity described above as well as the barotropic horizontal vorticity) is expected to vary according to the static stability and ambient vertical wind shear. In cases in which the density contrast across a boundary has dissipated, how long does the baroclinic vorticity persist, and how does this timescale vary?

- HYPOTHESIS: The horizontal vorticity dissipation rate increases as the mean static stability decreases and the mean vertical wind shear increases.

- TEST Measurements of low-level static stability (from mobile soundings, dropsondes, UAV, and aircraft stepped traverses) are negatively correlated with horizontal vorticity dissipation rates, as diagnosed by three-dimensional syntheses of mobile ground-based and airborne Doppler radar data, sounding data, UAV data, aircraft stepped traverses, and mobile profiler data. Measurements of the mean vertical wind shear (from multiple-Doppler radar wind syntheses) are positively correlated with horizontal vorticity dissipation rates.

- REFUTE: The dissipation rates of horizontal vorticity are uncorrelated or positively correlated with low-level static stability, and uncorrelated or negatively correlated with mean vertical wind shear measurements.

OBJECTIVE D6: Role of internal gravity waves to modulate minima and maxima of water vapor mixing ratio, cloud initiation, and cloud spacing (Wakimoto, Weckwerth)

- PROCESS TO BE STUDIED: Mesoscale circulations concentrate convergence at intersections of boundaries with horizontal convective rolls. This has expected consequences of locally increasing water vapor mixing ratio and depth of the moist layer and promoting convective initiation.

- HYPOTHESIS: Upper-level gravity waves appear to modulate the locations and spacing of convective cells along boundaries. Horizontal moisture variability occurs above the CBL. These variations are caused by internal gravity waves and may influence the initiation and organization of convection atop rolls and other boundaries.

- TEST: Doppler analysis resolves convective rolls. Airborne DIAL, profiler, and in-situ humidity measurements map water vapor distribution. Examine temporal-spatial correlations between rolls and cloud initiation.

- REFUTE: Upper level gravity waves are not observed with convective initiation, or cells develop in regions not predictable by upper level gravity waves. Make observations above the CBL and observe no variations in moisture or find no relationship between these variations and gravity waves.

OBJECTIVE D7: (Wakimoto)

- PROCESS TO BE STUDIED: Rotunno et al. (1988) (eg. RKW) have theorized that an optimal state of balance exists between the positive horizontal gradient of the vertical wind shear and the negative horizontal vorticity produced within the cold pool resulting in a storm with a strong, vertically oriented updraft. There have been some attempts (e.g., Carbone et al. 1990, Mueller et al. 1993) to verify the importance of this effect for the initiation of new convection, but there has never been a comprehensive data set to fully test the Rotunno et al. (1988) hypothesis. Indeed, Mueller et al. (1993)

found insufficient evidence whether a favorable low-level shear vector was a major factor in promoting storm initiation in their study. In addition, Fovell and Ogura (1989) have argued that long-lived squall lines can still exist when there are significant departures from this optimal state. A generalization of this principle is sought to boundary layers with solenoidal forcing outside of active thunderstorm outflows.

- HYPOTHESIS: Convective initiation occurs in regions where the vertical shear produced by a baroclinic circulation balances the environmental shear.

- TEST: Collect significant along-boundary data using ELDORA and DIAL, including thunderstorm outflows if non-thunderstorm outflow boundaries are also sampled. The dropsonde aircraft would fly legs perpendicular to and at least 100-175 km to either side of the boundary to determine the environmental and cool-side conditions.

- REFUTE: Convection initiates along boundaries that are significantly displaced from the balanced state proposed by RKW.

- SPECIAL MEASUREMENT REQUIREMENTS: Dropsondes are deployed with minimum spacing in a direction perpendicular to the boundary.

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