Scientific Overview Document

For
The International H_2O Project
(IHOP_2002)

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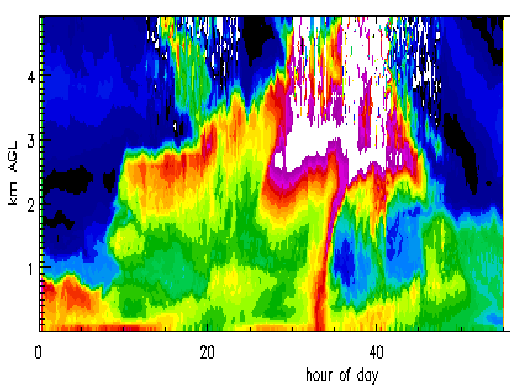
Improved Prediction of Convective Rainfall

Improved Water Vapor Measurements



Improved Understanding of Convective Initiation and Boundary Layer Processes

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1. Executive Summary

The International H_2O Project (IHOP_2002) is a field experiment scheduled to take place over the Southern Great Plains (SGP) of the United States from 13 May to 30 June 2002. The chief aim of IHOP_2002 is improved characterization of the four-dimensional (4-D) distribution of water vapor and its application to improving the understanding and prediction of convection. The region is an optimal location due to existing experimental and operational facilities, strong variability in moisture, and active convection. Currently, IHOP_2002 has attracted investigators from the U.S. university community, the National Center for Atmospheric Research (NCAR), various laboratories of the National Aeronautics and Space Agency (NASA) and of the National Oceanic and Atmospheric Administration (NOAA), and from Germany, France and Canada. A complete list of potential participants can be found in Table 1.

The IHOP_2002 investigators will focus on four coordinated and overlapping research components:

- *The Quantitative Precipitation Forecast* (QPF) research component seeks to determine the degree of improvement in forecast skill that occurs through improved characterization of the water vapor field. This work includes a variety of research and operational numerical modeling, assimilation, and nowcasting systems.

- *The Convective Initiation* research component seeks to further understand and eventually predict the processes that determine where and when convection forms. The convective initiation effort will also target mobile measurements where convective initiation is forecasted to occur and determine their impact on forecasts, following the strategy of winter experiments such as FASTEX (Joly et al. 1997).

- *The Atmospheric Boundary Layer Processes* research component seeks to improve understanding of the relationship between atmospheric water vapor and surface and boundary layer processes as they relate to warm season QPF. It is clear that forecasts beyond several hours require an accurate treatment of boundary and surface layer processes.

- *The Instrumentation* research component seeks to determine the optimal mix of water vapor measurement strategies to better predict warm season rainfall. This group will also work toward better quantification of measurement accuracy, precision and performance limitations as they relate to using water vapor measurements in warm season forecasts and assimilation systems.

2. Program Rationale

Accurate prediction of precipitation amounts has remained an elusive goal for the atmospheric sciences (e.g., Emanuel et al. 1995; Dabberdt and Schlatter 1996). Although improvements in QPF skill have occurred in recent years, QPF skill has not advanced as rapidly as the prediction of other variables. At present, QPF skill also varies seasonally (e.g., Uccellini et al. 1994) with the summer marked by significantly lower forecast skill (Fig. 1). An examination of the ratio of winter to summer QPF skill for recent years suggests that seasonal variations in skill score for heavier rainfall amounts may in fact be getting larger (Fig. 2). Thus, the small gains in QPF skill mentioned earlier are therefore likely occurring during the winter season when the skill is already significantly higher. The extremely low skill scores and the relative lack of progress for warm season rainfall are particularly worrisome as significant weather hazards result from warm season rainfall. For example, the overwhelming majority of flash floods take place during the late spring and summer (Maddox et al. 1979) (Fig. 3). Flash floods have recently been

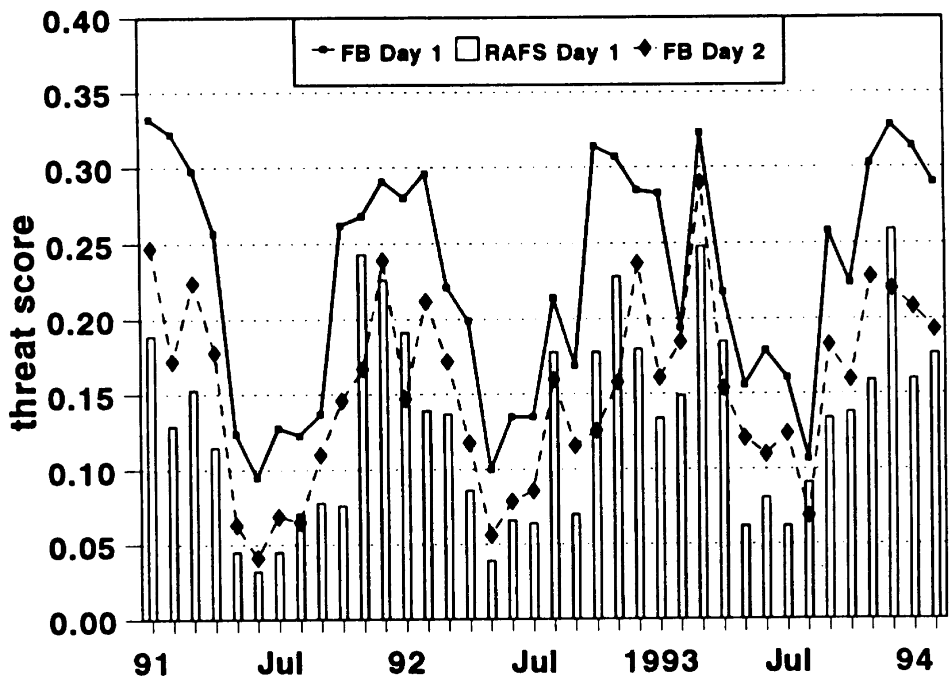

Figure 1: Monthly threat scores for quantitative precipitation forecasts at the 1" or greater threshold for the period from January 1991 through January 1994. Threat scores are plotted for the NGM/RAFS models for the 0 to 24-h period and for forecaster based (FB) predictions at the 0 to 24-h and 24 to 48-h. Adapted from Uccellini et al (1994).

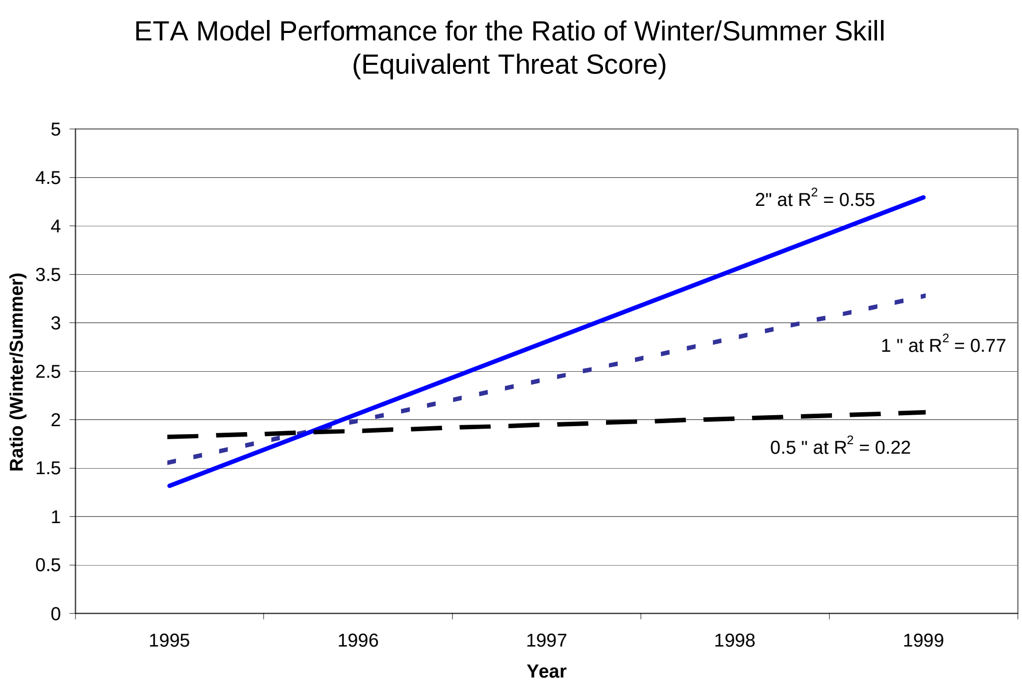

Figure 2: The ratio of QPF skill for the ratio winter (Dec., Jan. Feb.) skill divided by summer (June, July, Aug.) for the early Eta and Eta model. The three lines represent best fit lines for three different rainfall thresholds. The variances for each of the three threshold levels are plotted next to the best-fit lines. The general trends are for winter skill to be improving faster than the summer skill as the rainfall thresholds increase. From statistics found on http://www.emc.ncep.noaa.gov/mmb/mesoscale.html.

responsible for more deaths than either hurricanes, tornadoes, wind storms or lightning (Doswell et al. 1996). The annual property damage from flash flooding has been steadily growing with amounts recently exceeding $5 billion (U.S. Army Corps. of Engineers 1998). Even a casual review of literature during this past decade indicates that warm season floods are not a regional problem, but one that is national and international in scope.

Some of this lack of skill in summer QPF for heavy rainfall is surely related to the fact that current prediction models must parameterize convection as a sub-grid scale event. Evidence suggests, however, that an accurate characterization of water vapor in the lower atmosphere is a necessary condition for quantitative prediction of precipitation in models with parameterized convection (e.g., Perkey 1976; Mills 1983; Mills and Davidson 1987; Mailhot et al. 1989; Bell and Hammon 1989; Emanuel et al. 1995; Dabberdt and Schlatter 1996; Koch et al. 1997). Predicting the initiation of convection in cloud resolving models can also be highly dependent on very accurate estimates of water vapor within and just above the boundary layer (Crook 1996). Such a relationship is expected as prediction of convective precipitation is strongly dependent on the vertical profile of buoyancy within clouds and this buoyancy strongly depends on the magnitude of water vapor within the boundary layer. Once convection develops, the vertical profile of water vapor is of first order importance in the prediction of precipitation rates, since water vapor is directly involved in determining various thermodynamic and microphysical processes.

While water vapor may hold the key for improvements in QPF skill, water vapor presents a unique challenge for instrumentation technology as water vapor content can vary over three orders of magnitude in the troposphere. Atmospheric water also exists in three phases, which provides additional challenges for observing strategies. Despite the importance of water vapor to atmospheric studies, current observational technologies for measuring water vapor are inadequate. For example, large humidity biases that often exceed 5% throughout the troposphere have been recently documented in radiosonde data (Guichard et al. 2000). These biases make quantitative and sometimes even the qualitative interpretation of spatial and temporal changes in the CAPE (Convective Available Potential Energy) and CIN (Convective Inhibition), important parameters in diagnosing convective activity, extremely difficult (e.g., Guichard et al. 2000). Upper-troposphere biases also exist in this measurement (Soden and Lanzante 1996), potentially leading to an under prediction of clouds in numerical weather prediction models (Lorenc et al. 1996).

Accurate characterization of the three dimensional (3-D) distribution of water vapor is also difficult as water vapor observations can suffer from large sampling errors. Water vapor, for example, can vary substantially in the vertical as evidenced by thin cloud layers. Numerical models often lack sufficient vertical resolution to adequately represent these strong vertical variations, particularly near the top of the boundary layer where entrainment and detrainment processes are often poorly represented. Observational studies have also shown that there are frequently large variations in water vapor concentration in the pre-convective environments on the convective-scale (Weckwerth et al. 1996; Koch and Clark 1999) (Fig. 4) and on the mesoscale (Koch et al. 1997; Parsons et al. 2000). These variations have been linked to the initiation of severe

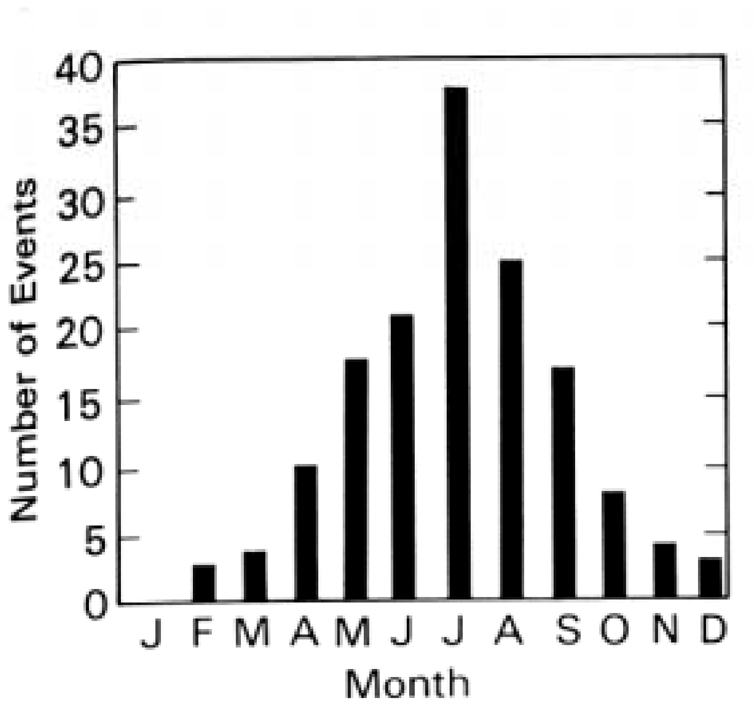

Figure 3: Distribution of 151 floods in a 5-year period. Adapted from Maddox et al. (1979).

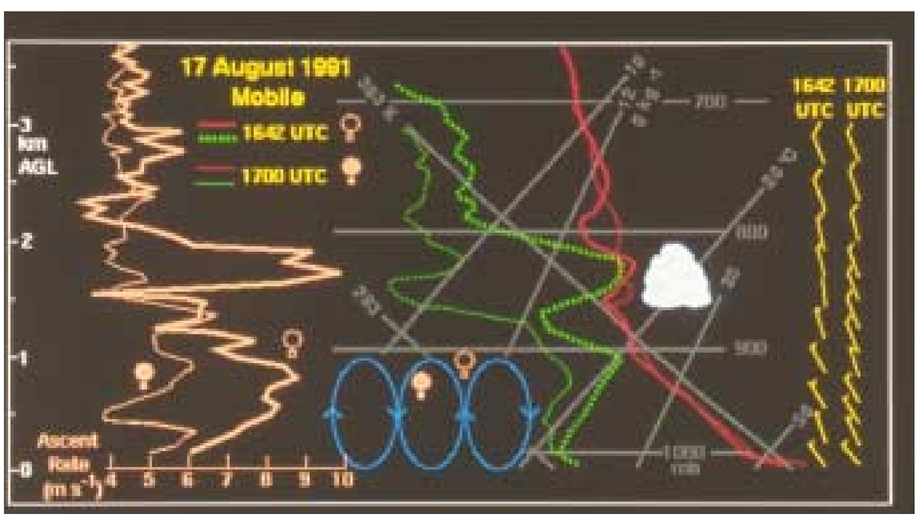

Figure 4: Ascent rate, water vapor mixing ratio, temperature and winds from two rawinsondes launched through a convective boundary layer in Florida. Although the soundings were taken only 18 minutes apart there are significant differences, particular in the mixing ratios. The reason for this difference is that one sonde ascended through the updraft of a convective roll, while the drier sounding was taken within a roll downdraft. Weckwerth et al. (1996).

weather. The large horizontal variations in the water vapor field are expected, since, unlike temperature, pressure and wind, water vapor is not constrained by dynamical balances to vary slowly on the scale of the deformation radius (Emanuel et al. 1995). When realistic mesoscale details in the relative humidity and surface moisture availability are included, pronounced improvements in forecast skill for convective events can occur (e.g., Koch et al. 1997).

New operational systems, such as Next- Generation Weather Radar (NEXRAD), Aircraft Communications Addressing and Reporting System (ACARS) and the Wind Profiler Network (WPN) deployed within the central United States, have improved the sampling of wind and other variables. In contrast, despite the importance of mesoscale variations in water vapor to forecasting convective activity, we note that there are no operational remote sensing systems for obtaining accurate vertical profiles of water vapor with correspondingly high vertical and temporal resolution. Fortunately, instrumentation to accurately measure water vapor does exist in the research community (e.g., Weckwerth et al. 2000) including water vapor Differential Absorption Lidar (DIAL) and Raman lidars, Fourier-Transform Infrared spectrometer (FTIR) spectrometers, radar refractivity techniques, Global Positioning System (GPS), interferometric Synthetic Aperture Radar (SAR) techniques, satellite Atmospheric Infrared Sounder (AIRS) measurements and combined sensor approaches. Despite this abundance of research instrumentation, to date there has not been a broad collection of ground-based and airborne water vapor remote sensors assembled to address the issues associated with *the time varying, 3-D distribution of water vapor and its impact on the understanding and prediction of warm season precipitation events.* In addition, studies of how these measurements can best be incorporated into prediction systems that employ modern assimilation techniques are in their infancy (e.g., Guo et al. 2000), so that the utility of these new data sets for prediction purposes is relatively unknown. For example, error co-variances and forward models have not been developed for the assimilation of some of the measurements taken by these new technologies. In addition, the performance limitations of water vapor instrumentation have not been sufficiently explored within the context of improved operational prediction of convective weather and heavy rainfall.

Thus, IHOP_2002 was originally motivated as follows: (1) The need to improve the 3-D characterization of water vapor and related surface properties through improved measurements and/or assimilation techniques. (2) QPF skill is extremely low during the warm season. (3) Warm season skill may not be improving as fast as for the winter season. (4) Significant national safety hazards occur with heavy rainfall during the warm season. (5) The degree to which warm season QPF skill can be improved through better characterization of the 4-D distribution of water vapor needs careful evaluation. This early motivation led to the formation of the QPF and water vapor instrumentation components. After IHOP_2002 was conceptualized, it became evident that in order for the project to be successful, the experiment needed to be broadened to include two areas crucial to the QPF problem where a lack of quality water vapor measurements have limited our scientific understanding and ability to predict convective activity. In particular, improved predictions of the location and timing of the initial convective development were determined to be fundamental to any attempt to improve warm season QPF skill. Successful predictions of convective initiation and subsequent predictions of rainfall amounts are also, in turn, directly dependent upon accurate determination of surface and atmospheric boundary layer processes. Thus, convective initiation and atmospheric boundary layer components were enthusiastically added to the project.

3. Relationship of IHOP_2002 to National Research Priorities

The U.S. Weather Research Program (USWRP) has convened Prospective Development Teams (PDTs) composed of small groups of scientists and technologists on a one-time basis to discuss critical issues and provide advice on the future direction of the program. The 1st PDT was convened to provide NOAA and the National Science Foundation (NSF) with long-range planning in research in atmospheric dynamics with an emphasis on examination of the research goals of the USWRP. The primary purpose of the 1st PDT, as summarized in Emanuel et al. (1995), was to identify intellectually challenging research areas that may lead to improvements in weather observations, forecasting and warning, and thus would be of great benefit to society. Among their recommendations, the 1st PDT concluded that

> "Improvement in numerical weather prediction, and especially quantitative precipitation forecasting, is severely impeded by poorly resolved and inaccurate measurements of atmospheric water vapor. High priority must be given to new water vapor measurement systems and to research that seeks to delineate the water vapor observations necessary to address specific forecast problems."

The 1st PDT (Emanuel et al. 1995) further notes in a summary of recommendations that

> "Much improved measurements of land surface properties, especially soil moisture, and better understanding of land-atmosphere interaction may hold the key to dramatic improvements in a number of forecasting problems, including the location and timing of the onset of deep convection over land, quantitative precipitation forecasting in general, and seasonal climate prediction".

A 2nd PDT (Dabberdt and Schlatter 1996) was convened to identify research opportunities from emerging atmospheric observing technologies and modeling capabilities. The 2nd PDT echoed the findings of the 1st PDT and in the summary of major recommendations stated

> "There is a need to conduct a comprehensive pilot field measurement and mesoscale modeling study to test the efficacy of possible composite operational water vapor observing systems, including those pertaining to satellite-derived moisture analyses (in conjunction with in-situ calibration data) for regional scale applications."

The close link between the goals of IHOP_2002 and the findings of the USWRP has led to IHOP_2002 being incorporated into the USWRP Implementation Plan, which also directs future research to help meet the recently outlined National Weather Service (NWS) forecast goals. Their implementation plan notes that IHOP_2002 will contribute to meeting the NWS forecast goals of improving the lead time for flash floods, of improving QPF skill for 24-h forecasts, and of determining the optimal mix of future measurement strategies. Table 2 details a list of potential deliverables to the operational community. IHOP_2002 will directly benefit other research areas as well, as knowledge of the distribution of water vapor is vitally important for many other key topics of the atmospheric sciences. For example, the National Academy Press recently published a report by the Board of the Atmospheric Sciences and Climate (BASC) entitled The Atmospheric Sciences:

Entering the Twenty-First Century (National Research Council 1998a). The report is meant to provide a comprehensive assessment of the atmospheric sciences and a vision of the future. Several areas of this report relate directly to the IHOP_2002 project. In terms of the importance of water vapor to the atmospheric sciences, the BASC notes

"On the storm scale, prediction of convective precipitation is limited by uncertainty in the distribution of water vapor in the atmosphere and the amount of water in the soil. On the longest time scale, water vapor is the most important greenhouse gas, and significant uncertainty in climate models can be traced to inadequate understanding of the water budget and water-induced radiation feedbacks. Water vapor in the atmosphere varies markedly over small scales vertically and horizontally; thus, its variability is significant at scales not resolvable by the radiosonde network."

The BASC report lists two high priority imperatives for the atmospheric sciences with the 1st being

"**To Optimize and Integrate Observational Capabilities:** The atmospheric sciences community and relevant federal agencies should develop a specific plan for optimizing global observations of the atmosphere, oceans and land. This plan should take into account requirements for monitoring weather, climate and air quality and for providing the information needed to improve numerical models used for weather, climate, air chemistry, air quality, and near-Earth space physics activities. The process should involve a continuous interaction between the research and operational communities and should delineate critical scientific and engineering issues. Proposed configurations of the national and international observing systems should be examined with the aid of observing system simulation experiments."

IHOP_2002 falls under this imperative as the experiment concentrates on establishing the observing requirements for improved numerical prediction of convective weather and will provide information necessary for conducting realistic observing system simulation experiments (OSSEs). Our focus on improving water vapor measurements and their use in research and operational forecasts falls within the 2nd Imperative of the BASC report, which is

"**Develop New Observational Capabilities:** The federal agencies involved in atmospheric science should commit to a strategy, priorities, and a program for developing new capabilities for observing critical variables, including water in all its phases, wind, aerosol, and chemical constituents, and variables related to phenomena in near-Earth space, all on spatial and temporal scales relevant to forecasts and applications….."

The BASC report further highlights the need for improved water vapor measurements, as the Working Group on Atmospheric Dynamics and Weather Forecasting also specifically states below the current shortcomings in measurement technology

"Yet existing means of characterizing the distribution of water vapor are greatly inadequate if not totally absent. First order improvements in both the quality and the quantity of atmospheric water vapor measurements will be necessary."

The BASC report also makes two recommendations

(1) "High priority must be given to new water vapor measurement systems and to research that seeks to delineate the water vapor observations necessary to address specific research and forecast problems."

(2) "We strongly encourage the support of research seeking to determine optimal combinations of satellite and ground-based remote sensing, and aircraft, balloon, and surface observations, as well as support of key technological developments such as satellite borne active sensing techniques, near-field remote sensing of atmospheric water vapor, and observations from commercial and pilotless aircraft."

Improved water vapor measurements are also crucial to climate research. The Committee on Global Change Research in their National Research Council (NRC) report entitled Overview Global

Environmental Change: Research Pathways for the Next Decade (National Research Council 1998b) discusses the need for better water vapor measurements. The report, for example, notes a key need in the area of technical innovation regarding

"Establishing the distribution of water in the atmosphere and the fluxes of water between the Earth's surface and the Earth's atmosphere."

This NRC report arguing that future climate change research must

"Clarify the distribution and fates of water vapor." as "Water is at the heart of climate change and impacts of climate variability. Any assessment of climate change, its causes and impacts, must be based on significantly better observations of water vapor."

4. Scientific Goals and Hypotheses

4.1 The Quantitative Precipitation Forecast Component

The primary hypothesis for the QPF component of IHOP_2002 is *"Improved characterization of the water vapor field will result in significant, detectable improvements in warm-season QPF skill."* The first step in testing this hypothesis is to accurately characterize the time varying, 3-D distribution of water vapor in a warm season environment. In order to characterize the water vapor field, we plan to utilize a network of existing and specially deployed ground-based sensors that include radar with refractivity capability for water vapor, Raman and water vapor DIAL lidars, passive radiometric profiling, radiometers designed to measure the vertically integrated water vapor content, and a network of GPS sensors designed to measure the vertically integrated water vapor and, in most cases, slant range water vapor measurements. We will also utilize satellite measurements, in-situ humidity observations taken by commercial aircraft, research aircraft instrumented with water vapor DIAL in a downward looking mode, with dropsondes and with mobile targeted measurements. With these observations, we will map the evolution of the 3-D distribution of water vapor over horizontal areas that approach $1\mathrm{x}10^5$ km^2. The aircraft measurements will also allow for the imitation of different operational sampling strategies. Thus, the measurements employed in IHOP_2002 will allow a determination, with unprecedented accuracy and resolution, of the magnitude and spatial scales of the variation in water vapor in pre-convective and convective environments. The improved characterization of the 3-D features within the water vapor field will allow us to better quantify the current degree of uncertainty in model initial conditions and the predicted evolution of the water vapor and, to a lesser extent, the cloud fields. Careful evaluation of water vapor fields in simulations can currently be difficult due to a general lack of accurate water vapor measurements on spatial scales that are compatible with the model's vertical and horizontal resolution, particularly for cloud resolving and mesoscale models.

An accurate characterization of the water vapor field also requires determination of how to best combine these diverse measurement, which is closely related to determining the optimal mix of measurement/assimilation strategies. IHOP_2002's inclusion of a variety of water vapor technologies will allow the relative impacts of the different sensors to be investigated and provide those working on assimilation with the opportunity to gain experience with these instruments and knowledge concerning their errors and performance limitations. The participating instrumentation experts are also committed to assisting those investigating assimilation techniques in deriving the error matrices and forward models necessary for assimilation techniques as those working in the area of data assimilation often agonize about the error matrices for new sensors when investigating the impact of new sensors in OSSEs. However, the question of when and where to disallow measurements in OSSEs due to the potential performance limitations of new sensors is an even larger unknown. The degree to which airborne or ground-based water vapor lidars will be unable to derive useful data ahead of active convective systems due to optically thick clouds, for example, remains relatively unaddressed. IHOP_2002 will provide insight into the performance characteristics of a variety of water vapor sensors so that meaningful OSSE and real-data assimilation experiments can be designed. In addition to efforts focused on assimilating water vapor measurements, work is also planned examining the impact of assimilating detailed surface and boundary layer observations (see subsequent section on boundary layer processes.)

The assimilation systems employed for IHOP_2002 generally match the modeling capabilities (Table 3) and range from operational strategies to 2- and 3-D variational approaches. Variational data assimilation techniques offer great promise for mesoscale forecasts of warm season rainfall, partly due to their ability to use measurements that are not predictive variables in forecast models. For example, MacDonald et al. (2000) suggest a large positive impact of GPS slant range measurements on the water vapor field through utilizing 3-D variational techniques in an OSSE. Using actual observations, Guo et al. (2000) found encouraging improvements in model initial conditions through assimilating different data combinations: surface rainfall, wind profiler measurements, ground-based GPS vertically integrated measurements, and surface dew point measurements within a 4-D variational approach. Guo et al. (2000) found assimilating the dynamical information (i.e., winds from the profiler network) produced a greater positive impact on the vertical profile of water vapor than assimilation of either the surface dew point or the GPS vertically integrated water vapor measurements, in contrast to the large positive impact found by MacDonald et al. (2000). The extensive IHOP_2002 data set will help address inconsistencies that arise from using different models, assimilation techniques, and weather situations in case study modes.

The final step in testing our primary hypothesis will be to determine the impact of improved water vapor characterization on QPF skill. Operational modeling efforts are committed to make full use of data sets produced by IHOP_2002. After the experiment, forecast impact studies will be undertaken on a variety of scales including operational, mesoscale, and cloud-resolving numerical models (Table 3). The impact of improved water vapor measurements on nowcasting techniques and radar-model mixed approaches (e.g., Wilson et al. 1998) will also be tested. Such approaches have shown relatively superior skill for short-range forecasts (<1-2 h) and have demonstrated significant improvement in forecast skill for short-range predictions of thunderstorm movement and evolution in operational settings. We believe that these nowcasting techniques are the most likely route for improving the current lead-time (i.e., < 1 h) for flash floods warnings. Precipitation and runoff estimation will also be undertaken in collaboration with operational efforts. Several investigators have also expressed interest in placing these impact studies in the context of understanding the limits of predictability for convective systems. This question is crucial to understanding the degree to which warm season rainfall predictions can be improved. In addition, investigators plan to use the knowledge of how water vapor varies in a pre-convective environment to determine how to conduct ensemble simulations for better prediction of convective rainfall.

4.2 The Convective Initiation Component

The impact of convective initiation on the warm-season QPF process may be likened to choosing a decision point in a semi-chaotic system (Stensrud and Bao 1992), wherein persistent isolated or widespread convection is set in motion depending on the probability of occurrence or non-occurrence of convective initiation. The forecast accuracy for a mesoscale model, for example, would be strongly dependent on the accuracy of the forecast of the initial convective development and then subsequently on how well the convective parameterization replicates both the subgrid scale and the upscale effects of convection (Kain and Fritsch 1992; Stensrud and Fritsch 1994). An important step toward realizing more accurate QPFs of warm-season convective precipitation in human and numerical forecasts would thus result from improved prediction of the timing and location of any initial convective development. It is not surprising that discussions between IHOP_2002 investigators and forecasters at the NOAA/NCEP/Storm Prediction Center and several NWS Southern Region forecast offices have identified the problem of where and when deep, moist convection will initially form as a key concern for operationally predicting severe convective weather.

The primary objective of the convective initiation group in IHOP_2002 is to improve the understanding of processes that initiate active deep, moist convection over the SGP. Our current understanding in this area is that there is increasing evidence from observational and modeling studies that mesoscale forcing along boundaries with widths of ~10 km or less is often critical to the initiation of convection, rather than storms simply forming as “air mass convection” resulting from some mean convective instability within a coarse model grid box. Successfully forecasting the location and timing of any convective initiation requires anticipating or observing the formation, movement, and structure of mesoscale boundaries. Another key to successfully forecasting convection initiation is to accurately predict the mesoscale forcing at these boundaries, which in turn requires accurate characterization of variations in stratification, wind shear, airflow convergence, and virtual temperature in the vicinity of boundaries as well as the mesoscale water vapor field. The work of this component centers on using measurements in the vicinity of boundaries to test hypotheses concerning how convective initiation typically occurs over this region. A full list of testable hypotheses related to the convective initiation research goals has been prepared and is available upon request. These hypotheses can be grouped into three main sub-themes: kinematic controls, moisture controls, and dynamical forcing, which are listed along with individual objectives as follows:

1) **Kinematic controls.** Dryline/outflow boundary kinematic effects on convective initiation or inhibition (Weiss 2000); Role of undular bores or solitary waves for convective initiation (Carbone et al. 1990; Karyampudi et al 1995; Koch and Clark 1999); Effect of boundary inflections and vortices on convective initiation and role of mesoscale circulations to modulate minima and maxima of absolute humidity and cloud spacing (Kingsmill 1995; McCarthy and Koch 1982); Effect of ambient mean cross-dryline flow in LCL-to-LFC layer on convective initiation (Peckham and Wicker 2000); Effect of lift along mesoscale boundaries on convective initiation (Ziegler and Rasmussen 1998).

2) **Moisture controls.** Moisture pooling along mesoscale boundaries and convective initiation (Crook 1996; Mueller et al. 1993; Wilson et al. 1992; Weckwerth et al. 1996; Weckwerth 2000); Origins of moist plume structures along boundaries and impact of water vapor plumes from dissipated cumuliform clouds on creating an environment more favorable for convective initiation.

3) **Dynamical forcing.** Variations in the depth of lifting at a convergence line (Crook and Klemp 2000); Generation of regional and local scale convergent secondary circulations near mesoscale boundaries (Mahrt 1981; Ziegler et al. 1997); Role of internal gravity waves to modulate minima and maxima of absolute humidity, cloud initiation, and cloud spacing.

The time continuous ground-based measurement sites deployed for the QPF and boundary layer studies will prove useful in characterizing the mesoscale environment and in understanding the forcing at boundaries that advect by these sites (Fig. 5 and 6). However, testing the various primary convective initiation hypotheses will largely rely on mobile sampling of kinematic and thermodynamic parameters, including a relatively improved sampling of water vapor. On a daily basis, forecasters and nowcasters will direct the mobile armada to a particular target segment of a boundary within the region that is judged to have a significant likelihood of storm development. In order for measurements to be candidates for study, the boundaries must be rather slowly moving, thus permitting detailed observation; surface-based, thereby facilitating operational detection; and rather common over the SGP during the proposed May-June time frame. A typical operating scenario would include mobile Doppler radars, a ground-based mobile radiometer, a Mobile Integrated Profiling System (MIPS), a mobile passive radiometer, mobile rawinsonde systems, ground-based and remotely piloted airborne mobile mesonets to be deployed to a specified boundary segment to intensively observe scales < 10 km. Airborne platforms with multiple remote sensing systems will also be utilized. Specifically, airborne measurements from a sideways-pointing water vapor DIAL, pseudo-dual Doppler radar, a Doppler cloud radar and a vertically-pointing aerosol lidar would be taken from an aircraft performing a series of large box patterns around the boundary with flight legs parallel to the primary boundaries of interest. The sampling would preferably commence well before the initiation of convection and encompass the period of active initiation of deep convection. Since the evolution of mesoscale structures hypothesized to control initiation must be resolved, an adequately refined sampling area is required for airborne legs of 40-50 km. A dropsonde aircraft would follow this aircraft at a higher altitude generating profiles at the maximum feasible rate. Surveillance radar observations from mobile and fixed ground-based systems are required for intercomparison and real-time field coordination of the sampling in the context of clear air radar signatures.

Ancillary objectives will be pursued using these data sets including:

1) Explore the accuracy, spatial scales, and temporal resolution of water vapor measurements necessary for successful operational prediction of convection onset using the high-resolution measurements of water vapor taken during IHOP_2002;

2) Establish how skillfully cloud resolving, mesoscale and operational models predict the initiation of convection;

3) Estimate the potential improvement in QPF skill when predictions of convective onset are improved by assimilating targeting measurements in the regions where initial convection is likely to form;

4) Evaluate the performance and improve the formulation of convective trigger functions in subgrid parameterizations of deep, moist convection commonly used in mesoscale models.

4.3 The Atmospheric Boundary Layer Processes Component

The characteristics of the atmospheric boundary layer (ABL) are central to both the QPF and convective initiation components discussed thus far. For example, most of the boundaries discussed in the convective initiation section are essentially examples of heterogeneity in the ABL. Also, it is the relatively warm, humid air in the ABL that provides a majority of the thermodynamic energy responsible for convective storms and it is well established that small changes in ABL moisture can translate into significant changes in surface rainfall. Thus, once convection forms, an accurate forecast of convective intensity will also depend on the evolution in ABL properties, especially for predictions beyond several hours. The distribution of water vapor in the ABL, critical to convective instability, cloud formation, radiative properties within the layer, and land-surface processes, is arguably the most important meteorological characteristic of the ABL. Consequently, understanding the dynamics of the ABL and its water vapor budget, not just at points in space or in single column fashion, but as a 4-D entity in space and time, is critical to advancing our ability to predict key characteristics of weather and even climate.

Understanding the dynamics of the ABL requires knowledge of the statistical properties of turbulence, the advection of water vapor, the latent heat flux divergence, and the storage term and how these processes interact to drive water vapor heterogeneity. To measure these terms, entrainment processes have to be resolved. There are two unique aspects to the IHOP_2002 ABL processes effort. First, within this project we will attempt to measure–what is to our knowledge for the first time–with a new generation of high-resolution active remote sensing systems all the previously mentioned terms directly and simultaneously and determine their dependence on space and time. This will enable us to investigate the causes of the observed heterogeneity in both ABL water vapor content and mixing depth. Second, IHOP_2002 will provide the opportunity to conduct extensive remote microscale observations of the ABL across hundreds of kilometers, and place these observations within a relatively comprehensive understanding of the mesoscale atmospheric and land-surface environment with a goal of improving the prediction of convective rainfall. The mesoscale variations will be determined from instrumentation currently deployed and from additional measurement facilities deployed for IHOP_2002.

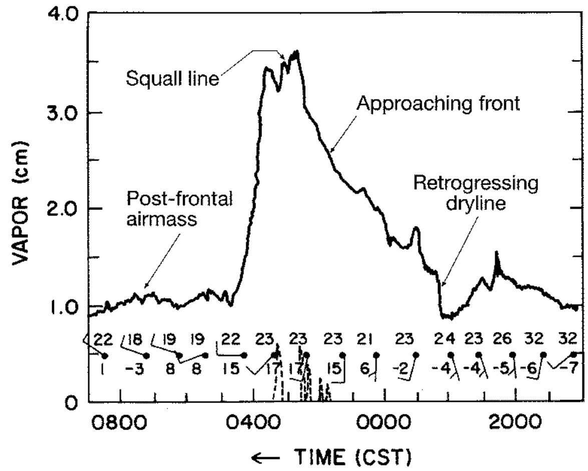

Figure 5: Time series of vertically integrated water vapor (solid line) and liquid water (dashed line) in a preconvective and convective environment over west Texas on 12-13 May 1985. Surface data is also shown. A squall line formed over this environment in response to destabilization from a frontal-dryline merger. (Parsons et al. 2000).

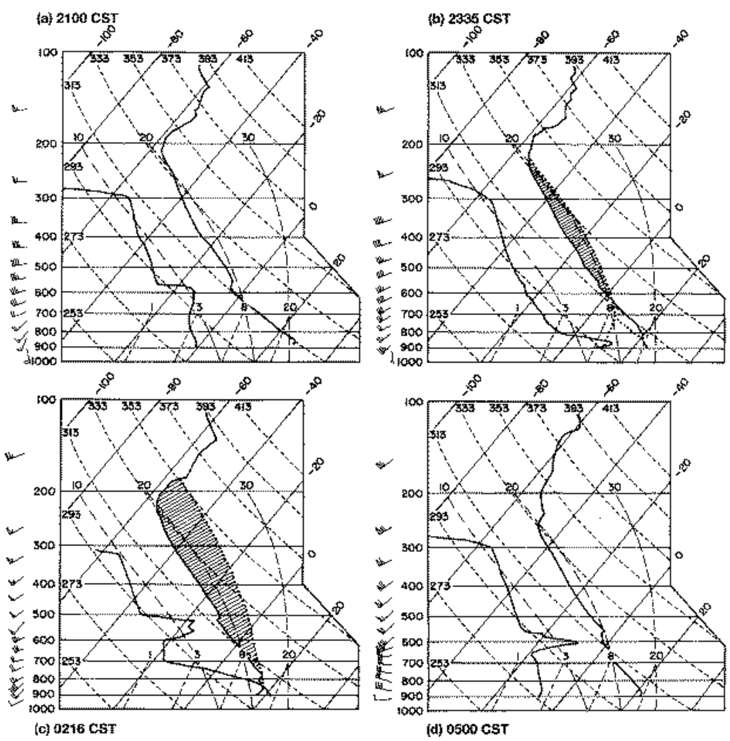

Figure 6: Serial radiosonde ascents from the event shown in Fig. 5. The increase in integrated water vapor corresponded to a rapid destabilization as the CAPE increased nearly 3000 J kg-1 in less than 3 hrs between 2335 and 0216 CST in a nocturnal environment (Parsons et al. 2000).

The specific major questions that can be addressed with the IHOP_2002 data sets include:

- What processes govern the water vapor distribution within and just above the ABL?
- How well are ABL processes simulated in mesoscale forecast models?
- How much does assimilation of detailed observations of ABL characteristics improve model performance?
- Can remote sensing instrumentation provide detailed ABL water vapor budget observations, particularly vertical flux divergence?
- What are the statistical properties of ABL turbulence, particularly its two dimensional spatial coherence, and how do these properties evolve over spatial scales of hundreds of kilometers?
- What are the microscale structures of entrainment at the ABL top?
- What mechanisms control water vapor heterogeneity within and above the ABL and how does this heterogeneity influence convection initiation and convective processes? Possible sources of heterogeneity include spatial variations in mixing depth and water vapor flux divergence, driven in part by land-surface processes, the convergence of air masses in the study region, and localized intense mesoscale flows.

In contrast, past studies of ABL processes have not been able to address such an extensive list of questions as these studies have often been limited by observational capabilities. For example, tower observations are fixed in space and limited in their vertical extent. Aircraft can traverse very long transects, but most instrumentation has been limited to in-situ measurements, resulting in lines of point measurements through space. These limitations make it difficult (e.g., Lenschow and Stankov, 1986) to measure quantities as fundamental as the vertical turbulent flux divergence, a dominant component of budgets in the ABL (e.g., Davis et al, 1997). These observational limits are contrasted by large eddy simulation (LES), which allows for exhaustive 3-D sampling of a numerical ABL. LES, however, is very limited in its ability to simulate realistic spatial heterogeneity stemming either from the land surface or from atmospheric conditions, and is typically limited to time scales of several hours and quasi-steady stability conditions.

High-resolution remote profiling instrumentation using passive remote sensing systems, radar, and lidar have revolutionized our ability to observe the ABL and IHOP_2002 plans to take full advantage of this revolution. Recent developments in remote sensing include ground-based passive remote sensing systems employed alone or in small networks that are able to continuously measure water vapor and temperature profiles up to 3 km (Feltz et al. 1998; Smith et al. 1999). Boundary layer parameters have also been derived from wind profilers and/or profilers with RASS (Radio Acoustic Sounding System), including boundary layer depth (e.g. White et al. 1991), the turbulent eddy dissipation rate (Jacoby-Koaly et al. 2000), information about the entrainment zone (Angevine et al. 1998), and vertical profiles of the sensible heat flux (Angevine et al. 1993). Ground-based lidars are capable of investigating atmospheric processes in clear-air with high resolution and range. Methodologies have also been developed for deriving various ABL parameters from lidar measurements, such as high-resolution ABL depth (e.g., Davis et al. 1997, 2000), ABL structures, and higher-order moments of winds and scalars (Mayor et al. 1997; Wulfmeyer 1999b; Lenschow et al. 2000). The placement of advanced radar and lidar systems on aircraft has provided observations that cover two-dimensional swaths of the atmosphere several kilometers deep and hundreds of kilometers across with spatial resolution smaller than the scale of convective eddies (e.g., Kiemle et al. 1997). The co-location of remote sensors has been particularly powerful, as water vapor differential absorption lidar (DIAL) with a profiler/RASS or Doppler lidar have directly measured latent heat flux profiles (Senff et al. 1996; Giez et al. 1999; Wulfmeyer 1999a) allowing estimation of the flux divergence.

The boundary layer component of IHOP_2002 will have co-location of remote sensors measuring different variables at several ground-based sites and we will extend this technology to airborne platforms. For example, airborne water vapor DIAL and Doppler lidar systems will enable large-scale observations of the spatial variations in the vertical profile of water vapor flux with low sampling errors and high spatial resolution when both sensors are deployed in a downward looking mode. These measurements will be validated against in-situ measurements of the turbulent quantities obtained with aircraft in-situ observations and with ground-based sites allowing extensive testing of methodology and evaluation of the relative utility of air-, space-borne and ground-based lidar measurements in providing information for warm season convective forecasting. The airborne and spatially distributed, continuous ground-based measurements undertaken for IHOP_2002 will aid in characterizing and understanding the causes of heterogeneity of water vapor and the initiation of convection. In order to address the heterogeneity, mesoscale variations in the land-surface forcing must also be characterized. Additional measurements of surface flux and soil moisture will be taken at fixed sites across the domain. The surface energy balance measurements can be merged with AVHRR or MODIS observations of vegetation cover and surface temperatures, and characterization of the surface water content to provide estimates of the spatial distribution of land-surface forcing, such as the ALEXI model, based on AVHRR and sounding data. Radar precipitation and a surface hydrologic model will also provide a spatially distributed estimate of surface soil moisture in order to better predict convective initiation (e.g., National Research Council 1998a). Finally, airborne microwave observations of soil moisture and tracer observations of scalars other than water vapor, such as CO_2, O_3 and CO, will help to delineate the origins of water vapor heterogeneity.

4.4 The Instrumentation Component

Three primary instrumentation-related goals have been identified for IHOP_2002:

a. Establish instrumentation accuracy and performance limitations for the convective forecast problem

A major goal of IHOP_2002 is to establish which measurements are candidates for providing large incremental improvements in forecast skill. A key component of this goal will be the assessment of instrument capabilities and limitations for water vapor measurement in a warm season convective environment. IHOP_2002 will allow comparison between existing measurement strategies (radiosondes and satellite soundings), recently deployed techniques, such as passive radiometric techniques and GPS measurements for integrated water vapor, and several relatively new developments in water vapor sensing. One of these relatively new developments is the technique that measures changes in the refractive index, or refractivity, of the air between a radar and a fixed ground target. The technique was developed by F. Fabry at U of McGill and applied in Montreal where sufficient ground clutter was present so that a high-resolution refractivity field could be retrieved. Since the refractivity of the air is a function of temperature, pressure, and humidity and most sensitive to variations in water vapor, it is possible to retrieve fields of water vapor near the surface (but not in height) given reasonable estimates of temperature and pressure. A number of questions regarding this method will be addressed during this experiment, including (1) the spatial resolution of the refractivity data in a relatively rural setting, (2) how best to utilize the surface data to obtain accurate estimates of water vapor from the refractivity measurements, (3) the achievable accuracy of the derived estimates of water vapor, (4) the degree to which the near surface measurements obtained from this technique will be representative of the properties of the boundary layer and (5) the utility of this technique to forecasting convective initiation, intensity and movement.

Other recently developed techniques that will be employed in IHOP_2002 use the GPS slant range information. The well-known GPS vertically integrated techniques are actually derived from individual estimates of the path delay obtained along the slant range between the ground-based receivers and up to 12 low-earth orbiting satellites. The slant range information can be used in a tomographic solution as is being developed by UCAR/UNAVCO and at Meteo France or assimilated using a 3-D variational approach (MacDonald et al. 2000). The 3-D fields of water vapor derived from ground-based and airborne measurements provide a unique opportunity to obtain characteristics on the accuracy and performance characteristics of slant range measurements and the tomographic technique. In general, IHOP_2002 will provide additional opportunities to establish relative instrument accuracies, and more importantly to compare the statistics of spatially sampled water vapor fields obtained by the aircraft sensors with temporally sampled fields observed from the ground. Characterizing uncertainties and representativeness of different measurements is important for optimal incorporation of the observations in data assimilation routines.

Ground-based lidars, such as DIAL and Raman, are another instrument often proposed for operationally providing improved water vapor characterization. However, these measurements degrade with increased range, requiring more powerful transmitters and/or larger receivers to maintain performance as range requirements increase. Thus, high performance systems capable of, for example, full tropospheric profiling of moisture, are expensive, and often introduce eye-safety issues. It is possible, however, to develop ground-based measurements extending only to near the top of the boundary layer that are compact, reliable, eye-safe and affordable. This idea is appealing, since we have discussed how predictions of convective initiation and intensity strongly depend on observations of water vapor within and just above the boundary layer. IHOP_2002 will investigate several issues associated with optical system sensitivity and design requirements relevant to these low powers systems including height coverage, temporal resolution, height resolution, and effects of degradation by clouds and precipitation. Resolution and sensitivity are key issues. Sensitivity can be improved by averaging over larger height increments and/or longer time increments. However, at some point, the averaging process can degrade the ability to detect key features, such as thin elevated moisture layers or abrupt moisture frontal or dryline passages. IHOP_2002 will investigate how forecast skill varies with spatial and temporal resolution under as many different measurement conditions as possible. Evaluations of the extent to which clouds and precipitation impact lidar measurements of water vapor is important for performance in warm season environments. Generally, lidar beams do not penetrate clouds and are attenuated by precipitation. Consequently, ground-based measurements will usually only be available to cloud base, and aircraft measurements to cloud top, possibly introducing different biases in the average estimates. Furthermore, even under scattered cloud conditions, the efficiency of long term averaging of weak signals will be somewhat degraded as clouds advect into and out of the lidar beam. These degradations are often overlooked when modeling and projecting potential lidar deployments for improving QPF. Data gathered during IHOP_2002 will be analyzed with the specific goal of determining whether ground-based DIAL instruments actually improve assimilated and forecast moisture fields for prediction of warm season convection.

b. Provide insight into the optimal mix for water vapor measurement instruments and the relative importance of water vapor measurements to other variables

The variety of water vapor observing systems allows a relative assessment of various potential measurement scenarios, such as ground-based lidars, GPS or radar refractivity. The airborne measurements of water vapor by the DIAL systems can be reprocessed to aid in the testing of different measurement strategies, such as the needed spacing, precision, and resolution of lidars in a ground-based network or future, low cost, down-looking systems on commercial aircraft or the merits of combined instruments. Another valuable aspect of IHOP_2002 is its combination of an unprecedented assortment of water vapor sensors with existing instrumentation over the SGP. Thus, investigators can examine the prediction impacts of water vapor measurements relative to such measurements as the unique WPN, while also investigating the combined impacts of these observations.

In many cases, combinations of instruments at a one site or combining airborne and ground-based measurements can provide information that far exceeds the measurement capability of a single instrument alone. For example, even when a ground-based DIAL system can only measure to cloud base, combining its observations with those from an integrated water vapor sensor such as a GPS instrument will enable partition of water vapor between the upper atmosphere and the boundary layer. Since cloud base height is also known from lidar returns, assumptions of saturation in the cloud provide additional information. Adding a cloud radar for cloud top height, and potentially incorporating satellite observations of cloud radiances and water vapor also add information that can improve moisture field characterization. A combined sensor approach may aid other water vapor measuring techniques. GPS tomography or passive radiometer approaches, for example, might be improved by knowledge of the boundary layer depth provided by a wind profiler. These issues will be extensively investigated in IHOP_2002. Combining moisture measurements with measurements of the wind field from aircraft and the WPN will also enable a better understanding of the distribution and fate of water vapor over the region, such as examination of moisture transport at lower levels as a low level jet is often present over this region.

c. Extend existing approaches and provide data for future design work

Our extension of existing measurement technology will have potential payoff for future experiments. Examples include our plans to combine airborne Doppler radar and sideward looking DIAL measurements from an aircraft for convective initiation research, the first airborne measurements of the vertical profiles of water vapor flux and flux divergence from down-looking Doppler lidar and DIAL water vapor lidar on an aircraft using eddy correlation techniques, and the first ground-based measured profiles of heat flux from Doppler lidar, wind profilers with RASS and Raman lidar. The variety of instrument techniques and sensor concepts employed over the IHOP_2002 experiment will also provide scaling and design information for the development of future instruments. At least three DIAL instruments are scheduled for deployment during the experiment. The systems operate at different wavelengths, pulse energies and pulse repetition frequencies. Comparison of performance and operating characteristics from the various instruments will be useful to examine the effect on performance of such design issues as wavelength, field of view, and dynamic range. Use of IHOP_2002 results to assess future instrument concepts will assist NSF in current efforts to develop a new airborne water vapor sensor for application on HIAPER and to enhance ground-based mobile remote sensing within the research community.

5. Experimental Design

5.1 Existing instrumentation

As stated earlier, IHOP_2002 is planned to take place over the SGP region partly due to the presence of numerous existing measurement facilities (Fig. 7). The region contains the standard operational rawinsonde, surface data, numerous WSR-88D S-band radars, and 29 sites of the 404 Mhz wind profilers comprising NOAA's WPN (http://www-dd.fsl.noaa.gov/online.html). Five of the WPN sites are also equipped with RASS systems providing hourly averages of virtual temperatures and nearly all have GPS receivers supported by NOAA/FSL that are used to derive vertically integrated estimate of water vapor. Additional GPS sites across Oklahoma are likely to be available through the newly founded SuomiNet. UNAVCO/ARM plans to have 25 stations operating continuously in an area smaller than 10x10 km in order to attempt tomographic solutions for 4-D fields of refractivity and water vapor.

The IHOP_2002 area (Fig. 7) also contains the Kansas and the extremely dense Oklahoma mesonets, the Argonne National Laboratory ABLE (Atmospheric Boundary Layer Experiments) array (http://www.atmos.anl.gov/ABLE) and the extensive measurement facilities supported by the ARM (Stokes and Schwartz 1994; http://www.arm.gov/docs/sites/sgp/sgp_instruments.html). In addition to the conventional surface meteorological measurements, numerous sites of the Oklahoma mesonet, ABLE and ARM also measure soil moisture and temperature and surface fluxes. ABLE and ARM facilities also

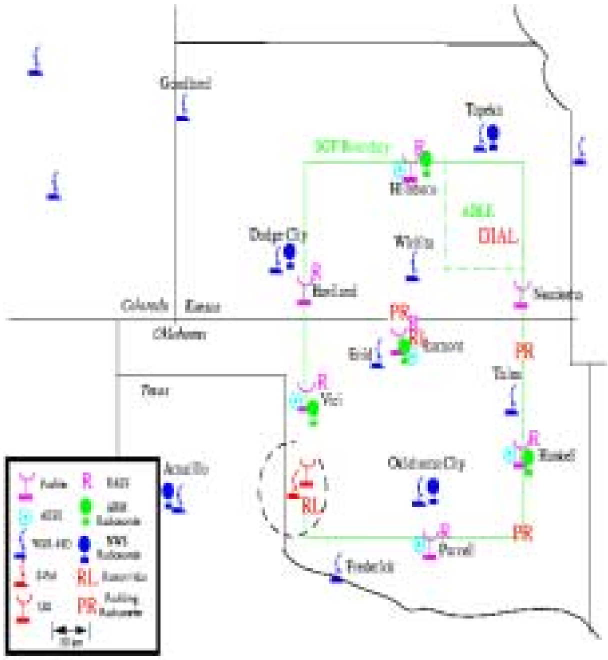

Figure 7: A schematic is shown depicting the location of existing facilities and the proposed experimental design. The green rectangle is the ARM domain

include several 915 Mhz wind profilers over this region. The boundary facilities at the edge of the ARM domain each support a microwave radiometer, a ceilometer, surface meteorology observations and a rawinsonde measurement system. It is planned that soundings will be taken from these sites every 3-h through a collaborative agreement with ARM that will cover at least half of the time span of experiment. Atmospheric Emitted Radiance Interferometers (AERI) are also located at the four ARM boundary facilities measuring downwelling infrared can be used to retrieve vertical profiles of temperature and moisture from the surface to 3 km (Fig. 8). Excellent skill in monitoring inversion intensity and convective inhibition, both extremely important for predicting convective initiation, have been demonstrated at 10 min intervals (Feltz and Meckalski, 2000) with the accuracy of the water vapor fields discussed in Turner et al. (2000). All five of these systems are producing retrievals within 30 mins of the radiance measurements (http://zonda.ssec.wisc.edu/~waynef) for nowcasting use by NOAA NWS within Oklahoma and Kansas. The ARM central facility (Fig. 7) contains an extensive array of instrumentation designed to accurately estimate the vertical profiles of cloud, radiation and basic meteorological state of the atmosphere over the site. The other measurements at this site most relevant for IHOP_2002 include detailed mapping of the cloud field over and around the site with sensors that include a ceilometer, a micropulse lidar, a millimeter-wavelength cloud radar, and video time-lapsed camera and a whole-sky imager and several novel water vapor sensors, such as a Raman lidar developed for ARM by Sandia laboratories (Goldsmith, et al. 1998). Data from this lidar (Fig. 9) has high vertical (up to 39 m) and

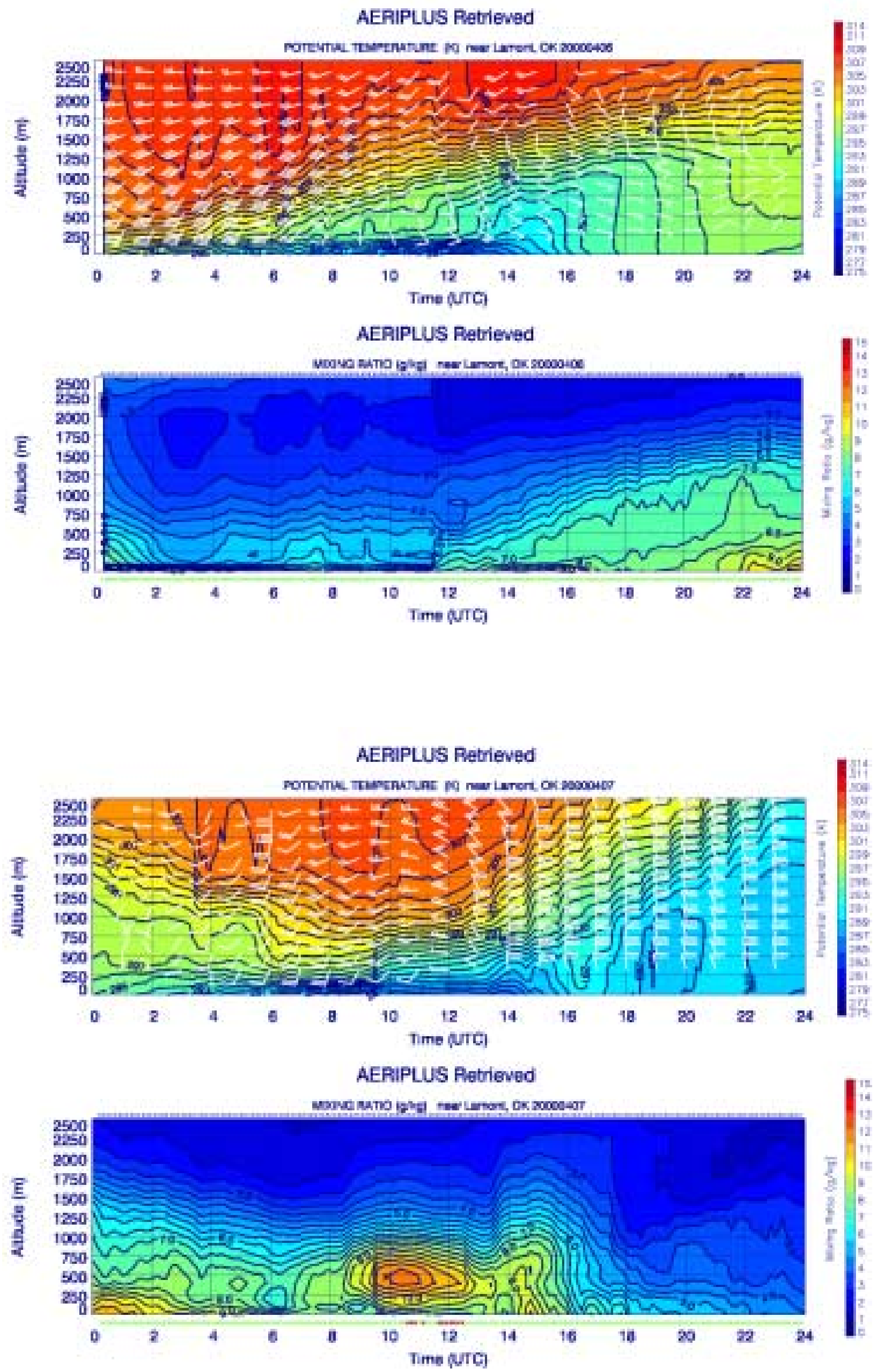

Figure 8: Potential temperature and water vapor mixing ratio measured by AERI at the ARM central facility showing frontal passages on 6 and 7 April 2000. The overlaid winds are from the Lamont wind profiler. (modified 1 Feb 2001)

temporal resolution (nominally 1 minute). In order to minimize the problems associated with weak discrimination of the Raman back-scatter signal above the background daylight and to maintain short-range signals, the system operates in a dual field-of-view.

Humidity and temperature measurements will also be available from the WVSS (Water Vapor Sensing System) on national and international commercial aircraft. The first generation is currently available on ~50 United Postal Service aircraft. For IHOP_2002 these measurements will provide water vapor and temperature profiles at flight level and upon ascent and descent into Tulsa. By the time of IHOP_2002, American Airlines may also be a participant in the program, which would add data into and out of Dallas/Ft. Worth. There will be occasional flight level data over the IHOP_2002 network. In calling for a field project aimed at improved characterization of the water vapor field, the USWRP PDT stated that such a field project needed to include satellite methods. The IHOP_2002 field and analysis phases includes active participation of the Atmospheric Research and Applications Division of NOAA/National Environmental Satellite Data and Information Service (NESDIS). This division will maintain a web site of specially selected data and derived products for the IHOP_2002, such as found in Holt and Olson (1999). The new GOES spacecraft carry separate imager and sounder systems with a 19-channel discrete filter radiometer sounder. Vertical profiles of temperature, dew point temperature and

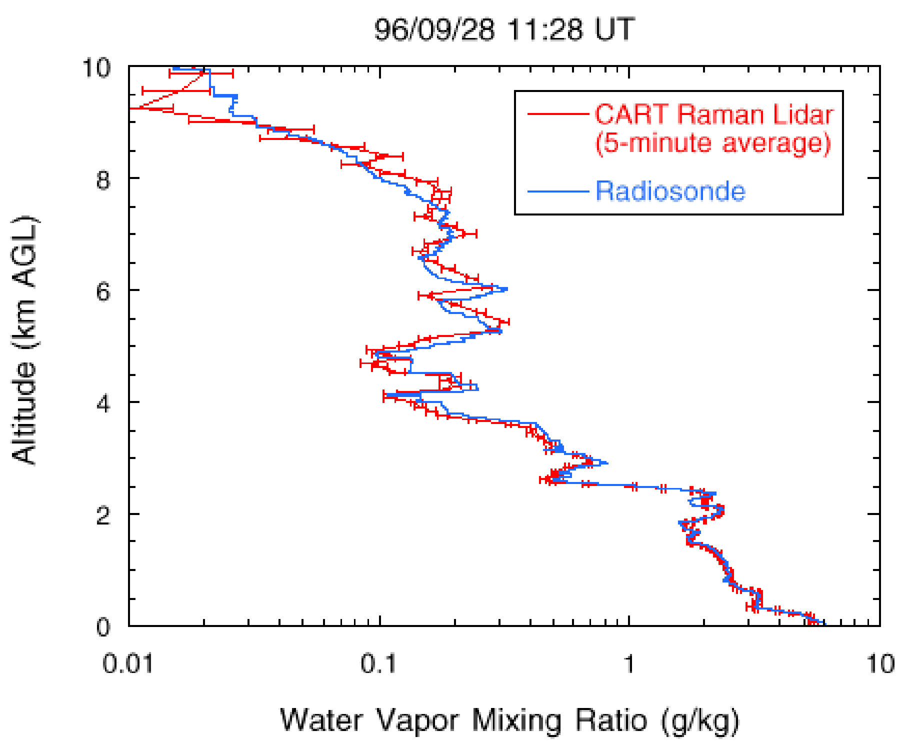

Figure 9: Comparison between the ARM CART Raman lidar and a Vaisala radiosonde launched from the CART site on 1128 UTC on 28 September 1996.

geopotential height are retrieved and stability parameters, such as CAPE and the Lifted Index, and layer and total estimates of precipitable water are derived. The sounder estimates are averaged and stored at a 30 to 50-km horizontal resolution. The higher resolution measurements of water vapor afforded by IHOP_2002 will allow determination of whether the subgrid scale variations of water vapor are crucial in either the initiation or maintenance procedure. IHOP_2002 will also make use of satellite precipitation estimates including the interactive flash flood analyzer, the experimental rainfall "autoestimator", multi-channel rainfall estimates and measurements of surface properties. The utility of these measurements in short-term forecasting and the impact of these satellite measurements relative to the other experimental water vapor techniques in assimilation procedures will also be tested.

5.2 Supplemental ground-based instrumentation

a. S-Pol

S-Pol is a state-of-the-art polarimetric Doppler weather radar. The polarmetric measurements are useful for hail detection and improvement in the accuracy of rain rate estimation accuracy, which are valuable to NWS flash flood forecasting and hydrology applications. The refractivity mapping technique discussed earlier will be available on S-Pol for IHOP_2002. In an optimal site, refractivity fields with an effective resolution of 2 km may be obtained up to 40 km range in near real-time (Fig. 10) as often as the radar makes a low-level scan. Conversion to water vapor may be made using an average temperature and pressure for the area covered, resulting in a water vapor field with an accuracy of about 0.5 g m^{-3}. For IHOP_2002, it is proposed that the radar be placed in the SW portion of the domain due to the uniqueness of the water vapor measurements from the refractivity (closer to moisture gradients) and the need to fill a gap in the NEXRAD coverage. The primary objectives of the S-Pol deployment summarized from our earlier discussion are to test the ability of the radar refractivity data to provide information useful for forecasts of convective initiation and to determine any impacts on QPF skill. If successful, refractivity capability could be implemented on operational WSR-88 D radars.

b. Ground-based Water Vapor Lidars

Two water vapor lidars are likely for convective initiation studies, for the QPF goals, for determining the accuracy, performance characteristics and utility of these systems, and for assisting in the characterization of the time varying 4-D water vapor field for ABL studies. One system is the Scanning Raman Lidar (SRL) of NASA Goddard (http://virl.gsfc.nasa.gov/srl/index.htm) that measures water vapor, aerosols, cloud liquid water, cloud droplet radius and number density, cloud base height and upper tropospheric temperature. The system can be scanned continuously from horizon to horizon or in a mode that allows vertical measurements and measurements at 5-10 degrees above the horizon in either direction. For nighttime measurements, profiles are typically acquired once per minute although good signal-to-noise is possible for boundary layer studies with averaging times of 5-10 seconds. For daytime measurements,

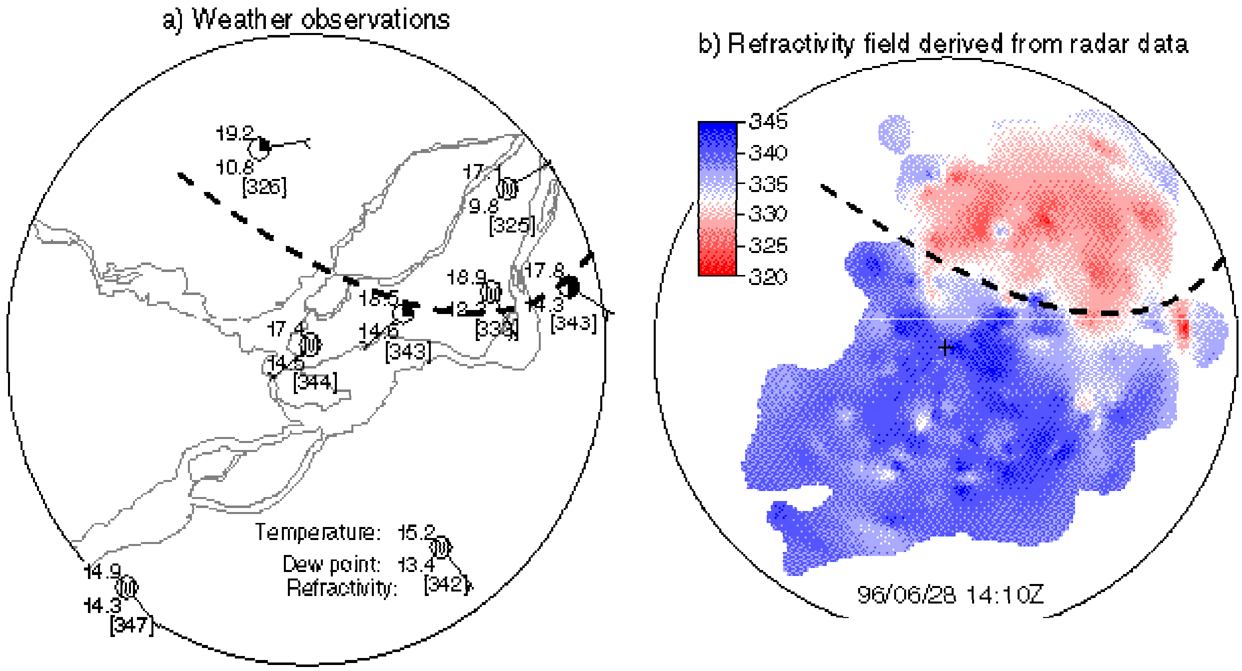

Figure 10: An example of weather observation and radar refractivity from observations taken near Montreal. The circle has a 45-km radius. Using a single site to provide temperature and pressure, dew point temperature was estimated with skill of ~.3-.4 C. From F. Fabry, U of McGill.

profiles to 4 km with 10% random error using 5-10 minute integration are possible. New data acquisition electronics permit measurements at 7.5 m resolution. Preliminary profiles/images of water vapor mixing ratio and aerosol backscattering ratio are available within 24 to 48 hours.

For the second DIAL, NOAA/ETL, in collaboration with NASA Goddard and NCAR, is currently building a small, automated, low-cost system to provide continuous water vapor measurements in the lower troposphere as discussed in the section on instrumentation goals. This ground-based, eye-safe lidar will profile to several kilometers with 100-m spatial resolution and 5 to10-minute averages. To extend the humidity profiles, the lidar measurements may be combined with observations of column-integrated water vapor obtained from ground-based radiometer or Global Positioning System methods. The instrument goal is a deployable, unattended instrument for continuous water vapor profiling with costs roughly equivalent to tropospheric radar wind profilers.

The location of these two systems within the experimental domain is largely determined by their operating characteristics and scientific need. We will place the SRL, with its rapid sampling and high resolution measurements, within the area covered by the S-POL radar refractivity measurements in the southwestern portion of the domain where sharp moisture gradients and convective initiation events are likely to occur. In order to make full use of the SRL as a research device for convective initiation and

ABL studies, we will co-locate the lidar with one of NCAR/ATD's Integrated Sounding Systems (ISS) consisting of a GPS rawinsonde system, a 915 MHz Doppler clear-air wind profiler with RASS and, an enhanced surface meteorological station. The wind profiler will be the MAPR (Multiple Antenna Profiling Radar), which is a spaced antenna design that allows rapid and continuous sampling of the horizontal and vertical winds, while remaining in a vertical pointing mode (Cohn et al. 1997). In addition, NASA/Goddard hopes to also bring a Doppler lidar. These measurements together with the virtual temperature measurements from RASS will allow exploration of the ability to derive sensible and latent heat flux profiles from the combination of the lidars and MAPR, which to our knowledge has not been accomplished with a Raman system. Examples of high-time resolution measurements from the SRL and from MAPR are shown in Figs. 12 and 13. The NOAA/ETL system with slower sampling times will be placed in the ABLE research area near one of their 915 Mhz wind profiler sites allowing some dynamic interpretation of the variations in moisture observed by this lidar.

c. Profiling radiometers

The recent efforts of the Radiometrics Corporation have been focused on developing radiometers to derive vertical profiles of temperature, water vapor, and cloud liquid water (Solheim et al. 1998). The microwave profiler passively observes atmospheric emission in 12 channels ranging from 20 to 60 GHz. Using these measurements and surface pressure, the instrument provides atmospheric temperature and humidity soundings to 10 km in height, and low-resolution cloud liquid water density profiles. Soundings are provided every 10 minutes in clear or cloudy weather in near real-time. The microwave profiler operates automatically, providing data retrieval from remote sites via cable, modem or Internet. The profiles are output at 100 m intervals up to 2 km and then 250 m up to 10 km. Typical accuracy (rms) of

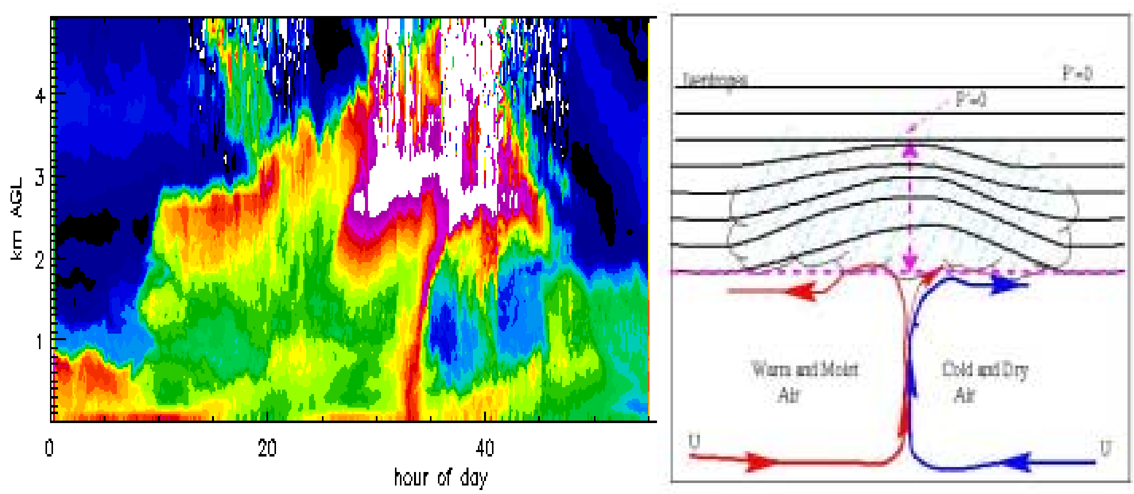

Figure 11: Schematic diagram showing a symmetric convergence line in a stratified atmosphere and relative humidity profile derived from the Raman lidar measured water vapor mixing ratio data on 28 September 1997 by the ARM lidar (CARL). The location of the clouds, the narrow convergence zone and lifting associated are all visualized in detail. Figure and caption provided by B. Demoz, U Maryland at Baltimore County.

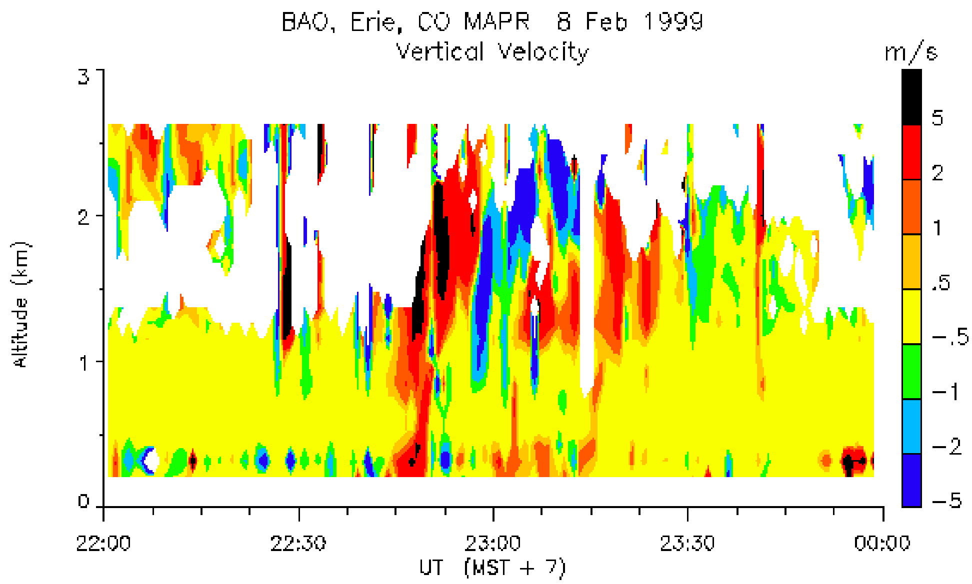

Figure 12: Vertical air motion from MAPR (Multiple Antenna Profiler) through a cold front. MAPR is also capable of measuring the horizontal winds at high-resolution (30s to several mins) and RASS measurements of virtual temperature. Courtesy of W. Brown, NCAR.

the temperature soundings is 1 to 2 degrees K below 5 km, and 3 to 4 degrees K below 10 km; for the humidity soundings the accuracy is typically better than 1.5 g/m^3 (Solheim et al., 1998). The accuracy of the cloud liquid profiles is currently being evaluated. IHOP_2002 hopes to have two profiling radiometers on loan from Radiometrics placed near the southern and eastern edges of the domain.

d. Microwave radiometers

NOAA/ETL has proposed deploying four or five 2-channel microwave radiometers in support of IHOP_2002. These radiometers would provide needed mesoscale water vapor boundary conditions for model initialisation and verification. Collocating the radiometers with the WPN will allow calculation of boundary layer horizontal water vapor flux into the region by making reasonable assumptions about the vertical distribution of water vapor. Data products will include integrated atmospheric water vapor and cloud liquid water every 5 - 60 sec with 30 sec being typical. An archivable data set will be available within 6 months to 1 year after the project. Water vapor convergence calculations should be available within a similar time frame. Additionally, one of the NOAA/ETL radiometers could be fully scannable in azimuth and elevation if appropriate funding is received. Otherwise, all the proposed radiometers are fixed zenith pointing.

e. Integrated Surface Flux Facility

NCAR operates the Integrated Surface Flux Facility (ISFF), which measures wind, temperature, humidity, pressure, solar radiation, precipitation, water vapor, net radiation, soil temperature, soil moisture, and fluxes of momentum, sensible, latent, and soil heat. The ISFF is suitable for remote operations with near real-time data transmission, possible almost anywhere in the world. For this experiment, IHOP_20002 will request six to nine systems from the NSF Lower Tropospheric Deployment

Pool. The systems will be used primarily for the goals of the ABL component by assisting in determining and understanding water vapor heterogeneity and for comparison with airborne flux estimates.

f. FM-CW S-Band radar

The University of Massachusetts has an S-band boundary layer profiler operating at a frequency of 2.7 GHz. The antenna diameter is 8 ft with a beamwidth of 3.4 deg. The range resolution is an impressive 2.5 m. The resolution volume at a range of 1 km is thus 2.5 X 59 X 59 m. Radar reflectivity images are available in real time in a range-time display and will be available in post-processing in UF or netCDF formats. These extremely high-resolution measurements would be useful in investigating the behavior of boundaries for the convective initiation component and in boundary layer studies.

5.3 Research aircraft

a. *NCAR Electra*

IHOP_2002 will request approximately 125 hours of the NCAR Electra through the NSF Lower Tropospheric Deployment pool. In addition to the standard research instrumentation deployed on board the NCAR/NSF Electra, we will request the Lyman-Alpha hygrometer and the new open path, tunable diode, laser hygrometer to measure the true water vapor concentration without the contamination from condensed phase water, which is associated with most water vapor measurements when made through an inlet system. Several remote sensors will also be deployed on the Electra for IHOP_2002 as follows:

♦ ELDORA is NCAR/ATD's airborne, X-Band Doppler radar mounted on the Electra (Hildebrand et al. 1996). This radar will be requested from the NSF deployment pool. The radar transmits two beams that respectively scan over two cones, one pointed 18 degrees forward and the other 18 degrees aft of a plane perpendicular to the aircraft heading allowing dual-Doppler information within 50 to 100 km. Clear air measurements have been made.

♦ LEANDRE II airborne DIAL lidar has been developed for tropospheric water vapor mixing ratio monitoring by the Service d'Aeronomie du Centre National de la Recherche Scientifique (CNRS) in cooperation with the Technical Division of INSU/CNRS. Sudden changes in the meteorological conditions are managed through selection from seven absorption lines, which is crucial over the IHOP_2002 region where water vapor content can vary substantially. On the Electra, a standard 10-s integration time (100 shots) corresponds to a 1-km spatial resolution. The average accuracy at heights between 300 m and 3.5 km is 0.16 g kg^{-1} with an average bias on the water vapor profile of 0.06 g kg^{-1}. DIAL systems are typically deployed in a downward-looking mode so that the general trend for decreasing signal to noise with distance from the lidar due to attenuation can be partly balanced by having the water vapor content increasing with distance. Thus, for flights aimed at mapping the larger-scale water vapor fields for the goals of the QPF and boundary layer groups, LEANDRE II will be downward-pointing using a mirror. For flights dedicated to convective initiation studies, the geometry of the error analysis for deriving winds using ELDORA requires as low a flight path as possible so that LEANDRE II will be placed in a sideward-pointing mode.

♦ Wyoming Cloud Radar (WCR) will be mounted on the Electra aircraft for the IHOP_2002 utilizing two antennas (both horizontal) oriented at different angles fore and aft, with an angle of 30-45 degrees between the two beams. Depending on the strength of the signals received and the distance between the aircraft and the region of interest, the WCR will utilize either a 275ns or a 500ns pulse. The WCR should have sufficient sensitivity to record useful data between 60-100 meters from the aircraft to a maximum of 3 or 4 km range with the 275ns pulse, or to a maximum of 6-8 km range with the 500 ns pulse, sampled at either 30m intervals or 60m intervals, respectively. The motion of the aircraft will cause the aft-beam to sample the same region as the fore-beam after a short time lag of ~7-8 seconds per km from the aircraft, up to a maximum of roughly 30 seconds (275 ns pulse) or 60 seconds (500 ns pulse). After a flight the Doppler velocity will be corrected for the effects of platform motion and then data from the two beams will be projected onto a common grid for dual-Doppler analysis with grid of ~25x25m (275ns pulse) or ~50x50m (500ns pulse).

♦ SABL (Scanning Aerosol Backscatter Lidar) is a compact, reliable and simple aerosol backscatter lidar system supported by NCAR that detects backscatter from air molecules, aerosols, and hydrometeors (water and ice). The instrument operates at two wavelengths: 532 (green) and 1064 nm (infrared). SABL is a high-resolution instrument, which provides 7.5 m gates and an along-track resolution of 4 m. The operator has the option of displaying real-time data which is logarithmic/range corrected or as raw linear data. SABL will be pointed in an upward pointing mode to monitor ABL depth and cloud base for low flying convective initiation studies.

b. DLR Falcon 20 aircraft

The meteorological research aircraft Falcon 20 (D-CMET) of the German Aerospace Center (DLR) carries a data acquisition and quick-look system and an extensive in-situ instrument package in order to measure the basic meteorological data set including atmospheric turbulence parameters. Additional instrumentation is available on request. The Falcon has a maximum endurance of 5 h carrying a payload of 1100 kg and a maximum operating altitude of 45,000 ft (13,700 m). The aircraft will provide data crucial to ABL, QPF and convective initiation studies.

♦ DLR airborne water vapor DIAL has flown on the Falcon 20 providing precise water vapor DIAL measurements in the troposphere as well as in the stratosphere (Ehret et al. 1998). The transmitter is designed to be operated at either the weak 4ν vibrational absorption bands of water vapor near 830 nm or 925 nm suitable for tropospheric measurements or at the one order-of-magnitude stronger 3ν vibrational absorption band lying in the 940 nm spectral region. For IHOP_2002 we propose to use this new 100 Hz DIAL system tuned to appropriate water vapor absorption lines in the 925 nm spectral region. The new system is expected to have a spatial resolution of 200 m (both vertically and horizontally) at an accuracy of 5 % for boundary layer measurements, and an aircraft speed of 150 m s^{-1}. In the free troposphere the vertical (horizontal) resolution is 300 (1000) m, in order to meet the same accuracy. In-flight quicklooks of aircraft and lidar data are standard with preliminary water vapor cross sections available 2-3 h after the flight. Evaluation of the aerosol backscatter provides for IHOP_2002 research interests i) separation of different air masses, ii) boundary layer top heights and statistics, iv) aerosol optical depth, extinction coefficient profiles, while the water vapor evaluation could provide i) two-dimensional water vapor cross sections at various spatial resolutions; ii) profiles of mean, variance, skewness and integral scale and iii) estimation of entrainment flux at the boundary layer top (Kiemle et al. 1997).

♦ High-Resolution Doppler Lidar (HRDL) is a coherent, completely eye safe Doppler lidar operating at a wavelength of 2 µm operated by NCAR and NOAA/ETL. The pulse duration is about 200 ns, which corresponds to a range resolution of 30 m. It has an along-track resolution of 75-150 m. The combination of HRDL with the DLR water vapor DIAL will directly measure the latent heat flux profile using the eddy correlation technique. From the airborne platform we will be able to considerably reduce the most important error source in latent heat flux profiling: the atmospheric sampling error. The error will be low enough to measure for the first time the divergence of the flux profile, thus giving an important part of the water vapor budget in the convective boundary layer. Cross-sections are available in real time.

♦ GPS dropsondes will be deployed on the DLR Falcon. The GPS dropsonde measures horizontal winds with an accuracy of 0.2 to 0.5 m s-1 and a vertical resolution of ~5 m (Hock and Franklin 1999). The sonde also provides measurements of temperature, pressure and relative humidity. The accuracy of the sonde measurement of relative humidity is better than 5 %. The dropsondes will be used to provide a characterization of the thermodynamics and kinematics of the large mesoscale environment so that the high-resolution water vapor measurements can be placed within a reasonable dynamic context. The winds and temperature measurements will also allow assimilation studies to investigate the importance of water vapor measurements relative to improved observations of other variables. The dropsonde system allows for simultaneous operation of up to four sondes per aircraft. Typical fall times are 2, 4, 7 and 9 minutes for sondes dropped from 850, 700, 500 and 400 mb, respectively. Sonde preparation takes ~2 to 3 min due to electronic component warm-up time. Several sondes may be prepared in advance for a series of rapid launches.

c. U of Wyoming King Air

The University of Wyoming maintains a Beechcraft Super King Air 200T, which is instrumented with a wide variety of sensors for atmospheric research. The aircraft is available through the NSF Lower Atmospheric Observing Facilities deployment pool. One of the primary uses of this aircraft will be to fly at different heights within the boundary layer taking in-situ flux measurements to verify the remote sensing estimates of the latent heat flux. This goal requires that the King Air be equipped with the full gust probe flux measurement system that was deployed recently for the CASES 99 project. The other use of the King Air involves dropsondes for flights parallel or perpendicular to boundaries to provide a thermodynamic context to interpret the measurements taken for convective initiation studies.

d. Additional lidar aircraft

The NASA DC-8 or one of the NASA or NOAA P-3s is a possible participant in IHOP_2002 for housing the LASE DIAL and the MACAWS Doppler lidar systems.

- The Lidar Atmospheric Sensing Experiment (LASE) operates in the 815 nm region and is designed to provide high-resolution profiles of water vapor, aerosols, and clouds throughout the troposphere. In the current mode of operation, LASE is locked to a strong water vapor line and electronically tunes to any spectral position on the absorption line to choose the suitable absorption cross-section for optimum measurements over a range of water vapor concentrations in the atmosphere. In addition, LASE can operate over two or three water vapor concentration regions to cover a broad altitudinal zone in the troposphere. This unique method of operation permits rapid and more flexible absorption cross-section selection capability for water vapor measurements over the entire troposphere in a single pass. The LASE team typically provides real-time color images with preliminary data files produced within 24-48 hours after the completion of a flight. LASE has demonstrated the capability to measure water vapor distributions over the entire troposphere with values ranging from about 15 g/kg near the ocean surface to about 0.01 g/kg near the tropopause in the tropical region and at mid-latitudes with an accuracy of better than 6% or 0.01 g/kg, whichever is greater, across the entire troposphere.

- The Multi-center Airborne Coherent Atmospheric Wind Sensor (MACAWS) is an airborne, pulsed, scanning, coherent Doppler laser radar (lidar) that remotely senses the distribution of wind velocity and aerosol backscatter within 3-D volumes (http://wwwghcc.msfc.nasa.gov/macaws/). MACAWS, presently configured to fly on the NASA DC-8 research aircraft, was developed jointly by the atmospheric lidar remote sensing groups of NASA Global Hydrology and Climate Center, NASA Marshall Space Flight Center (MSFC), NOAA/ETL, and the Jet Propulsion Laboratory (JPL). MACAWS employs three methods to remotely sense the atmosphere. In the first method, 2-D fields are derived using a technique called side- or co-planar scanning, which provides direct measurement of 2-D winds within +/- ~25 deg elevation. The line-of-sight resolution is 450 m and velocity accuracy is ~1 m s^{-1}. Finer spatial resolution or increased coverage is possible by varying the pulse duration and the accuracy of the radial velocities may be improved by correcting the apparent Doppler velocity returns from the surface. The second method provides 3-D coverage over a limited atmospheric volume by directing the lidar beam within up to five scan planes. Finally, detailed vertical profiling is possible with MACAWS by holding the lidar beam fixed, up to a limit of plus or minus ~30 deg elevation angle relative to the surface or feature of interest.

e. Flight tracks

Many of the IHOP_2002 participants have extensive experience in designing flight plans for boundary layer, mesoscale and convective studies. The general strategy regarding flight plans can be found in the previous sections. An example of flight tracks for a multiple objective mission are shown in Fig. 14. Further details will be presented in an operations plan.

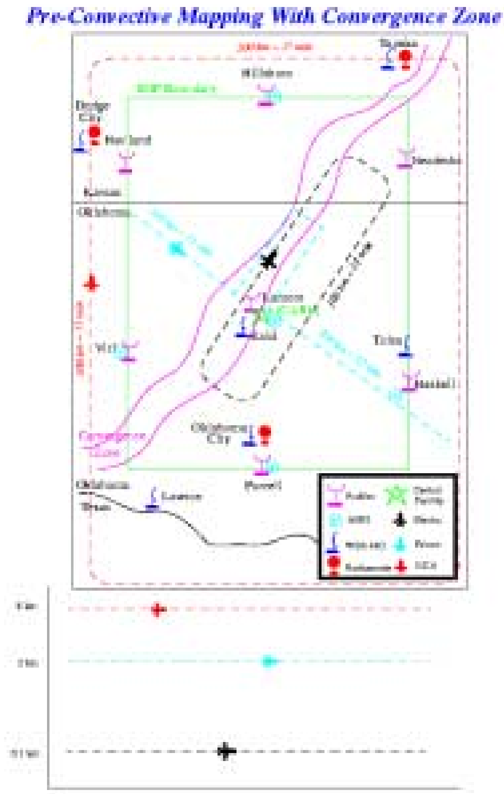

Figure 14: A schematic of a possible flight plan for IHOP_2002 for a three aircraft operation. In this example, the Electra is taking targeted measurements aimed at convective initiation studies. A second aircraft with dropsondes is flying perpendicular the initiation boundary. The third aircraft is mapping the larger-scale environment for the QPF component of the experiment. This third aircraft could be deploying dropsondes or utilizing DIAL to map vertical profiles of water vapor.

5.4 Mobile instrumentation

A tightly coordinated collection of instrumentation will be used to study convective initiation.

a. Mobile Sounding Systems

Two NCAR and two NSSL Mobile GLASS (GPS or Loran Atmospheric Sounding Systems) facilities will be requested for surface data and rawinsonde soundings to document the water vapor and temperature distributions in meso-gammascale phenomena related to convection initiation. The soundings will be obtained on either side of boundaries, or at other locations deemed important by IHOP_2002 investigators. The mobility gives the project planner the option to deploy to a specific site, make a sounding and move to another site for the next sounding. Data can be transmitted using a cellular phone or a packet radio communication system. If NCAR's new mobile ISS is available, then we will request one mobile ISS with GLASS capabilities and one mobile GLASS from NCAR.

b. Mobile Integrated Profiling System (MIPS)

The University of Alabama – Huntsville Mobile Integrated Profiling System (MIPS) consists of a five-beam 915 MHz profiler, a Doppler sodar, a lidar ceilometer and standard surface instrumentation including solar radiation (see http://derecho.atmos.uah.edu/profiler/profiler.html). Full spectra will be collected by the wind profiler. Profiles of backscattered power obtained by the profiler are particularly useful for monitoring turbulence within the ABL, moisture gradients, stable layers, and the CBL depth. The three-beam Doppler sodar provides detailed wind profiles at 20 m vertical resolution, beginning at 40 m AGL. With a pulse repetition period of about 6 s, vertical motion is measured at about 20 s intervals, up to maximum measurement heights of typically 200-600 m. Cloud base, thickness and visibility profiles are obtained by the lidar ceilometer, which acquires measurements of backscattered power at 15 m intervals, beginning at 15 m AGL. Time resolution can be set between 15-60 s, while the surface measurements are recorded at 1 Hz. MIPS is an excellent tool to characterize ABL structures and associated cloud fields and will provide significant insight on boundary layer structures and convective initiation with near real-time displays.

c. Mobile Doppler radars

Several research groups with mobile Doppler radars have proposed participation in IHOP_2002 dependent on the timing of other research experiments. One of the mobile systems is the pair of the Doppler On Wheels (DOW). The DOWs are mobile 3-cm (X-band) scanning pulsed Doppler radars. The deployment time is < 1 minute. The antennas have a 0.95 deg beamwidth and can scan up to 30-60 deg/sec. PPI, SUR and RHI scans are programmable. The range is 200 m to 200 km with accuracy and precision of the velocity measurements being similar to stationary weather radar. The reflectivities need to be calibrated in the field through comparison to S-Pol or other weather radars. Attenuation in heavy precipitation and hail is strong. Scanning in winds over 40 m s^{-1} is somewhat impaired.

The Shared Mobile Atmospheric Research and Teaching Radars (SMART-R) is another pair of mobile radars that may be available for IHOP_2002. The radars will be fully mobile, with the design being very similar to the existing DOWs. For this time frame, one of the SMART-Rs will be retrofitted for dual-polarization capability for studies of precipitation systems that are often severely attenuated at X-band. In IHOP_2002, these S-band radars will be deployed to make clear-air measurements in the vicinity of boundaries. It is planned to integrate deployments with the DOW X-band radars to improve the accuracy of the velocity solutions using multi-Doppler techniques. In some deployments, the pairs of radars may be deployed on different, sometimes adjacent, segments of boundaries in order to increase the spatial coverage.

Another possible participant is the new C-Band polarization mobile radar, which is being developed by P. Ray at Florida State University. This radar will be deployed on a 5.5-ton truck. The planned antenna diameter is 7.5 ft with a 2.2 deg beam width. It is expected that the mobile radar will be available and tested for IHOP_2002. The University of Massachusetts also operates a mobile, 3 mm (95 GHz) wavelength, pulsed Doppler radar. Typical products include PPI, VAD and mobile fixed beam reflectivity and Doppler velocity images. The range resolution is very high at 30 or 15 m, which gives a resolution volume of 12 X 12 X 15 m at a range of 4 km using 100 ns transmitted pulses. The radar reflectivity and Doppler velocity images are available real time in a range-time display. The data is available in UF or netCDF format within a few days after data collection.

d. Mobile radiometer

The Desert Research Institute (DRI) mobile radiometer is a dual-channel instrument that operates at frequencies of 20.6 and 31.65 GHz (Hogg et al. 1983; Huggins 1995). Statistical retrieval techniques are used to compute path-integrated depths of water vapor and liquid water (Westwater and Strand 1972; Hogg et al. 1983). The radiometer receiver, computer, and antenna control mechanism are housed in the cargo area of the vehicle with a 6.5 kW power generator installed into a sound- and heat-insulated compartment serves as the power source for the instrument in mobile mode. A spinning reflector is used externally to direct microwave emission to this antenna and to repel precipitation particles from the reflector surface. In stationary operation, the antenna housing can be pointed vertically or rotated to collect data in scans at fixed elevation angles. For mobile operation, the antenna is locked to a zenith-pointing position. For stationary operations, data are typically averaged over 1-5 minute periods, while mobile operations are updated more frequently (i.e., between a few seconds up to almost a minute).

e. NOAA Mobile mesonet

In IHOP_2002, we plan to deploy six mobile mesonet systems (Straka et al. 1998). These will obtain 1-s samples of pressure, temperature, humidity, and position, as well as wind direction and speed at 3 m AGL. Further, we will have the capability of digital recording and time stamping of operator observations, and possibly digital recording of images. In previous experiments, we have had good success operating about half of the vehicles at roughly 20 m s^{-1}, providing good sampling of meso-gamma scale features, and the other half at 2-5 m s^{-1}, providing sampling of cloud scale features. We have documented instances of drylines collapsing to 180 m width, as well as numerous vortices (100-1000 m scale) embedded in boundaries.

f. Remotely Piloted Vehicles (RPVs)

During IHOP_2002, we intend to conduct a demonstration and test of a new concept in in-situ sensing. Rasmussen (NSSL), in collaboration with Wyndemere Inc., is developing the capability for formation flying of model airplane RPVs. These aircraft will be instrumented for pressure, temperature, humidity, and wind measurements. Other sensors are possible. The aircraft will be flown remotely by monitoring the telemetry of position and meteorological data, and then commanding various maneuvers for the lead aircraft. Roughly five other aircraft will maintain a formation with the lead aircraft. We intend to fly between 500 and 2000 m AGL, with aircraft separation in the vertical and horizontal of roughly 100 m. Airspeeds will be roughly 30-40 kt, with about 1 h flight durations. These systems should be ideal for sampling a variety of meso-gamma scale features.

6. Participants and Project Management

Since introducing the concept of this experiment, we have encouraged input from all interested scientists and engineers. We have had two planning meetings, made several briefings to the interagency panel for the USWRP and to the USWRP Science Team, and at the AMS Annual Meeting. A list of interested participants can be found in Table 1. From this list, we have formed a U.S. Scientific Steering Committee (Table 4) that includes representatives from the research and operational communities. The Scientific Steering Committee will make major decisions about the experiment. The co-chairs of this committee are the three scientists that originally proposed IHOP_2002. The International Scientific Committee (composed of the International participants in Table 1) will have two representatives on the

U.S. Scientific Steering Committee. If this overview document is successfully reviewed, than we will propose that a small IHOP_2002 project office be formed that is affiliated with the USWRP Scientific Office in Boulder to assistance in project planing (meetings, newsletters, an operations plan and field communication). It is likely that the Joint Office of Scientific Support (JOSS) will assist in these activities.

7. Data Management

The data management will take place on several levels. First, we will encourage and work towards near real-time transmission of all data as the operational forecast centers have asked for this capability. Next, we also encourage quick look data sets as soon as possible after the daily operations. In most cases, investigators will be able to provide quick look data within 24-h after a flight. Finally, we will have what we call Level I data sent to our data management centers within 1 year of completion of this experiment. We will likely have data stored at both the ARM and JOSS (CODIAC) data centers. For some of the large remote sensing data sets, links back to the principal investigators may be required. We consider both the ARM and JOSS data centers to be state-of-the-art.

Acknowledgements: The co-chairs acknowledge the assistance of the participants at the experimental planning meetings for much of the material in this overview document. In particular, they would like to acknowledge the assistance of C. Zeigler (NSSL) for writing the initial draft for the section on convective initiation. He was assisted by E. Rasmussen (OU/CAPS) and R. Wakimoto (UCLA). We would also like to acknowledge K. Davis (U Minn) and V. Wulfmeyer (NCAR) for taking the lead on the section on boundary layer processes. He was assisted by D. Lenschow (NCAR), P. LeMone (NCAR), and B. Grossman (CU/CIRES). T. Schlatter, B. Gall and R. Carbone, all affiliated with the USWRP, are to be thanked for guidance on scientific and planning issues. J. Lukas (NCAR) is thanked for his technical editing.

Table 1: Planned Participants in IHOP_2001 and Their Research Interests

Name:	Institution:	Research interests:
Jian-Wen Bao	NOAA/ETL	Data assimilation, model physics improvements and model validation
Dan Birkenheuer	NOAA/FSL	Various including real-time model support, Validation research, model initilization
Howard Bluestein	U of Oklahoma	Understanding convective initiation, vertical circulations at drylines, fronts and outflows
Edward Brandes	NCAR/RAP	Radar quantitative rainfall estimates with S-POL
Edward Browell	NASA/Langley	Applications of airborne DIAL
John Brown	NOAA/FSL	Impact of improved water vapor on RUC
Fred Carr	U of Oklahoma/CIMMS	Data assimilation and QPF
Fei Chen	NCAR/RAP	Land surface modeling
Andrew Crook	NCAR/MMM	Quantifying lifting at boundaries for convective initiation studies
Ken Davis	Penn State	Processes that govern water vapor within and just above the ABL, including vertical flux divergence, mesoscale structures/ entrainment
Belay Demoz	U of Maryland BC	Raman lidar applications to goals of IHOP
Tim Doggett	Texas Tech.	Convective initiation, applications of new mobile platforms, real-time simulations
Kelvin Droegemeier	U Oklahoma	Improved prediction of convection with high resolution numerical models and assimilation
Gerhart Ehret	DLR	Airborne lidar measurements of PBL fluxes
Frederic Fabry	McGill U.	Implement and test radar measurement of phase delay from clutter
Andreas Fix	DLR	Airborne lidar measurement of PBL fluxes
Cyrille Flamant	CNRS	Rolls, PBL studies, convective initiation, spatial variations in water vapor
Robert Gallus	Iowa State U	QPF studies with 10-km Eta model
Bart Geerts	U of Wyoming	Cloud streets in PBL, motions near cloud base, cloud evolution before convective initiation
Robert Grossman	CU/PAOS	Water vapor boundary layer and surface processes

Seth Gutman	NOAA/FSL	GPS water vapor techniques and assimilation of GPS data
Samuel Haimov	U of Wyoming	Cloud streets in PBL, motions near cloud base, cloud evolution before convective initiation
Mike Hardesty	NOAA/ETL	Project co-chair: Various lidar applications
Peter Hildebrand	NASA/Goddard	Hydrology, QPF and water vapor
Frances Holt	NOAA/NESDIS	Applications of satellite measurements to water vapor measurements, convective forecasts and QPE
Jeff Keeler	NCAR/ATD	Implement and test radar measurement of phase delay from clutter
David Kingsmill	DRI	Convective initiation and mobile radiometer
Kevin Knupp	U of Alabama at Huntsville	Convective initiation and mobile profiling
Steve Koch	NOAA/FSL	Convective initiation, QPF
Robert Kropfli	NOAA/ETL	Investigate and document mesoscale water vapor flux and impact on precipiations
Robert Kuligowski	NOAA/NESDIS	Applications of satellite measurements to water vapor measurements, convective forecasts and QPE
Bill Kuo	NCAR/MMM	Water vapor variations and GPS Met, data Assimilation
Wen-Chau Lee	NCAR/ATD	Convective initiation
Peggy LeMone	NCAR/MMM	Diurnal cycle of water vapor in PBL, causes of water vapor variations in PBL and relationship to surface conditions
Don Lenschow	NCAR/MMM	Processes that govern water vapor within and just above the ABL, including vertical flux divergence, mesoscale structures/ entrainment
David Leon	U of Wyoming	Cloud streets in PBL, motions near cloud base, cloud evolution before convective initiation
Janet Machol	CIRES-NOAA/ETL	Test the utility of miniature DIAL for weather prediction via assimilation
John McGinley	NOAA/FSL	Various including real-time model support, Validation research, model initilization
Cindy Mueller	NCAR/RAP	Convective forecasts/Autonowcaster
John Norman	U Wisconsin	Surface energy budget

Brad Orr	NOAA/ETL	Investigate and document mesoscale water vapor flux and impact on precipitation
David Parsons	NCAR/ATD	Project co-chair, impact of water vapor on QPF, data assimilation, lidar and profiler studies of PBL
Andrew Pazmany	U Mass	Tornado radar and FM-CW applications to the goals of IHOP
Jacques Pelon	CNRS	Rolls, PBL studies, convective initiation, Spatial variations in water vapor
Fernando Porte-Agel	U of Minnesota	Improved sub-grid scale parameterizations
Erik Rasmussen	NOAA/NSSL and CIMMS	Convective initiation, applications of new mobile platforms, real-time simulations
Peter Ray	FSU	Convective initiation and mobile radar
David Reynolds	NCEP/HPC	Operational hydrometeorological prediction
Rita Roberts	NCAR/RAP	Convective forecasts/Autonowcaster
Chris Rocken	UCAR/UNAVCO	GPS tomography
Jeff Rothermal	NASA/Marshall	Airborne Doppler lidar measurements
Thomas Schlatter	NOAA/FSL	Data assimilation, QPF
Brent Shaw	NOAA/FSL	Various including real-time model support, Validation research, model initilization
B. Boba Stankov	NOAA/ETL	Combined sensor retrieval approach for water vapor retrieval
David Stauffer	Penn State	Assimilation of ABL and surface properties Performance of mesoscale models for water vapor and ABL processes
Jerry Straka	U of Oklahoma	Convective initiation, applications of new mobile platforms, real-time simulations
David Turner	Pacific Northwest Natl Lab	Three-dimensional variations in water vapor over ARM domain
Joel Van Baelen	Meteo France	GPS water vapor and tomography
Randolph Ware	UNAVCO/Radiometrics Corp.	Extension of GPS to real-time slant range and application of profiling radiometers
Roger Wakimoto	UCLA	Convective initiation and water vapor variations
Tammy Weckwerth	NCAR/ATD	Project co-chair, convective initiation and PBL studies

Morris Weisman	NCAR/MMM	Predictability, convective initiation
Marv Wesley	Argonne Natl Lab	Land surface modeling
David Whiteman	NASA/Goddard	Measurement inter-comparison, Convective initiation, mesoscale variability in water vapor from fronts, drylines etc.
James Wilczak	NOAA/ETL	Data assimilation, model physics improvements and model validation
James Wilson	NCAR/ATD	Convective forecasts/Autonowcaster
Josh Wurman	U of Oklahoma	DOW applications for IHOP
Volker Wulfmeyer	NCAR/ATD U of Hohnheim	Boundary layer water budgets, turbulent transfer and entrainment
Conrad Ziegler	NOAA/NSSL	Convective initiation, applications of new mobile instrumentation
Xiaolei Zou	Florida State U.	Data assimilation of water vapor measurements and QPF

Table 2: Some deliverables to the operational community. Included as per suggestion of the USWRP Interagency Panel

- Insight into the optimal mix for improved characterization of water vapor
- Insight into how to improve warm season QPF (<24 h) and flash flood warnings and contribution to improved skill
- Insight into the relative role of predictability for warm season convection versus improved measurements
- Improved measurement technology for water vapor
- Improved assimilation of measurements by new water vapor technologies
- Knowledge of performance limitations and accuracies for new sensors
- Evaluation of satellite techniques
- Improved communication between the measurement and assimilation communities
- Improved model treatment of boundary layer and convective initiation processes

Table 3: Model Groups[1] Participating in QPF Impact Studies

MODEL	LEAD INVESTIGATOR	INSTITUTION
10-km Version of the Eta Model	W. Gallus	U of Iowa
APRS Non-Hydrostatic Model[2]	F. Carr	U of Oklahoma and Center for the Analysis and Prediction of Storms
Operational Rapid Update Cycle (RUC)	J. Brown	NOAA/Forecast Systems Laboratory
Non-hydrostatic RAMS	C. Zeigler	NOAA/National Severe Storms Laboratory
Scalable Forecast Model/LAPS[1]	S. Koch	NOAA/Forecast Systems Laboratory
Klemp-Wilhemson Cloud Model[1]	M. Weisman	NCAR
MM5 Mesoscale Model[1]	X. Zou (and others)	FSU (and others)
CRAS Mesoscale Model	J. Norman/K. Davis	U of Wisconsin/Penn. State
Precipitation and Runoff Estimation	E. Brandes	NCAR
Interactive Flash Flood Analyzer and Rainfall Autonowcaster	F. Holt	NOAA/National Environmental Satellite Data and Information Service
NCAR Autonowcaster	J. Wilson	NCAR

[1] In addition, conversations have begun between IHOP_2002 investigators and L. Uccellini and D. Reynolds about the participation of NCEP's Hydrometeorological Prediction Center.
[2] During the post-field phase, we anticipate that these modelling teams will move toward the new Weather Research and Forecasting (WRF) model.

Table 4: Scientific Steering Commitee

M. HARDESTY	CO-CHAIR	NOAA/ETL
D. Parsons	Co-Chair	NCAR/ATD
T. Weckwerth	Co-Chair	NCAR/ATD
E. Browell	Steering Committee Representative	NASA/Langley
F. Carr	Steering Committee Representative	U. of Oklahoma
K. Davis	Steering Committee Representative	Penn. State U.
G. Ehret	International Representative	DLR-Germany
C. Flamant	International Representative	CNRS-France
F. Holt	Operational Representative	NOAA/NESDIS
D. Reynolds	Operational Representative	NOAA/NCEP/HPC
T. Schlatter	USWRP Representative	NOAA/FSL
R. Wakimoto	Steering Committee Representative	UCLA
D. Whiteman	Steering Committee Representative	NASA/Goddard
C. Zeigler	Steering Committee Representative	NOAA/FSL

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