Forecast Systems Lab / Forecast Research Division
Planning for IHOP
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Quantitative Precipitation Forecast

Hypothesis: "Improved characterization of the four-dimensional water vapor field will result in significant, detectable improvements in warm-season QPF skill."

Hypothesis: "Warm-season QPF may be improved significantly by using 3-D variational approaches to assimilate integrated precipitable water (IPW) measurements from GOES sounder estimates of clear-column IPW at ~40-km resolution and from an array of GPS sensors at 250-km spacing."

Hypothesis: "The combination of 3-hourly soundings at the ARM boundary facilities, continuous measurements from wind profilers and profiling radiometers (or other profiling sensor systems) stationed at each of the 6 profiler sites, and assimilated GPS and GOES retrievals (see above) will enable accurate determination of the moisture budget over the scale of the ARM facility at a temporal resolution of 30 min."

Stepwise requirements for hypothesis testing:

1. Characterize the mesoscale distribution of water vapor with horizontal resolution <20 km, 200 m vertical resolution, and hourly or greater frequency
2. Determine how best to combine the diverse field measurements of moisture
3. Derive error covariance matrices and forward radiative transfer models necessary for assimilating the diverse remote sensing data
4. Account for the performance characteristics and sampling limitations of water vapor sensors so that meaningful data assimilation strategies can be designed
5. Determine the impact of improved water vapor characterization on QPF skill
6. Assess impact as a function of scale and type of precipitation system
7. Use this knowledge of moisture variability in a pre-convective environment to determine how to conduct meaningful OSEs and ensemble forecasts

Measurements required for testing this hypothesis (prioritized):
Those data that could be incorporated in real-time are shown by (*).

1. Fixed ground-based
    1. * Profiler/RASS/GPS network (404 MHz and 915 MHz) and WSR-88D data: needed to map moisture convergence and precipitation fields over larger domain
    2. * At least 5 Radiometrics profiling radiometers at the profiler locations
    3. * Oklahoma Mesonet
    4. CART Central Facility 3-h radiosonde, GPS slant range & tomography: provide requisite horizontal mapping of water vapor for data assimilation

5. * CART 3-h radiosondes at boundary facilities: needed to estimate boundary moisture flux convergence for moisture budget studies
6. CART profiling radiometer, AERI, Raman lidar: provide the vertical detail and temporal evolution needed to understand boundary layer moisture profiles
7. S-Pol polarimetric Doppler radar: validate LAPS Water-In-All-Phases analyses
8. Fabry radar refractivity fields from S-Pol: provides low-level moisture and wind field mapping to obtain moisture convergence

2. Mobile ground-based measurements:
   1. C-band Polarization Mobile Radar: this system from FSU would allow mobility in measuring hydrometeor distributions, in conjunction with the stationary S-Pol
   2. Mobile Mesonet
   3. Mobile GLASS (nice to have but not necessary)

3. Airborne sensor systems:
   1. German DLR Falcon or NASA DC-8 dropsondes
   2. German DLR Falcon water vapor DIAL
   3. Commercial aircraft WVSS water vapor measurements
   4. Remotely Piloted Vehicles: RPV could add to the spatial resolution of water vapor fields obtained from the other mapping systems

4. Satellite measurements:
   1. GOES sounder (30-50 km res.) estimates of precipitable water & cloud tops
   2. GOES imager estimates of precipitable water & cloud tops
   3. NESDIS experimental rainfall estimates from satellite

Necessary locations for mobile ground-based instrumentation:
S-Pol and C-band Polarization Mobile Radar should be operated in the vicinity of boundaries if possible, but more importantly, to sample hydrometeor distributions in mesoscale convective systems and their environment.

Mobile Mesonet and GLASS should be deployed across suspected air mass boundaries and in the vicinity of convergence boundaries in conjunction with aircraft traverses (see examples under Convective Initiation section of this proposal).

Desired meteorological conditions:
Aircraft should fly patterns that *minimize data gaps* to make it easier to render a composite analysis of the water vapor field. For purposes of comparing with GOES IPW analyses, clear sky or scattered low-level cumulus conditions are optimal (both for the airborne lidar and the GOES infrared sounders). It would be highly desirable to fly the aircraft in the pre-convective boundary layer *on both sides of a boundary* like the dryline for assessment of the GOES product (see below). This is also the ideal time to map the larger-scale moisture convergence from the soundings. On the other hand, the S-Pol and C-band Polarization Mobile Radar data are most useful when a *variety of cloud type* with varying water and ice contents exists, which may be following convection development.

Among the features that are prerequisite to the development of mesoscale convecrtive systems (MCSs) in the Central Plains is the existence of a *low-level jet* (LLJ) within the surface boundary layer. A strong LLJ can provide continuous delivery of moist air from the Gulf of Mexico to the location of an existing frontal or other surface boundary. At the boundary, lifting of the moist air often results in organized and long-lasting convection, ocasionally in the form of an MCS. Whether or not an MCS will form during a given day, as well as its intensity, longevity, and rainfall production after it forms, will depend on characteristics of the moist inflow (eg., its depth, moisture convergence profile, and perhaps width). Because MCSs produce a substantial fraction of rainfall in regiona where they are frequent, understanding (and eventually realtime observations) of the detailed structure of the jet and its associated water vapor field can potentially improve our ability to predict rainfall over much of the central U.S.

We propose midlevel flights of aircraft with downward-looking lidar and deployment of mobile surface observation platforms to observe the three-dimensional structure of winds and water vapor during periods when an intense LLJ over the IHOP domain either has produced, or is expected to produce, strong convective development either within or to the north of the domain. Ideally, these observations would continue during an entire lifecycle of convective development and decay, or until the system and jet moved eastward out of the IHOP domain. We foresee that in conjunction with standard (radiosonde, profiler, radar, and satellite) observations, these new data will provide a spatially and temporally detailed picture of the structure and development of a few cases of an LLJ that leads to significant mesoscale convection and rainfall, and perhaps a case that does not for comparison. Ultimately, these case study data can be assimilated into initialization fields of operational and research mesoscale models or used in budget studies, with the goal of understanding better how the water vapor fields are involved with the convective initialization and precipitation.

Operations center needs:

1. <u>We wish to provide real-time operational support for IHOP, with a mesoscale analysis and prediction system based on LAPS (Local Analysis and Predicition System)</u>. At a minimum this mission planning activity should be included since FSL is in a position to offer this capability with minimal funding. LAPS would be run at FSL and made available via the web to mission planners, or possibly on an FX-Net workstation (?) The exact suite of static output can be negotiated. The capabilities of user-specified products now exists on the web and can possibly be enhanced to render needed forecast variables for daily mission planning. The LAPS Water-In-All-Phases (WIAP) that assimilates multiple sources of information concerning the spatial and physical distribution of water in the atmosphere would be performed as part of this real-time system alongside the LAPS analysis not utilizing WIAP, in order to examine the utility of performing this kind of initialization. Forecasts would be generated hourly to half-hourly over the IHOP domain. A 1km grid could be set up to best resolve small-scale features. If Oklahoma Mesonet could be networked to FSL, that data could be used in these real-time model runs. FSL would use its locally acquired GOES imager and sounder data, and profiler data (we currently ingest the Lamont OK data). We would participate on-site at the

operations center to ensure that the forecast products are utilized optimally, and we would also like to be on the operational forecast staff.

2. We propose to produce research-quality mesoanalyses at FSL in the post-field phase. These integrated and complete multi-scale analyses of water vapor and wind fields using LAPS at grid resolutions of 10 km or finer can be accomplished with sufficient funding. The lidar, radiometer, and other remotely sensed water vapor and wind fields could be the subject of data assimilation, but the effort required to do this varies greatly among the various sensing systems (see below). The analyses will be archived for use by IHOP researchers, such as for initializing and verifying numerical simulations performed to examine specific convective initiation mechanisms, conducting model moisture budget studies, and increasing understanding of mechanisms for creating inhomogeneous moisture fields in the convective environment.

3. Post-field phase research at FSL using the data acquired during IHOP will be most useful for case studies: 1) to determine the most useful data for improvements in model forecasts (i.e., data have the most impact on QPF), 2) to render better water vapor analyses to obtain a clearer picture of water vapor structure, and 3) to validate the LAPS/MM5 model “hot start” procedure that includes clouds and precipitation in the initial state. Analyzing available data to gain an improved overall view of the scales involved can accomplish these goals. The work should be prioritized to integrate data that that will benefit the operational forecasting community the most. Generally when a data interface is established in LAPS, those data interfaces can be easily applied to operational applications in AWIPS. This activity would provide two main elements needed in IHOP: 1) the improvement of moisture analysis and gaining insights to moisture processes, and 2) the advantage that the work done for the first element facilitates operational use of new data sources. Since LAPS is in the local forecast office, these improvements have a direct route to field application.

We would also like to perform full 3-D variational data assimilation with the more experimental mobile and airborne data systems after the field exercise to determine the benefit of better specification of the ambient moisture field for forecasts of the state variables and precipitation fields. This clearly is a major research undertaking involving the development of forward models and error covariance statistics for each of the observing systems in IHOP. We seek to understand how the strengths of lidars to profile in clear air with exceptionally high spatial resolution may be best combined with the strengths of radars, GPS, radiometers, and other systems for measuring moisture in the presence of clouds and precipitation.

Convection Initiation

Hypothesis: The preferred locations for the initiation of deep convection are dependent upon the horizontal distribution and depth of water vapor along convergence zones (drylines, outflow boundaries, undular bores, etc.).

Hypothesis: The depth of ample moisture beneath a strong capping inversion is controlled by a combination of the strength of the local convergence along a boundary, the depth of this convergence zone, and the Froude number above the boundary layer.

Hypothesis: A thermally-direct, secondary circulation generated by cross-frontal variations in sensible heat flux arising from the total cloud cover distribution and the moisture availability field across the frontal zone will initiate frontal line convection provided that there is sufficient CAPE.

Hypothesis: Interaction of small-scale southerly “jetlets” with air mass boundaries (warm fronts, stationary fronts, outflow boundaries, etc.) creates local maxima in upward motion, leading to convection initiation north of such intersection points.

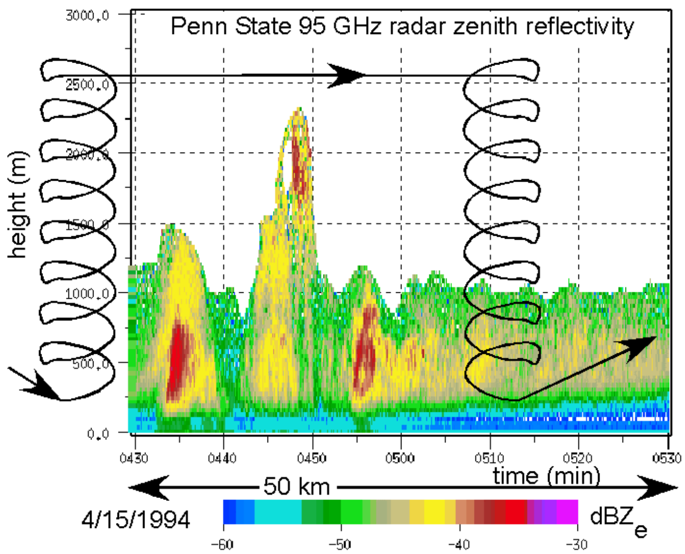
Measurements required for testing this hypothesis (prioritized):

- Fixed ground-based
  1. Oklahoma Mesonet
  2. Ground-based water vapor DIAL: to measure changing moisture variability at two points, each at one side of the convergence boundary
  3. Scanning Raman lidar: water vapor profiling in vertical plane normal to boundary
  4. Passive 12-channel radiometric profiling of water vapor
  5. AERI and Raman lidar are useful only if boundary passes overhead
  6. Surface heat (Bowen ratio) fluxes from surface mesonets and aircraft
  7. 5-75 cm deep soil moisture measurements from the Oklahoma Mesonet
  8. Vegetation fields obtained from polar-orbiting satellite (NDVI)

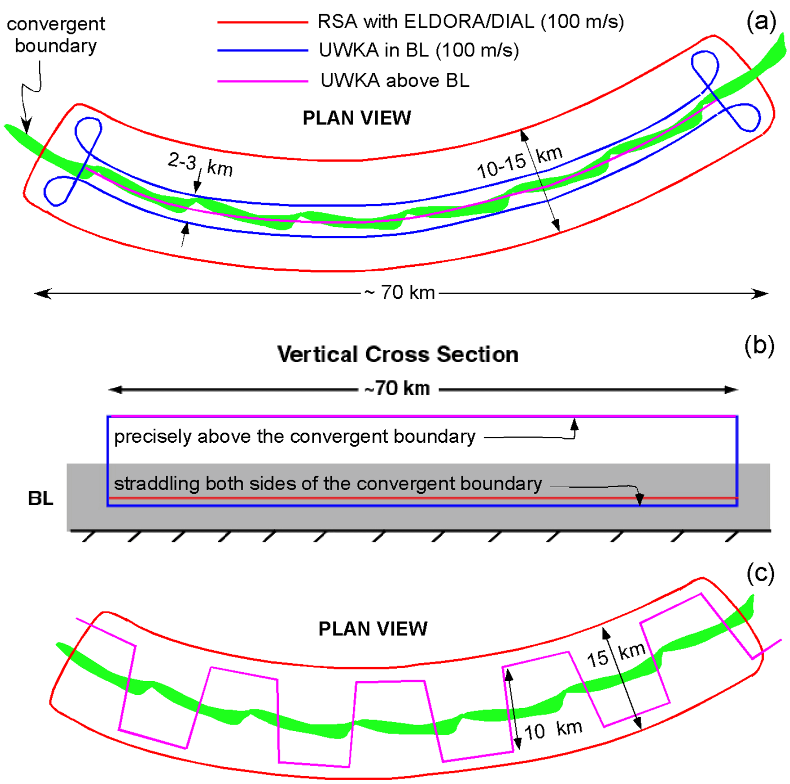
- Mobile ground-based measurements:
  1. Mobile mesonets
  2. Mobile GLASS on either side of boundaries
  3. U-Mass ground-based 3 mm Doppler radar
  4. Mobile Integrated Profiling System (MIPS): 5-beam 915 MHz profiler, 3-beam sodar, lidar ceilometer, water vapor radiometer
  5. SMART-R scanning S-band Doppler radar: for detailed wind field analysis
  6. IPW mobile radiometer: to relate moisture depth changes to jetlets

- Airborne sensor systems:
  1. Electra or NRL P-3 ELDORA dual-Doppler radar and CNRS LEANDRE DIAL in sideways-looking mode: for study of detailed kinematic and moisture structure

2. Wyoming King Air dual-Doppler measurements coordinated with LEANDRE DIAL: detailed study of 3-D environment around convergence boundaries
3. German DLR Falcon or NASA DC-8 dropsondes
4. MACAWS on NASA DC-8 for measuring 3D volumes of winds and aerosols



Boundary overflights and soundings. Flight across the boundary above the BL top, emphasizing Wyoming King Air (WCR) observations, with soundings on both sides of the boundary. Used when the dropsonde aircraft does not participate. Three or more soundings are possible in complex boundary conditions (waves/bores/ gravity currents). The reflectivity pattern providing a background for this figure was collected by the Penn State University 95 GHz ground-based radar (image courtesy of B. Demoz). A wavetrain can be seen with highly variable amplitudes. Clearly the echo pattern from the BL to the wave clouds is continuous. The ascent/decent rate for this pattern is about 1000 ft/min. Pattern duration: 13-43 min.



Sampling along-line variability. (a) and (b): continuous sampling: the UWKA first flies above a convergence line, at ~ 2 km AGL. The aircraft is guided by visual clues, yet should not depart much from level flight, to allow vertical dual-Doppler measurements. Next two low-level flight legs are conducted, at the same flight level as the RSA, on opposite sides of the boundary. RSA coordination is aimed at validation of LEANDRE-II water vapor DIAL measurements, and to assess along-line variability. (c) discrete sampling: UWKA transects above the BL are repeated at 5-10 km intervals along the line.

Desired meteorological conditions:

Aircraft will perform a series of large box patterns around the boundary with flight legs parallel to the primary boundaries of interest. Each flight leg will be ~50 km in length and would preferably commence well before the initiation of convection.

Accurate characterization of variations in vertical winds, stratification, wind shear, horizontal wind fields, temperature and moisture in the vicinity of boundaries are required.

Necessary locations for mobile ground-based instrumentation:

Operations center needs:

Boundary Layer Processes

Hypothesis: "Spatial variations in moisture depth have a direct influence upon convection initiation and evolution."

Hypothesis: "Spatial variations in water vapor flux divergence have a direct influence upon convection initiation and evolution."

Hypothesis: A thermally-direct, secondary circulation generated by cross-frontal variations in sensible heat flux arising from the total cloud cover distribution and the moisture availability field across the frontal zone will initiate frontal line convection provided that there is sufficient CAPE.

Measurements required for testing this hypothesis (prioritized):

- Fixed ground-based and satellite data:
    1. Continuous measurement of vertical water vapor flux divergence up to 3 km from CART profiling radiometer, AERI, Raman lidar (moisture) collocated with boundary layer profilers (winds)
    2. Integrated Surface Flux Facility
    3. Continuous measurement of variations in boundary layer depth
    4. CASES/ABLE arrays (several 915 MHz profilers with RASS + minisodars + SMOS + Bowen or eddy-correlation flux stations)
    5. Mesoscale variations in land-surface forcing measured with AVHRR or MODIS

- Mobile ground-based measurements:
    1. MIPS (a 915 MHz profiler, Doppler sodar, lidar ceilometer, and SMOS)
    2. Mobile GLASS: to provide profiles of basic atmospheric variables
    3. Continuous measurement of vertical profiles of sensible and latent heat fluxes from MAPR spaced antenna wind profiler and NCAR ISS (GPS radiosonde + 915 MHz wind profiler with RASS + SMOS)

- Airborne sensor systems:
    1. Wyoming King Air dual-Doppler sampling of the same air volumes as LEANDRE DIAL: for study of detailed variations in moisture convergence and moisture depth surrounding low-level convergence boundaries
    2. High-resolution remote profiling of ABL from airborne and mobile platforms
    3. German DLR Falcon flying with water vapor DIAL and HRDL to measure water vapor flux profiles
    4. P3 SABL upward-pointing aerosol lidar for monitoring cloud base and ABL depth

5. Airborne water vapor DIAL in combination with downward-looking Doppler lidar to estimate turbulent flux divergence profiles using eddy correlation techniques
6. Airborne and mobile ground-based pseudo-dual Doppler radar

Necessary locations for mobile ground-based instrumentation:

5 ISFF needed at CASES/ABLE site and 4 at CART Central Facility

Desired meteorological conditions:

Operations center needs: