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The Water Cycle Across Scales: An NCAR Initiative

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1. INTRODUCTION

Daily newspaper headlines of floods and droughts reflect the critical importance of the water cycle in human affairs. Flood damage estimates are in the billions of dollars annually, with thousands of lost lives, while drought costs are of similar magnitude and often lead to devastating wildfires. Floods are often fairly local and develop on short time scales, while droughts are extensive and develop over months or years (Figure 1). *Both extreme and moderate manifestations of the water cycle are controlled by processes at a wide range of both spatial and temporal scales.* For instance, whether or not a thunderstorm occurs may depend on water vapor amounts that vary on small scales and depend on boundary layer and surface processes such as those associated with heterogeneous vegetation and soil moisture. But large scale and systematic patterns, such as the diurnal cycle, are also important. Thus, in order to accurately predict the water cycle in both weather and climate models, including both extreme and more moderate manifestations, detailed knowledge of processes at all scales is necessary.

Figure 1 Low water level at Lake Dillon, Colorado on August 8, 2002 (Photo courtesy of Richard Anthes

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NCAR is well positioned to address many of the outstanding Water Cycle problems as a result of its expertise in both climate and weather time and space scales, and its strong connection to University scientists. This initiative represents a coordinated effort to bring to bear both NCAR and community expertise to improve our understanding of the water cycle across scales, and to use this understanding to improve predictions on both the weather and climate scale of the water cycle.

The initiative is organized by a cross-divisional and cross-disciplinary steering committee. The present membership is: Jim Hack, Peggy LeMone, Mitch Moncrieff, Dave Parsons, Roy Rasmussen*, Kevin Trenberth, Tom Warner and Jim Wilson. Roy Rasmussen* is the current head of the Steering Committee.

2. MOTIVATION AND SCIENTIFIC BACKGROUND AND ISSUES

2.1 Motivation

While the water cycle is a global problem, increased knowledge over the continental US will lead to significantly better understanding and prediction of key aspects, on scales ranging from storm-scale to climatic fluctuations. This improvement has the potential to dramatically alter the public's ability to plan for and react to significant weather events. Thus we decided to focus our efforts on understanding how water vapor, precipitation, and land-surface hydrology interact across scales to define the hydrological cycle up to the U.S. continent scale during the summer. Based on this understanding, parameterizations of convection and land surface processes will be improved, and as a result, so will large-scale prediction models. The IHOP water vapor field program will serve as a focal point for this initiative due its focus on the accurate measurement of all three components of the water cycle across the diurnal cycle and over a fairly large domain in the mid-continental region of the U.S. during the summer.

2.2 Scientific background and issues associated with the summer water cycle over the continental U.S.

The mean pattern of continental summer U.S. precipitation is characterized by late afternoon maxima over the Southeast and Rocky Mountains and midnight maxima over the region east of the Rockies and the adjacent plains. Diurnal variations of precipitation are weaker in other seasons, with early to late morning maxima over most of the United States in the winter. The diurnal cycle in precipitation frequency accounts for most of the diurnal variations, while diurnal variations in precipitation intensity are small (Dai et al. 1999).

The solar driven diurnal and semi-diurnal cycles of surface pressure result in significant large-scale convergence over most of the western United States during the day and over the region east of the Rocky Mountains at night (Dai and Deser 1999). As shown by Dai et al. (1999) the diurnal cycle of low-level large scale convergence suppresses daytime convection and favors nighttime moist convection over the region east of the Rockies and the adjacent plains. The nocturnal maximum in the region east of the Rockies is also enhanced by the eastward propagation of late afternoon thunderstorms generated over the Rockies. The recent study by Carbone et al. (2002) has shown episodes of convection originating from the Rockies on a diurnal basis that typically propagate ~ 1000 km and last 20 hours or so. Another factor is the presence of a low level nocturnal jet in this region, which favors convection in the evening due to the moisture transport. Recent results from the International H2O Project (IHOP) have revealed a possible role for undular bores in maintaining nocturnal convection in this region as well. Over the Southeast and the Rockies, both the static stability and the surface convergence favor afternoon moist convection in summer, resulting in very strong late afternoon maxima of precipitation over these regions.

Prediction models that use convective parameterizations can typically simulate some, but not all of the diurnal precipitation pattern describe above. For instance, a number of models tend to produce the maximum precipitation about local noon, corresponding to the time of maximum heating. In the models having convection parameterization schemes explored by Dai et al. (1999), all produced too much cloudiness over the Southeast, which reduced surface solar radiation and thus altered the peak warming at the surface. Model criteria for onset of moist convection are typically too weak, and so moist convection in the model starts too early and occurs too often. Premature triggering of convection and thus cloudiness disrupts the proper heating at the surface of the continent and thus prevents the continental-scale “sea breeze” and associated convergence and divergence patterns from developing properly. The surface heating is also affected by the moisture content of the soil, which in turn is also effected by the intensity and frequency of precipitation. Frequent light precipitation will tend to saturate the soil, reducing sensible heat fluxes and increasing latent heat fluxes, while less frequent but more intense precipitation will tend to runoff and produce less moisture in the soil, increasing sensible heating. These processes in turn affect the large scale transport of moisture and its role in setting up convective instabilities is disrupted.

In addition, the premature initiation of convection leads to relatively weak clouds with weak downdrafts and gust fronts. Convergence at the leading edge of gust fronts and during collisions of gust fronts has been well established as one of the primary initiation mechanisms for triggering new convection. Thus, only weak or no convection may be initiated by weak gust fronts, which tends to further the trend for weak convection. The recent discovery by Carbone et al (2002) of long lived precipitation episodes represents another modeling challenge. Recent studies by Moncrieff and Liu (see next section) have shown that current convective parameterizations do not capture this phenomenon properly.

It is these kinds of interactions and processes that must be better simulated in models. The following section describes the research plan designed to address these deficiencies.

3. FY03 – FY05 Research Plan

The main goal of the NCAR water cycle initiative for the next three years is to improve our understanding and prediction of the summer diurnal cycle of water across the continental United States, with emphasis on the mid-continent region. This emphasis is motivated by the relatively poor representation of the diurnal cycle of convective precipitation in weather and climate models in this region as discussed above.

Four main areas of emphasis have been identified to address this goal: 1) diagnostic analysis of precipitation on a continental scale from observations and models, 2) cloud-system simulations of warm season convection over the IHOP mid-continent domain and development of improved convective parameterizations, 3) analysis of water vapor data from the IHOP field program and investigations into the triggering mechanisms for warm season convection using IHOP data, and 4) measurement, analysis, and prediction of land-surface processes and their interaction with the atmosphere. A schematic summarizing these phase I activities is given in figure 2. The first row in this figure gives the areas of emphasis described above. The second row provides the key objectives under each emphasis area. The achievement of these objectives will lead to a better understanding of the water cycle and also improved prediction. Note the progression from understanding to improved prediction of the water cycle through the development of improved convective and land surface parameterizations in weather and climate models. The key role of the IHOP field data is also emphasized.

Section 4 describes some of the accomplishments during the first year of the initiative and future plans. Concluding remarks are given in section 5.

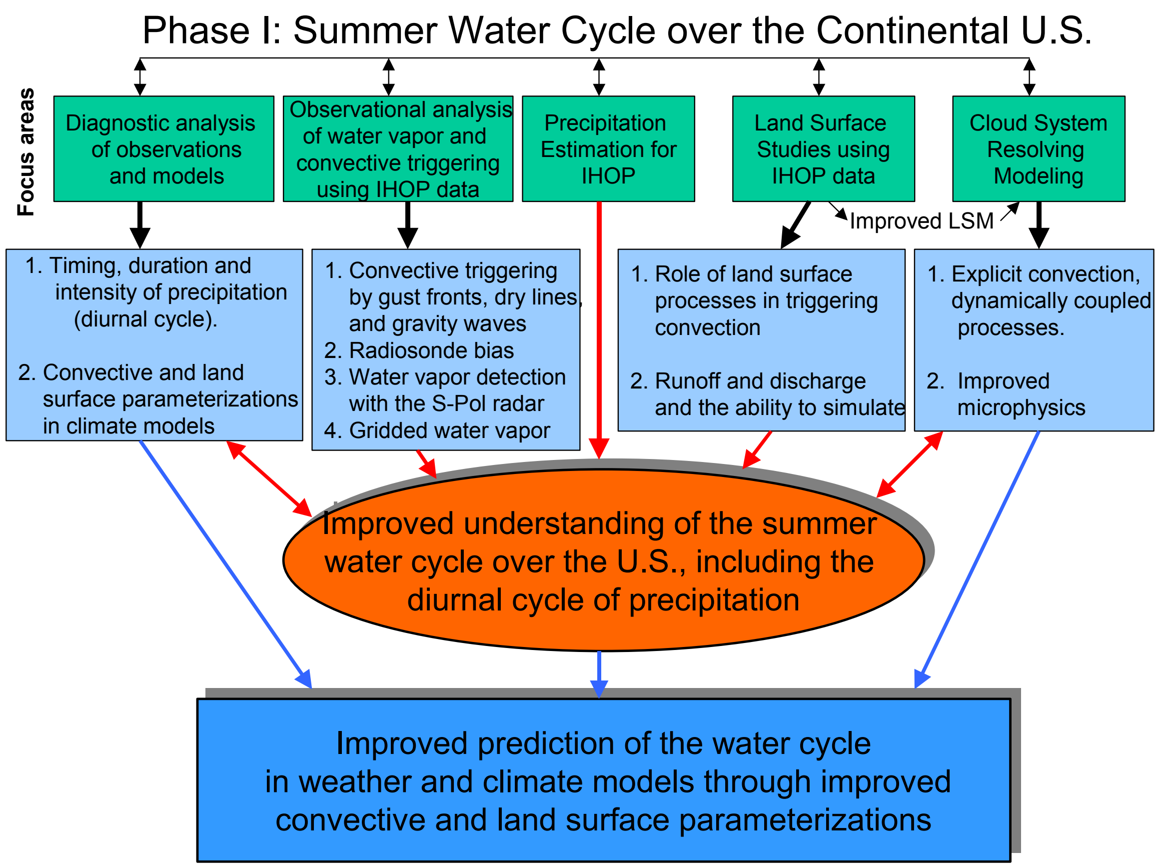

Figure 2 Schematic diagram of the Phase I activities of the Water Cycle initiative

4. Accomplishments to Date and Future Plans

4.1: Diagnostic Analysis of Precipitation on a Continental Scale

Accomplishments to Date:

Aiguo Dai performed analysis of the NCAR Community Climate Model (CCM) runs on the diurnal cycle and the frequency and intensity of rain. His analysis showed that the diurnal cycle of precipitation is poorly represented in current climate models, with rain occurring too early (Figure 3, Dai 2001) and with too light of an intensity, as compared to observations. Note in particular the maximum near local noon in model predicted rainfall over the mid-continent of the U.S. as compared to a midnight maximum in rainfall frequency in the observations.

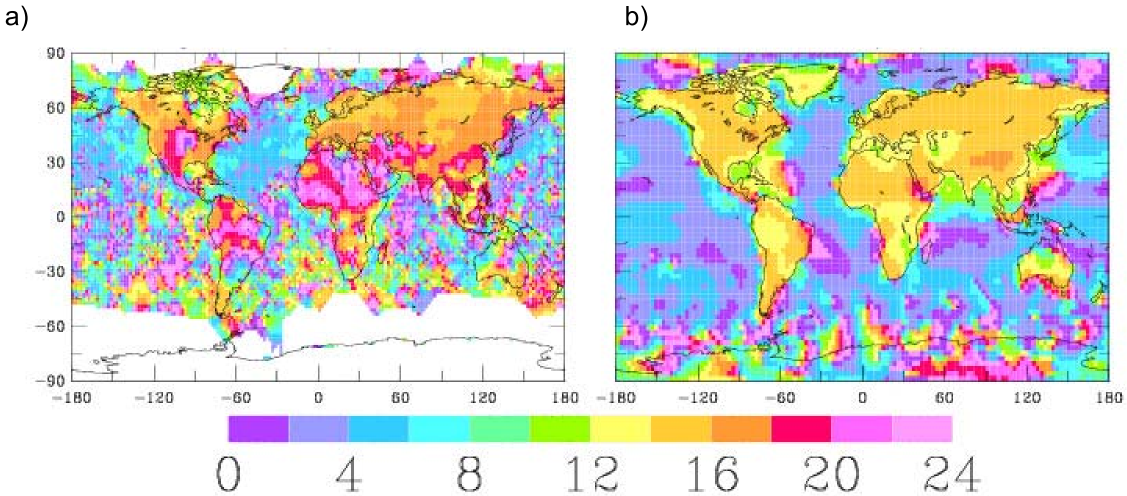

Figure 3 Local time of maximum frequency of convective precipitation for June, July, and August from a) Synoptic observations from 1976 – 1997 (Dai 2001), b) CCSM 1983 – 1988.

Complementary work has resulted in new estimates of freshwater fluxes (Evaporation minus Precipitation E-P) and, exploiting those, new estimates of surface runoff and discharge from land into oceans (Dai and Trenberth 2002).

Future Plans:

Work will continue on the determination of freshwater fluxes (E – P) using re-analysis diagnostics. This will also include an evaluation of the re-analysis datasets with reference radiosonde and water vapor fields from IHOP. In addition, diagnostic work regarding deficiencies in the diurnal and surface fluxes in the CCSM will continue. Experiments will be conducted to determine the importance of higher time rate exchange of ocean surface fluxes on the diurnal cycle, including the development of a “Lake Model”.

A new effort will start to improve the CCSM land surface model based on diagnostic data from the global river and runoff work discussed above, and using surface fluxes and ancillary vegetation and soil data from IHOP.

A second new effort will examine causes for the poor representation of the diurnal cycle of precipitation in climate models by examining global model details at the process level using a combination of diagnostic analyses in conjunction with idealized single column model simulations employing the CAM2 physics package.

4.2: Cloud-system Simulation

4.2.1 Simulation of cloud systems over the mid-continent U.S. during the warm season.

Accomplishments to Date:

Mitch Moncrieff and Changhai Liu examined the formation of convection over the continental U.S. using the MM5 mesoscale model with different convective parameterization schemes. The MM5 was initialized with NCEP Global Data Assimilation System (GDAS) incorporated into the MM5 objective analysis. The results showed that while sequences of convection are sometimes realized in MM5, with differences among the convective parameterization schemes tested (Betts-Miller, Grell, Kain-Fritsch), they move too slowly, are too weak and have other major deficiencies.

In order to investigate this further, several 5-day two-dimensional Cloud System Resolving Model (CSRM) simulations were performed using a 3,200 km x 20 km model domain centered on the mid-continental U.S.. The horizontal and vertical grid spacing were 1 km and 0.2 km, respectively. The model was initialized with the composite thermodynamic fields derived from a 10-day simulation with MM5 (described above) and deep westerly shear. The control simulation was forced with diurnal-varying boundary conditions, surface fluxes and vertical advection as composites from the MM5 analysis. A regular pattern in the diurnal convective development and translation occurred. Convection initiated over the Rockies each afternoon, then propagated eastward at about 14 m/s, resulting in nocturnal rainfall over the eastern plains (Figure 4). This behavior is broadly consistent with Carbone et al. (2002) observational results, but the convection is too weak. The convective organization was dominated by fast-moving squall-type convective systems. Isolated short-lived convection occurred in moderate low-level shear. The analysis of these results is ongoing and further results will be reported at this conference.

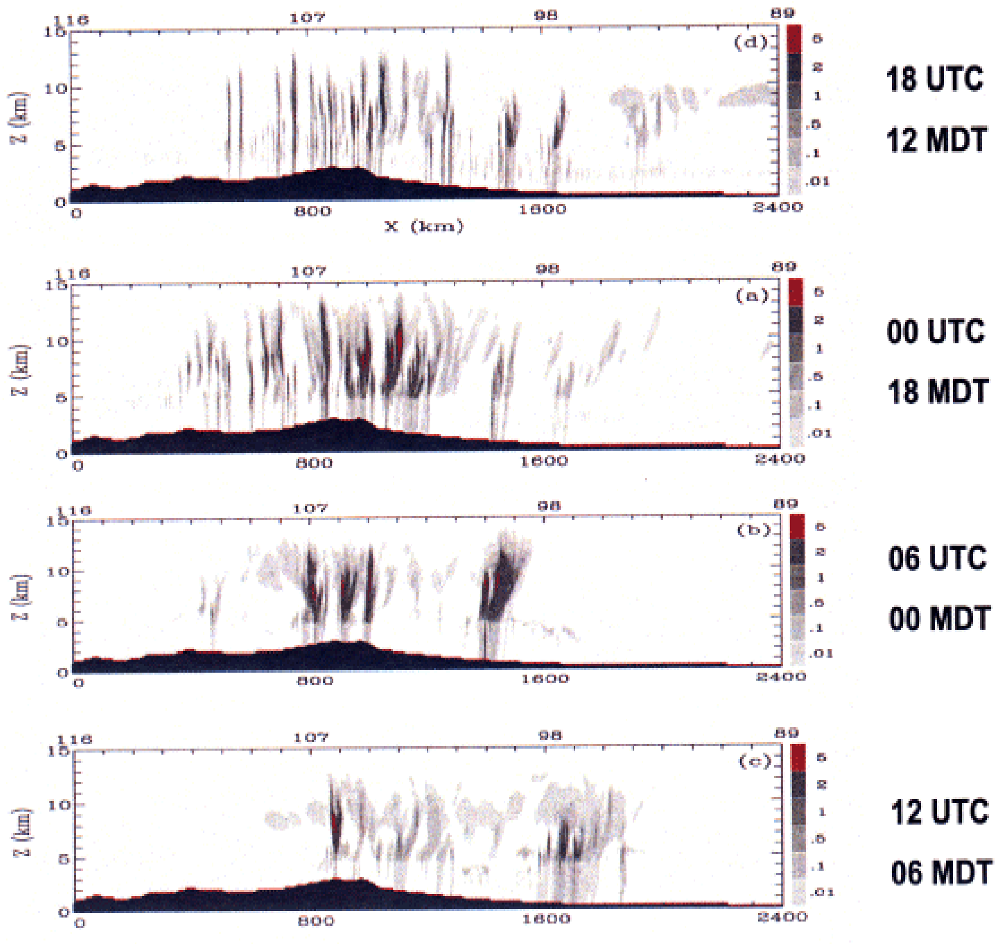

Figure 4. Snapshots of total condensate (rain + snow + cloud water) from the 2D resolved-convection simulation. Convection starts over the Rockies, evolve into mesocale convective systems that subsequently travel eastward at about 14 m/s (from Moncrieff and Liu 2002).

Future Plans:

Three-dimensional CRM simulations will be conducted in order to generate synthetic 3D datasets for IHOP, analogous to the three-dimensional numerical experiments conducted over the tropical oceans; e.g., Wu and Moncrieff (1996), Grabowski et al., (1998). Synthetic 3D data (and data from 2D simulations) will be used to : i) derive quantities useful for parameterization development; ii) provide a large-scale context for detailed observations and translate convection initiation results (Wilson and Parsons) into a parameterization context, such as trigger functions. These synthetic data may also be used to evaluate a new CAPE-based closure for convective parameterization schemes (Guang Zhang, Scripps Institute).

4.2.2 Improve microphysical parameterizations

Accomplishments to Date:

Roy Rasmussen and Vidal Salazar participated in the IMPROVE II field program in the Oregon Cascades from Nov. 28 – Dec. 20. This program was designed to collect a dataset for improving microphysical parameterizations. This field program collected an excellent dataset on 13 storms.

Future Plans:

A few high priority cases will be chosen from this project and simulated with the Geresdi detailed microphysical model. Improvements will be made to the bulk microphysical scheme based on comparison to the observations and the detailed microphysical model. These improvements will be implemented into the Cloud-System-Resolving Model (CSRM) discussed above.

4.2.3 Large Scale numerical test bed for parameterization of moist convection as guided by CSRM simulation results.

This new effort will evaluate formulations of deep convection and boundary layer processes in climate models against comparable CSRM simulations, and comparable available observational datasets. Both the mean and transient behaviors, with an emphasis on the diurnal cycle, will be explored, refined, and tested in the CAM2 Single Column Model (SCM). The detailed in-situ observational datasets that will be utilized in both the modeling and analysis components of this work include ARM SGP measurements, and results from the recent IHOP experiment.

4.3: Water Vapor and warm season convection

4.3.1: Participation in the IHOP field program.

Accomplishments to date:

A key initial activity of Water Cycle scientists was participation in the International H2O field Program (IHOP, Figure 5) held from May 13 – June 25, 2002. Dave Parsons and Tammy Weckwerth (both involved in the Water Cycle initiative) co-led the field program. An excellent dataset describing all components of the water cycle was obtained, with special emphasis on the measurement of water vapor, surface fluxes, and convective precipitation. Data from this field program will be used in many of the proposed FY03 – FY05 activities.

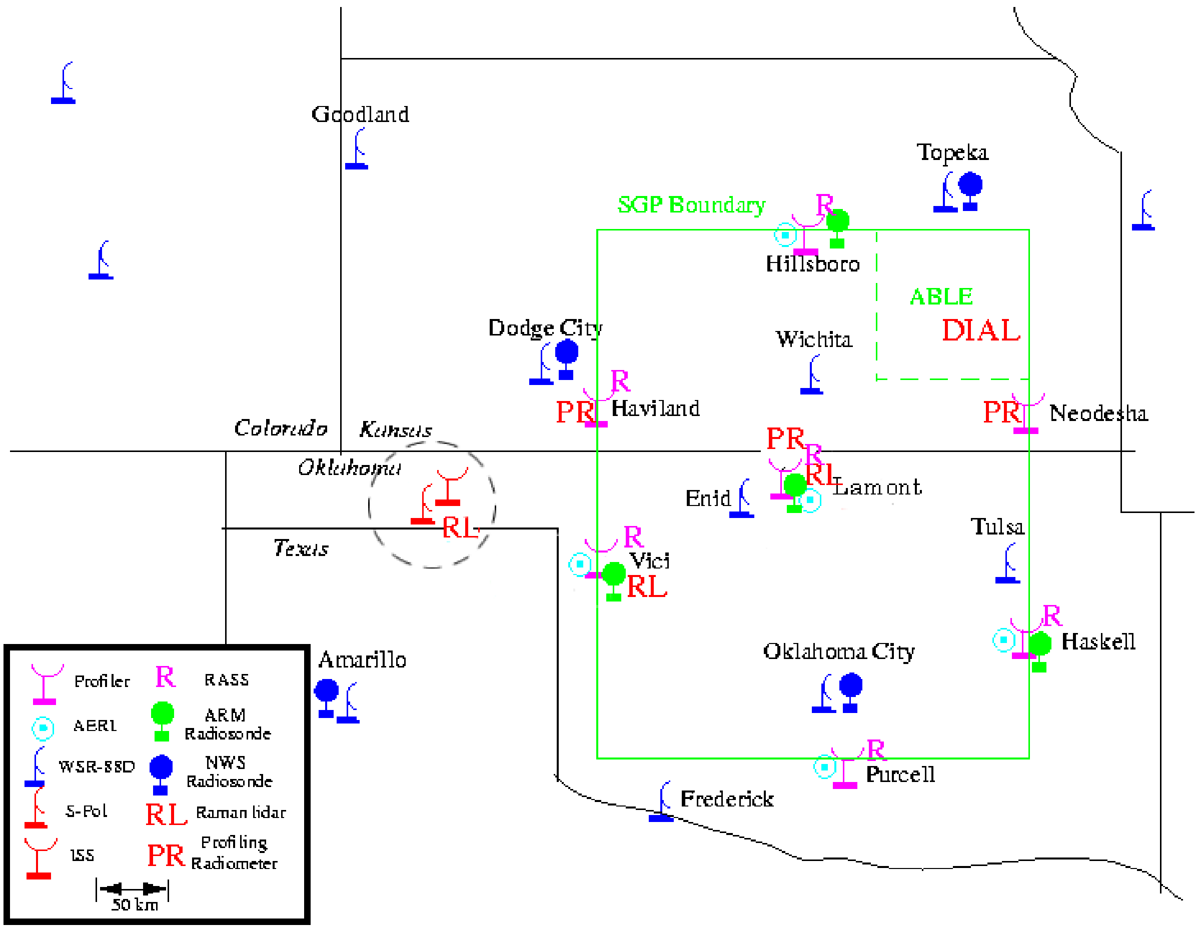

Figure 5. Schematic of the instrumentation deployment during IHOP

4.3.2 Reference radiosondes for the IHOP field program.

Accomplishments to date:

The Water Cycle initiative supported deployment of reference radiosondes in IHOP was motivated by recently detected errors in the measurement of humidity by operational soundings (e.g., Wang et al. 2001) and the finding that these sounding errors induce differences in the radiation budget that exceeds the projected impacts of doubling CO_2 (Guichard et al. 2001).

Sixty reference radiosonde systems were developed and deployed during IHOP. Preliminary analysis of the data show that the standard radiosondes have significant bias (Figure 6). The impact of these errors on model simulations will be a focus for the next three years

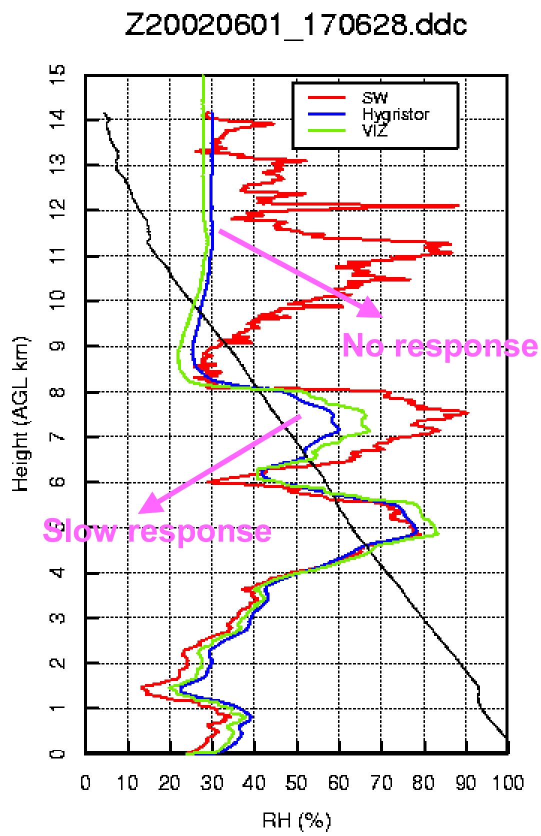

Figure 6 Comparison of the reference radiosonde (red line) to NWS sondes.

Future Plans

Analyze the reference radiosonde data for IHOP and collaborate with investigators involved in emphasis area 4.1 to understand the impact of these errors on NCEP/NCAR re-analysis data sets and the climate record.

4.3.3 Predictability research on warm season convection

Accomplishments to date:

IHOP data sets have been assembled for examining in unprecedented extent and detail the factors controlling convective storm evolution. Data sets include operational satellite, radar, sounding, surface and numerical models and numerous research data sets. These data sets are being compiled in common formats for viewing in NCAR sophisticated display systems called ZEBRA and CIDD. During the field programs extensive computerized notes and analysis were prepared that provide initial positions of boundary layer convergence lines and time and locations of storm initiation (Fig. 7). These data sets and their display will form the basis for the detailed studies to be conducted on convective initiation.

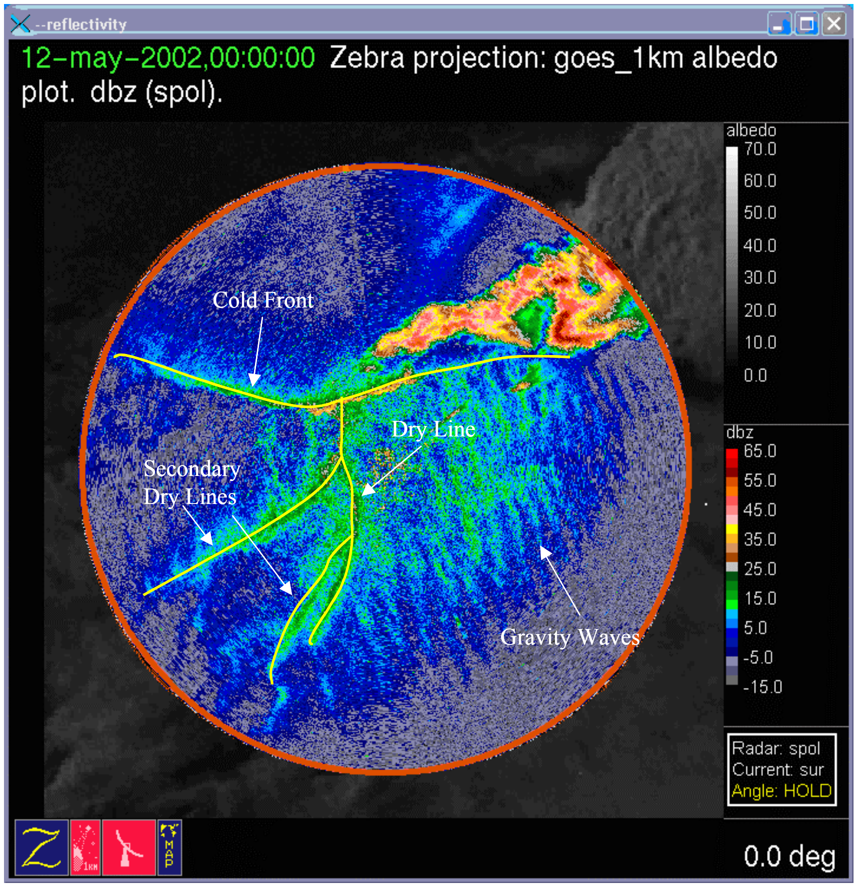

Figure 7 Example of boundary layer forcing mechanisms as observed by S-pol during IHOP. The large storm was initiated as the cold front moved south intersecting the dry line. Subsequent storms were also initiated at their intersection..

Future Plans

Using the data collected during IHOP, an assessment will be made of storm triggering mechanisms on multiple scales for all precipitations events during IHOP. This will include an analysis of the relationship between convection initiation and boundary layer convergence lines and stability. These results will also be used to evaluate the treatment of convective rainfall in numerical models.

4.4: Atmosphere-land interaction

4.4.1: Precipitation estimation

Accomplishments to Date:

Improved precipitation estimation algorithms were developed and used to estimate precipitation during IHOP.

Future Plans:

Produce gauge-adjusted radar-based rainfall maps for major events occurring the the Walnut River watershed during IHOP and CASES 97 and use these estimates to support soil moisture and runoff studies for the Walnut River watershed using radar and gauge data.

4.4.2: Surface hydrology and runoff modeling

Accomplishments to Date:

The USGS Precipitation Runoff Modeling System was adapted to a few demonstration runoff watersheds in the Denver area. In addition, radar estimated rainfall has been merged with Denver and Front Range rain-gauge data to facilitate comparison and interpretation.

Future Plans:

Radar- and gauge-estimated precipitation fields for the Whitewater watershed (uncontrolled sub-basin of the Walnut, within the IHOP domain) will be used to perform the following work. 1) The USGS physically based Precipitation Runoff Modeling System's (PRMS) treatment of overland flow and channel flow will be improved. 2) The PRMS will be adapted to efficiently handle IHOP precipitation estimates. 3) Uncertainty in rainfall estimates and the resulting runoff predictions will be estimated. 4) The capability of the PRMS to simulate erosion and sediment transport will be enhanced. 5) The PRMS output will be compared to the operational NWS Area Mean Basin Estimated Rainfall (AMBER) system. Studies will also be conducted for wildfire burned areas in Colorado and for the Denver urban area with respect to the use of radar/gauge-estimated precipitation and physically based discharge models for flash-flood prediction.

4.4.3: Surface and atmospheric boundary-layer processes in the water cycle – the use of IHOP data

Accomplishments to date:

A team took soil moisture/temperature measurements to enhance the IHOP surface-tower observation array. The team includes Dave Yates, Jeff Cole, Fei Chen (RAP), Peggy LeMone (MMM), Steve Semmer (ATD), and Richard Cuenca (OSU). They enhanced 10 surface flux measurement sites with measurements of soil temperature and moisture, weekly vegetation characteristics, and sampled horizontal heterogeneity along 45 m transects. This allowed for comprehensive soil and vegetation measurements at the same location of the flux measurements. An excellent dataset was collected during IHOP, and analysis of this data will be a focus of study during the next three years.

Future Plans:

The importance of accounting for surface effects and boundary-layer effects in weather and climate models and the need for improvement has been widely demonstrated. As discussed in the previous accomplishments section, the land surface measurements during IHOP were enhanced with the addition of soil moisture and temperature sensors and measurements of the vegetation characteristics were made. This and other IHOP data will be used to improve our understanding of surface and boundary layer processes, and to improve the representation of those processes in numerical weather prediction models.

The following tasks will be performed: 1) Prepare and provide surface flux, vegetation, soil-profile, and aircraft datasets suitable for evaluation and development of LSMs. 2) Prepare and provide analyses of long-term hourly 4-km soil-moisture and evaporation using the NCAR high-resolution land-data assimilation system for the study region. 3) Document the effects of surface heterogeneity on surface fluxes and boundary-layer structure, and integrate/compare with data from other platforms.

5. CONCLUDING REMARKS

This paper provides an overview of the NCAR Water Cycle Across Scales initiative, including some initial results and future plans. The focus for the next three years is on improving our understanding of the summer water cycle over the mid-continent region of the United States, and using this improved understanding to improve convective and land surface parameterizations for both weather and climate models. Achieving this goal requires coordinated scientific efforts at a variety of time and space scales. This initiative provides a framework to achieve this coordination. While a number of university scientists are involved, we seek additional collaboration from both university and laboratory scientists in order to achieve this challenging goal. In the future we plan to address global issues related to the water cycle, in particular, how well our understanding of the summer water cycle in the mid-continent of the U.S. transfers to other regions of the globe.

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