Front Range Observational Network Testbed – Precipitation Observations and Research on Convection and Hydrometeorology 2013

FRONT-PORCH 2013

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Project Summary: The *Front Range Observational Network Testbed - Precipitation Observations and Research on Convection and Hydrometeorology* (FRONT-PORCH) experiment is an investigation of meteorological and hydrological processes that are important to accurately predict the timing, location and intensity of orographic and convective precipitation and its hydrological response in complex terrain. The multi-organizational FRONT-PORCH experiment in the summer of 2013 will provide critical insight into a comprehensive range of processes contributing to convective and orographic precipitation over the mountains, foothills and plains in the FRONT domain. This scientific proposal will accomplish this by executing the following four principle research tasks:

Task 1-Physcial Process Studies: Conduct hydrometeorological process research into the controls on warm season convection initiation, evolution and its hydrological responses in complex terrain

Task 2-Radar Retrieval Research: Perform basic research with multi-parameter microwave radar systems on the spatially and temporally continuous retrieval of precipitation, wind, humidity and hydrometeor structures

Task 3-Real-time Demonstrations: Demonstrate real-time, end-to-end, hydrometeorological (e.g., precipitation and streamflow) nowcasting capabilities through assimilation of high resolution data into both NWP-based and extrapolation-based prediction systems

Task 4-Collection of Radar Data Sets for Classroom Use: Obtain radar data sets which will serve as the basis of web-accessible modules designed to illustrate key mesoscale storm structures for upper level undergraduate and graduate students.

Essential in addressing the research objectives in FRONT-PORCH is the usage of the FRONT radar network (i.e., NCAR S-PolKa, CSU-CHILL and CSU-Pawnee) in conjunction with numerous other deployable assets described in the adjacent proposal.

Intellectual merit: Accurate prediction of the timing, location and amount of precipitation over complex terrain continues to be a grand meteorological challenge as it depends on complex, multi-scale processes ranging from orographic airflow dynamics to atmospheric thermodynamics to cloud microphysics. The proposed measurements in FRONT-PORCH are the first in the western U.S. to track both meteorological and hydrological connections between the ‘outputs’ (location and amount of precipitation and hydrological runoff) and the ‘inputs’ (upwind flow, humidity, temperature and surface fluxes) of the hydrometeorological regime through study of the intermediate transformational steps (orographic flow modification and formation of precipitation). By integrating data from multiple observation systems with data assimilation and modeling systems we will create a unique opportunity to evaluate existing hypotheses on orographic-convective processes and will be able to quantify principal sources of error in the hydrometeorological prediction chain. These discoveries will help answer the fundamental question: “What is the predictability of the timing, location and amount of convective-orographic precipitation and hydrologic responses over complex terrain of the Colorado Front Range?”

Broader Impacts: Improving the ability to predict the timing, location and amount of convective-orographic precipitation will have a direct impact on flood prediction skill and on a wide range of human activities. One of the most important scientific impacts will be on hydrological modeling and forecasting since uncertainty in the location and amount of precipitation is one of the greatest sources of error in hydrological predictions. The societal threats imposed by severe convection in the Colorado Front Range (CFR) region are endemic in many other mountain front regions around the world such as the southern Alps in Europe, the southern fronts of the Himalaya and the Hindu-Kush in south Asia, and the Sierra Madre Occidental and Oriental in Mexico. Using the CFR as a natural laboratory for such hydrometeorological regimes, the FRONT-PORCH project will make significant, transferrable discoveries in fundamental earth system processes while also making significant strides in improving the accuracy and timeliness of hazardous weather impacts predictions. Furthermore, the proposed education plan will offer educators and students a unique, hands-on experience in conducting field research in hydrometeorology.

Project Description

1. Scientific Background and Objectives

It is widely recognized that the prediction skill, in terms of lead time and accuracy, of warm season, convective precipitation and runoff events lags significantly behind that of typical cool season, frontal events in the mid-latitudes. While intense diurnal forcing and large landforms can provide some organizational influence on precipitation and runoff activity, the comparatively weaker dynamical forcing of the continental summertime climate permits respectively greater roles of relatively small scale (O 1-100km or 'classical mesoscale') atmospheric and land surface features in determining the occurrence and intensity of precipitation events and their hydrologic responses. These mesoscale features include boundary layer convergence lines, moisture gradients, weak temperature inversions, drylines, weak wind shear profiles, vorticity and potential vorticity anomalies, land surface thermal and hydrologic heterogeneity and 'sub-mountain block' terrain features (e.g., valleys/ridges and terrain orientation and slope). Many such evolving atmospheric and land surface features have often been 'un-observable' which has limited the fidelity of atmospheric and land surface analyses and, ultimately, hindered prediction skill from extrapolative nowcasting and numerical weather prediction (NWP) systems. However, advanced atmospheric sensing technologies, initially through the use of satellite and Doppler weather radars and more recently with dual-wavelength and dual-polarization radars, are now providing high spatial and temporal resolution depiction of key atmospheric conditions including winds and hydrometeor fields. In combination with data assimilation systems and other existing and emergent sensing technologies such as GPS occultation, cosmic-ray sourced soil moisture detection, lightning detection and lidar, we now have the potential to create regional analyses of the lower troposphere and land surface hydrology with much greater precision, accuracy, spatial resolution and frequency than was heretofore possible.

The underlying hypothesis of this proposal is that data from state-of-the-art polarimetric weather radar and additional new sensing platforms, in combination with land surface and atmospheric data assimilation systems and physics-based prediction models, can provide significant improvements in warm season hydrometeorological prediction skill as measured by deterministic and probabilistic forecasts of precipitation, soil moisture and streamflow.

Warm season precipitation has long been studied in the Colorado Front Range (CFR) region (e.g., Wilson and Schreiber 1986; Banta and Schaff 1987) and the vulnerability of the region to episodic inundating rainfall, flash flooding and debris flows is well documented (e.g., Peterson et al. 1999). Despite the recognition of weather related threats to the region, the predictability of such events remains relatively unknown and actual prediction skill outside of a few tens of minutes is low. Most NWP models fail to routinely accurately forecast specific severe convective events. Similarly, the skill of hydrological predictions is significantly hindered by the complexity of the regional terrain and the accompanying lack of accurate precipitation estimates.

The FRONT-PORCH experiment proposed here is designed to help answer the basic research questions: *"What is the predictability of the location and amount of convective and orographic precipitation over mountainous terrain?"* and *"How does improved predictability in precipitation relate to the predictability of damaging flood events produced by such phenomena?"* Successful execution of the principle research tasks listed on the first page above will also provide a demonstration of the value of emergent observational, data assimilation and numerical prediction technologies thus highlighting advances in core NSF-sponsored, community research facilities. In doing so, the FRONT-PORCH experiment will attempt to obtain information on the most extensive-to-date range of processes contributing to convective precipitation events over the CFR. The research will focus on heavy, transiently-forced convective precipitation events occurring in the CFR between May-July and the more monsoon-type, slow-moving, heavy precipitation events (HPEs) in the CFR observed in July-August.

The paragraphs below detail the scientific rationale behind the formulation of the four principle research tasks, listed in the project summary above, by describing specific scientific questions, hypotheses and objectives to be engaged through the experiment. Additional specifics on the measurement objectives of the different research platforms to be used in this research are also discussed. The Task Description is outlined in Section 2 while Sections 3-7 contain specific details related to the measurement campaigns, data management and educational plans. Throughout, the case is made for why these categorical areas need to be studied in tandem in order to holistically test the principal hypothesis of improving forecast skill through use of advanced measurement technologies.

2. Description of Tasks

Task 1: Physical Process Studies

Task 1.1 Diurnal thermally-driven circulations (Gochis, Zeng)

The study of terrain influences on diurnal convective circulations (as distinct from stable flow over orography) has received considerable treatment over the last several decades (e.g., Orville 1964; Abbs and Pielke 1986; Pielke 1985; Egger 1987; Whiteman 2000; Ciesielski and Johnson 2008; Zangl et al. 2009; Zardi and Whiteman 2012). This body of work has established the importance of thermally-induced upslope circulations in deepening the planetary boundary layer (PBL), triggering moist convection and initiating precipitation when sufficient moisture is present and in the presence of 'favorable' large-scale forcing. The complex interactions between diurnal, thermally-forced circulations and the large-scale (or 'synoptic-scale') environment have also been examined (e.g., Segal et al. 1989; Ye et al. 1987; Dalu et al. 1996). Similarly, the impact of mesoscale (10-100 km) heterogeneity in land surface conditions (e.g., soil moisture, vegetation) on PBL growth and convective circulations has also received attention (Anthes 1984; Segal et al. 1988; Avissar and Pielke 1989; Zeng and Pielke 1995; Chen et al. 2001; Findell and Eltahir 2003; Ek and Holstag 2004; Roy et al. 2003, Konings et al. 2010). In the presence of weak to modest synoptic forcing, both terrain- and land surface hydrology-forced circulations can have a significant influence on vertical motions (Dalu et al. 1996). Less studied, however, are the combined or 'superpositional' impacts of land surface conditions in complex terrain regions on resulting mesoscale circulations and precipitation. Only a handful of analytical (e.g., Ye et al. 1987) and numerical studies (Molders and Ruhaak 2002; Maxwell et al. 2007; Chow et al. 2006; Weigel et al. 2007; Pineda and Carbajal 2009) have investigated these processes. Since partitioning of the surface energy budget is controlled largely by surface hydrological conditions (e.g., soil moisture, snow cover and vegetation), variations both along slopes and between slopes of different aspects can, at times, have a significant influence on the development of thermally-forced circulations in complex terrain. Figure 1 illustrates a hypothetical framework for studying orographic convection where a 'background' diurnal thermally-driven upslope flow (top panel) is potentially enhanced (middle panel) or suppressed (lower panel) by a superposition of land surface flux conditions (shown in color where red tones indicate greater sensible heat transfer) that modify air temperatures in the overlying air masses.

While several of the aforementioned studies have addressed these processes through either large eddy simulation or numerical weather prediction models, few have diagnosed the necessary magnitudes and patterns of land surface states and fluxes necessary for modulating terrain-forced thermal circulations. <u>Specifically, critical questions remain unanswered as to how variations in late-spring/early-summer snow cover, vegetation and soil moisture in complex terrain either enhance or suppress thermally-induced terrain circulations in the absence of strong synoptic forcing.</u> These questions include: *How do horizontal variations in the surface Bowen Ratio impact background mountain-plain and ridge-valley circulations? How are the diurnal thermal circulations linked to the timing, magnitude and longevity of convective cloud development? How does the synoptic regime influence the strength* *and evolution of the diurnal thermal circulations?*

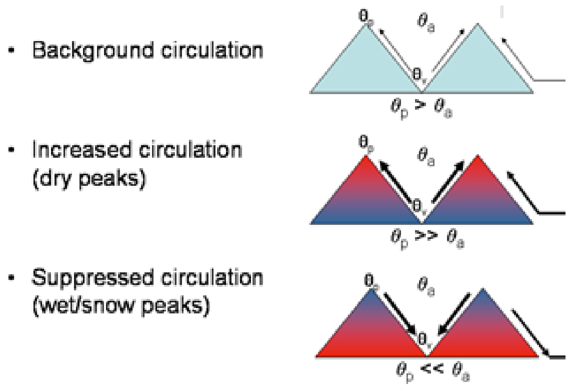

Figure 1. Hypothetical depiction of thermally-driven circulations modulated by land surface flux behavior. (See text above for description)

One of the principal reasons for these outstanding questions has been the lack of an integrated, high-resolution in space and time, depiction of land surface and atmospheric conditions in a complex terrain region. *The FRONT-PORCH project directly addresses these issues through a methodological combination of observational, diagnostic and modeling studies.* We propose to diagnose the role of land surface flux partitioning on the diurnal thermal circulation structure and convection initiation through the use of a network of special land surface and atmospheric observations deployed in conjunction with the FRONT radar assets. Operational and special supplemental soundings, surface meteorological stations, microwave radiometers combined with GPS receivers, and radar-derived wind and humidity products will provide a diurnally-evolving characterization of the CFR wind, temperature and humidity fields. Two zonally-oriented transects of eddy covariance, soil moisture surface flux stations will be deployed across the predominate terrain gradient from the high elevation regions east of the continental divide to the eastern end of the FRONT study domain (see Figure 6 below). These surface flux stations will provide continuous measurements of precipitation, surface energy and water fluxes, soil moisture, evaporative fraction, surface Bowen ratio and enable precipitation and soil water collection for isotopic analysis. From this suite of measurements we will diagnose the role surface energy flux partitioning has on modulating the timing and intensity of the diurnal mountain-plain circulation, boundary layer growth and convection initiation across the CFR terrain gradient. Through continuous operation of the FRONT-PORCH observing network from mid-May to mid-August we will also examine the intra-seasonal variability of the terrain circulation regime as it responds to both surface forcing and synoptic scale variability.

It is also recognized that heterogeneity in land surface conditions due to ecosystem distribution and land use may significantly impact the surface flux partitioning behavior (e.g., Chase et al. 1999). In Task 3 below, we describe a model-based framework for defining the role two prominent land use categories, urbanization and irrigation, have on land surface flux behavior. From a measurement perspective, our surface flux transects will deliberately sample members of urban and irrigated agriculture land use classes in addition to more 'natural' vegetation. The use of stable isotope tracers will help in determining the relative contribution of this to the regional atmospheric water balance.

Task 1.2 Microphysics (Friedrich, Rutledge, Noone)

In addition to understanding the convectively driven circulation regime, a major knowledge gap relates to understanding microphysical transformations occurring within convective and orographic cloud structures. The microphysical transformations are a critical step in producing precipitation at particular locations. Small-scale updrafts produce pockets of high liquid water content where precipitation particles grow efficiently by coalescence, aggregation, and riming (Fig. 2). These microphysical processes produce large and/or rimed particles that fall out rapidly over the terrain slopes. Understanding these processes is critical to being able to forecast intense rain in complex terrain.

Microphysical processes in warm season convection affect storm behavior and evolution by serving as a crucial link between the storm dynamics and thermodynamics. For example, melting of hail and graupel influences the strength and size of the low-level cold pool, which changes the near-surface buoyancy tendency and, as suggested by several recent studies, the tornadogenesis potential (Markowski et al. 2002; Shabbott and Markowski 2006; Grzych et al. 2007). Many studies have emphasized the importance of understanding and monitoring the dominant microphysical processes (growth by accretion of liquid water, collision/coalescence, breakup of raindrops, evaporation) in convective clouds to improve results from cloud-modeling studies. Furthermore the importance of warm-rain processes on non-bright-band orographic systems (Neiman et al. 2005) in the region remains unknown. Key questions to address with FRONT-PORCH are: *What are the cloud-scale dynamics and microphysics mechanisms leading to HPEs? What is the role of non-bright band orographic convection on precipitation amount and distribution?*

Wind and hydrometeor fields derived from scanning and the vertical profiling radars in combination with surface in-situ measurements of particle-size distributions and thermodynamic properties will allow for determining the role of the cloud-scale dynamics and microphysics. Radar-derived rainfall maps and surface rain gauges will permit improved analysis of surface precipitation fields which, in turn, will be used to validate numerical models. The collection of precipitation for isotopic analysis will be used to provide constraints on evaporation rates of falling hydrometeors derived from radar estimates. High-resolution observations of wind and microphysical structures will help to study the role of low-level convergence and turbulence related to convective-scale features on vertical velocity distribution, precipitation efficiency, precipitation amount, and precipitation distribution. We see an opportunity to document in unprecedented detail the hydrometeor species, 3D-winds, raindrop spectra, and subsequent surface rainfall patterns over complex terrain that result in intense rainfall. We anticipate these unique observations will improve our basic understanding of the mesoscale thermodynamics, dominant microphysical processes, and surface-rainfall patterns relative to underlying basin characteristics (e.g., soil-moisture conditions, drainage topology, land use) that cause precipitation and potential intense rain with possible flash flooding.

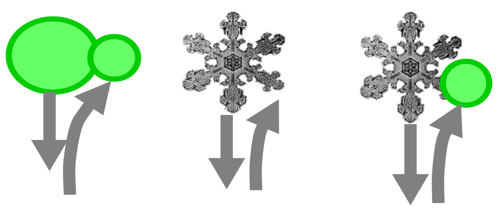

Figure 2: Growth by droplet coalescence, ice aggregation or riming.

Task 1.3 Convection initiation and evolution (Weckwerth, Wilson)

One of the reasons for the long-standing deficiency in warm season, convective precipitation prediction skill is the inaccurate and incomplete depiction of water vapor in the lower troposphere (e.g., National Research Council 1998). The pre-convective moisture field varies significantly (~ 1 g/kg) under clear-air conditions (e.g., Weckwerth et al. 1996) and this has a dramatic impact on the convective potential for the day (Crook 1996; Weckwerth 2000). Convection initiation along enhanced terrain and the Denver Convergence Zone will be addressed (e.g., Wilson et al. 1992). Once convective precipitation forms, previous studies suggest that the precipitation over inland mountains is enhanced by small-scale cellularity, independent of whether the upstream flow is statically unstable or stable (Medina and Houze 2003; Houze and Medina 2005). The propagation and eventual growth or dissipation of the systems as they propagate eastward will be studied. Key questions remain as to the underlying processes that account for the interactions between convective circulations in complex terrain that lead to the formation of HPEs which include: *What are the mesoscale environments most conducive to thunderstorms and orographic precipitation? What enhancements in the ability to monitor and predict HPEs can be achieved by state-of-the-art instrument networks and numerical prediction models? What is the role of the complex orography on HPEs in the region? What are the major causes for the growth or decay of orographic precipitation as it moves into the plains?*

To explore these influences the time-varying (15 min) moisture field will be sampled on the km-scale to assess the relevance of high-resolution moisture measurements on convection initiation and evolution, as well as on the rebound of the boundary layer after convection has dissipated. The combination of water vapor observations from multiple sources, along with the 3D wind fields, will be necessary to achieve this objective. Daily mid-day soundings will be used to distinguish between the likelihood of convection initiation on various days. Stability profiles will be compared with the microwave radiometer profiles to evaluate the importance of the diurnal variation in stability upon convective development. The 3-hourly radiosondes during IOPs will also be useful to study the temporal variability leading to convective development. A mosaic of radar refractivity retrievals (Fabry et al. 1997) from the S-Pol, CHILL and KFTG radars will be used as a proxy for low-level moisture variability which will also be monitored by surface stations. The tomographic retrieval from multiple GPS receivers will be used to characterize the 3D moisture field to determine where there may be hot spots for increased likelihood of convective development. Further retrievals will be performed when clouds are present to obtain vertical profiles of water vapor and liquid water content in the clouds using the dual-wavelength retrieval algorithms (Ellis and Vivekanandan 2010, 2011). It is desired to also use multiple water vapor DIALs profiling the lowest ~4 km to study the diurnal variations of moisture throughout the project period. This DIAL system is currently being upgraded and field-hardened at NCAR/EOL and Montana State University (c.f. Nehrir et al. 2011). These water vapor sensor data and retrievals will be combined with the wind fields derived from dual-Doppler analyses and VDRAS (Variational Doppler Radar Assimilation System) retrievals to obtain time-varying high-resolution 3D moisture field.

Task 2: Radar Retrieval Research

Task 2 of FRONT-PORCH is to utilize a unique deployment of special observation platforms including supplemental soundings, surface hydrometeorology stations, wind profilers and ground-based GPS sensors to quantitatively validate the accuracy of radar-derived wind, humidity, precipitation and hydrometeor type fields and to develop new methodologies for addressing deficiencies in those retrievals. The collection of data by a well-calibrated radar, while crucial, is only the initial step in providing the scientific community with meaningful meteorological data. Data artifacts must either be eliminated or identified and censored via signal processing to achieve high data quality. Effective and reliable use of radar data for quantitative precipitation estimation (QPE), nowcasting, data assimilation, hydrometeor classification and severe weather identification, depends directly on the quality of radar data being used. In this section we highlight three specific radar retrieval research topics which will be addressed either during FRONT-PORCH or through posterior analysis of FRONT-PORCH data. The three topics include; a) polarimetric radar validation and calibration for QPE, b) interpreting polarimetric radar signals and artifacts, and c) multi-Doppler wind retrieval.

Task 2.1 Validation and calibration of polarimetric retrieval algorithms (Gochis, Friedrich, Rutledge)

Significant progress has been made over the past two decades in advancing the utility of polarimetric radar information for QPE. It is now well-established that instead of relying on a single quasi-empirical relation to associate backscattered power from a single polarization radar emission (Z_H) to rain rates, multiple parameters such as the ratio of horizontally to vertically polarized reflectivity echoes (differential reflectivity, Z_{DR}), and the specific differential phase between the two polarized echoes (K_{DP}) can provide much needed constraints on hydrometeor characterization which lead to improved rain rate estimates (e.g., Petersen et al. 1999; Bringi and Chandrasekar 2001; Ryzhkov et al. 2005a,b; Cifelli et al., 2011; Matrosov et al., 2012). The superior performance of dual-polarization radars in estimating precipitation across a wide range of precipitation regimes and even in complex terrain, has led to the national implementation of polarimetric radar technology into the U.S. National Weather Service (NWS) NEXRAD radar systems, which is presently underway. However, QPE provided by polarimetric radars can still suffer from significant sources of error. Lingering issues related to uncertainty in hydrometeor size distributions, problems in characterizing mixed-phase hydrometeor regimes (i.e., liquid and ice), beam-blockage in complex terrain regions, and, generally, equifinality (i.e., non-unique solutions) in precipitation-rate retrieval algorithms must still be addressed in order to maximize the utility of polarimetric radar information for QPE applications such as hydrological prediction.

The FRONT-PORCH project will directly address these issues through a comprehensive ground validation/calibration effort which will emphasize improving the polarimetric QPE retrieval process across a large gradient in terrain and precipitation form. Several existing QPE algorithms currently exist for each of the CSU-CHILL, NCAR S-Pol and NWS WSR-88D radars which form the backbone of FRONT-PORCH. Estimates from these retrieval algorithms will be evaluated in terms of their spatial, temporal and intensity characteristics against a vast surface observing network. The surface network (see Fig. 6) includes regional ALERT rain gauges, long-term, operational precipitation observing stations, research grade, precipitation networks, precipitation collection for isotopic analysis, optical disdrometers, vertically-pointing K-band frequency modulated continuous wave (FMCW) radars and mobile, scanning polarimetric X-band radars. Many, though not all, of these ground-based networks already exist within the FRONT-PORCH domain and their data are already processed and quality controlled by FRONT-PORCH investigators. In combination with ancillary atmospheric sensing information from sounding- and radar-derived estimates of sub-cloud water vapor, we will evaluate various retrieval methodologies while also providing additional constraint to their various estimators through confrontation with novel data streams, such as sub-cloud thermodynamic profiles. In this manner we seek to assess the efficacy of the various precipitation estimation approaches throughout the QPE chain, not just at the end precipitation estimate. While this multi-criteria approach emphasizes the use of hydrometeor drop size distributions, it also entails characterizing the evolution of hydrometeors from the cloud to the ground in terms of their physical state and their interactions with the surrounding thermodynamic environment.

In performing the 'retrieval-based' research described above, we will be generating ensembles of polarimetric QPEs for use in hydrological prediction and land data assimilation activities (described in Task 3 below). These multiple realizations of QPEs can then be weighted according to their estimation skill in an ensemble prediction framework. This application of ensemble QPE products to hydrological prediction offers a truly unique hydrometeorological research opportunity, particularly in a complex terrain region such as the CFR.

Task 2.2 Interpreting polarimetric radar signals and artifacts (Hubbert)

Data quality of the dual polarimetric variables directly impacts microphysical retrievals. Simultaneous transmission and reception of H (horizontal) and V (vertical) polarized waves (called SHV mode) has become a very popular way to achieve dual polarization for weather radar (Doviak et al. 2000). The NWS NEXRADs are currently being upgrade to dual polarization using the SHV technique. However, it has been shown that oriented ice crystals with a non-zero mean canting angle (relative to the earth) causes cross-coupling between the H and V transmitted electric fields that will bias polarimetric variables, especially Z_{DR}. Theoretical models show that oriented ice crystals will cause errors in Z_{DR} that are persistent in range resulting in radial Z_{DR} stripes (Ryzhkov and Zrnic 2007; Hubbert et al. 2010). Although unconfirmed, it is hypothesized that ice particles, which are aligned due to the presence of an electric field (Caylor and Chandrasekar 1996; Krehbiel et al. 1996; Metcalf 1995), cause this bias. Figure 3 shows an example of this taken from Ryzhkov and Zrnic (2007). Note the radial streaks in Z_{DR} (both positive and negative). The area marked by the black outlined box in Fig. 3 shows that while Z_{DR} has both positive and negative streaks, ϕ_{dp} is decreasing in range indicating the mean canting angle of the ice crystals is greater than 45 degrees. There will be three S-band polarimetric radars which can be used to compare and contrast polarimetric signatures: CHILL: fast alternating H and V transmit (FHV) (considered bias free); S-Pol: FHV and SHV modes; KFTG: SHV mode. Hence, there will be an unprecedented opportunity to further investigate and verify such biases caused by cross-coupling with

SHV transmit radars. Furthermore, these data will also be compared to the LMA (Lightning Mapping Array) data to assess indirectly the electric fields which may be present.

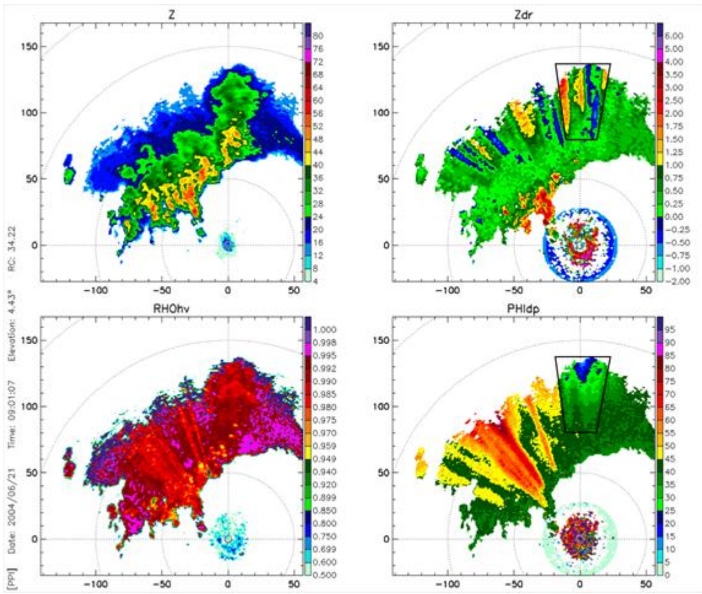

Figure 3: KOUN SHV data taken at 4.4 deg. elevation angle. Top left: reflectivity; Top Right: Zdr; Bottom Left: ρ_{hv}; bottom right: ϕ_{dp}. Note the blue and yellow-red radial streaks in Zdr. This is caused by oriented ice crystals. Taken from Ryzhkov and Zrnic 2007.

The radar data quality problem. The problem of range overlaid echoes is well known (Sachidananda and Zrnic 1999; Frush et al. 2002; Bharadwaj and Chandrasekar 2007). Fundamentally, all pulsed radar systems are limited by the range-velocity ambiguity dilemma which is determined by the radar's PRF (Pulse Repetition Frequency) and wavelength. S-Pol usually operates at a PRF (Pulse Repetition Frequency) of 1000Hz which yields a maximum unambiguous range of 150 km. Thus, there are frequently range overlaid echoes (second and third trip echoes) which degrade data quality. One technique to extend the unambiguous range is phase coding of the transmit pulses, which offers potential to extend the unambiguous range from 150 km to 450 km without affecting the unambiguous velocity. This, in turn, would increase radar coverage area by a factor of nine. 'SZ'-phase coding (Sachidananda and Zrnic 1999) is currently used on the NWS NEXRAD single polarization radars with very good success. However, to our knowledge, SZ phase coding has never been demonstrated on FHV transmit radars such as S-PolKa and CSU-CHILL. For FRONT-PORCH we propose to demonstrate, test and verify the use of SZ phase coding using S-Pol so that SZ phase coding is operational for FRONT-PORCH. Theory shows that the SZ algorithm should provide about 40 to 50dB of separation of the overlaid echoes. If successful, this innovation in signal-processing will significantly improve the data quality of S-Pol and CSU-CHILL.

Task 2.3 Doppler wind retrieval (Shapiro)

A common approach to mitigate errors associated from the non-simultaneity of radar conical scan data collection is to make use of so-called advection-correction techniques based on the Taylor frozen-turbulence assumption. The result is constant advection correction terms, U and V. Advection correction is an important step in multiple-Doppler wind and vertical velocity analysis procedures, and in QPE generation where radar- and/or satellite-based accumulated rainfall maps are generated. Recently, Shapiro et al. (2010a,b) have derived and tested a technique to obtain spatially variable U and V fields based on the motion of the reflectivity field. The next step will be to derive (and test) a new procedure specifically designed to advection-correct *radial* velocity data. During FRONT-PORCH the new radial-velocity-based advection-correction technique will be tested alongside the Shapiro et al. (2010a,b) reflectivity-based advection-correction technique as well as traditional (constant U, V) procedures. The primary data for the tests will be radar data obtained in rapid-scan mode (preferably obtained over low-altitude sector volumes with a 1 min volume scan rate). In this manner the data can be progressively "thinned" in time and the associated errors in the advection correction procedures can be explored as functions of the scan time. Also, most importantly, data at the "thinned" volume scan times (i.e., not used in the advection correction procedure) can be used to validate the advection correction results, thus providing a particularly stringent test of the procedures. Such tests could be performed with just a handful of rapid-scan datasets, each dataset spanning perhaps 10 or 15 minutes in both clear air and heavy precipitation conditions.

A second part of the Doppler wind retrieval research is to incorporate analyzed radial wind data (i.e., processed by the new advection-correction procedures described above) into a new dual-Doppler wind analysis technique, with a goal of improving the analysis of the *vertical velocity* field. The technique supplements traditional dual-Doppler wind analysis constraints with the anelastic vertical vorticity equation. The idea for this technique was explored in a highly idealized form in Mewes and Shapiro (2002) and, thereafter, explored somewhat more realistically in Shapiro et al. (2009) and realistically in Potvin et al. (2012). The focus of the new work will be on exploring the improvement in the vertical velocity analysis in the common scenario of missing low-level data (e.g., due to terrain or the fact that the lowest beam is typically 0.5 to 1 degree above the ground). Dual-Doppler data will be gathered at relatively low elevations (e.g., < 10-15 deg) in rapid scan mode (as in the advection-correction experiments) and the lowest level data would be withheld from the analysis. Validation of the radar-based retrieval of vertical velocity will be done in clear air and light rain conditions using data from the NCAR ISS-449 MHz wind profiler. This particular research effort will be of interest in several additional areas of FRONT research. First, the reflectivity-based advection-correction technique may be useful to those working with successive volume scans of dual-polarization data (i.e., scalar fields). The reflectivity-based advection correction technique can also be used in the generation of radar- and/or satellite-based accumulated rainfall maps, which is important in QPE generation. Dual-Doppler wind and (especially) vertical velocity analyses may be useful in data assimilation and in refinement of fall speed-dependent hydrometeor identification procedures.

Task 3: Real-time Demonstrations

A particularly unique and exciting part of this proposal will be a real-time demonstration of short-term QPE, QPF and streamflow prediction techniques. Basic understanding of mesoscale and cloud-scale processes from Task 1 will be tested as forecast rules in nowcasting tools such as the NCAR AutoNowcaster. Radar calibration, radar quality control, polarimetric precipitation estimates, radar moisture retrieval and radar wind retrieval activities from Task 2 will be directly used by the observation-based and numerical model-based nowcasting and NWP systems. To this end, the NCAR Short Term Explicit Prediction (STEP) Program has identified FRONT-PORCH as a focus point for demonstrating state-of-the-art nowcasting techniques for precipitation and streamflow. Previously, the STEP program has demonstrated state-of-the-art nowcasting techniques in the Beijing 2000 Olympic Games and the Whistler 2002 Olympic Games. As described next, the proposed FRONT-PORCH experiment offers a suite of new opportunities in such short-term prediction research.

Task 3.1 Data assimilation and forecasting (Sun, Wilson)

Task 3 of FRONT-PORCH is to assess the impacts that radar-based, high time and space resolution observations of convective environments, mesoscale circulations and precipitation have on atmospheric and land data assimilation systems and resultant forecasts. The land data assimilation component of this task is described further below. Development of advanced atmospheric data assimilation techniques that enable the assimilation of high-density data obtained by various instruments has accelerated in the last decade. These techniques have been demonstrated to produce accurate high-resolution atmospheric analysis (e.g., Sun et al. 2010) and improvements in the short-term (i.e., less than 3 hours) prediction of convective weather when high-resolution remote-sensing and high-density in-situ data are assimilated (e.g., Hu et al. 2006; Sun and Zhang 2008; Kain et al. 2010). Presently, there are a number of different high-resolution data assimilation systems that have the capability of assimilating wind estimates from Doppler radar within the Weather Research and Forecasting (WRF) modeling system, including VDRAS (Variational Doppler Radar Analysis System), WRF-based 3DVAR (3-Dimensional VARiational analysis), WRF-RTFDDA (Real Time Four Dimensional Data Assimilation), and WRF-DART (Data Assimilation Research Testbed). The primary data sources are high-resolution Doppler velocity, radar reflectivity, and high frequency surface observations as well as radiosondes, profilers, and microwave radiometers. VDRAS (Sun and Crook 1997) is designed for single- or multiple-Doppler radar analysis using a 4D variational (4DVAR) data assimilation technique based on a cloud-scale model. VDRAS produces dynamically-balanced, 1-3 km resolution wind, temperature perturbation, and humidity fields with a high temporal frequency (12-18 min). The WRF 3DVAR system's radar data assimilation capability (radial velocity and reflectivity) was first developed in 2005 (Xiao et al. 2005) and has since been enhanced. The WRF RTFDDA system is a Newtonian-relaxation-based observation nudging scheme (Liu et al., 2008). The assimilation of radar reflectivity was recently added to RTFDDA using a scheme that adjusts the model latent heating based on that estimated from reflectivity observations. The WRF-DART is an ensemble Kalman filter (EnKF) system (Anderson et al. 2009). Although WRF-DART has a radar data assimilation capability (Aksoy et al 2009), we plan to run it on the CONUS domain for this proposed project without the assimilation of radar observations in real-time, with retrospective studies planned using radar assimilation on a sub-domain over the FRONT-PORCH region. Each of these systems have shown promise in improving analysis and very short term prediction of convective storms through recent retrospective studies over the central Great Plains region and the Colorado Front Range region (Sun et al. 2012).

We will conduct an assessment of the strengths and weaknesses of the four aforementioned data assimilation systems during the FRONT-PORCH field period by conducting real-time integrations with overlapping domains. The proposed VDRAS domain for FRONT-PORCH will cover the five radars (SPolKa, CHILL, PAWNEE, KFTG, and KCYS – See Fig. 6) in the Front Range with a 2 km resolution. The two WRF-based radar data assimilation systems, WRFDA 3DVAR and RTFDDA, will be run with an O-1000 km^2 domain centered at S-PolKa with a 3 km resolution, assimilating the five Front Range radars as well as all the surrounding operational WSR-88D radars in the model domain. The two prediction systems, WRF-3DVAR and WRF-RTFDDA will be run simultaneously, providing 0-12 hour forecasts every 3 hours. Additionally, the WRF-DART system will be run on a CONUS domain with a coarser resolution of 10 km and will provide a first guess analysis of atmospheric conditions for VDRAS and WRF 3DVAR. Control simulations without any radar assimilation will also be executed to demonstrate the impact of analysis refinement using the techniques noted above. We expect to run these in real time.

Task 3.2 Land surface hydrology modeling (Gochis, Zeng)

As discussed in Task 1 above, the role of land surface energy and moisture fluxes on the diurnal growth and decay of the planetary boundary layer, convective cloudiness and precipitation is expected to be significant in the FRONT domain. Therefore one of the key modeling and prediction tasks of FRONT-PORCH is to properly simulate the states and fluxes of water and energy in the terrestrial system and this will be performed via real-time execution of the state of the art High Resolution Land Data Assimilation System (HRLDAS-Chen et al. 2007) coupled to the NCAR Distributed Hydrological Modeling System (NDHMS-Gochis et al. 2003, 2012). Combining the HRLDAS/NDHMS develops a real-time depiction of land surface thermal and hydrologic states. These 'spun-up' model states can then serve as initial conditions for NWP forecasts or 'hydro-nowcasts' when driven by radar nowcasts of precipitation that were described previously and further below. The combined HRLDAS/NDHMS has already been implemented for the FRONT domain and has exhibited appreciable skill in simulating streamflow responses to polarimetric radar-generated QPE fields including extreme flood events such as the 1997 Fort Collins and 2011 Fourmile Canyon floods. During FRONT-PORCH we will simultaneously use the HRLDAS/NDHMS system as a diagnostic tool for understanding land-atmosphere exchange processes as well as a model analysis and prediction system for regional hydrological and weather prediction. Real-time land surface analyses and hydrologic predictions will be made publically available throughout the FRONT-PORCH project as a demonstration of the integrated technology and these real-time forecasts will serve as benchmarks for subsequent improvements to emerge from FRONT-PORCH research efforts. Lastly, we plan to implement an isotope tracer module into the WRF model coupled to an existing version of the NCAR Community Land model with isotopic tracers which will provide a moisture-source tracer that can be used in comparison with isotope measurements to further assess the relative strengths of the different assimilation techniques.

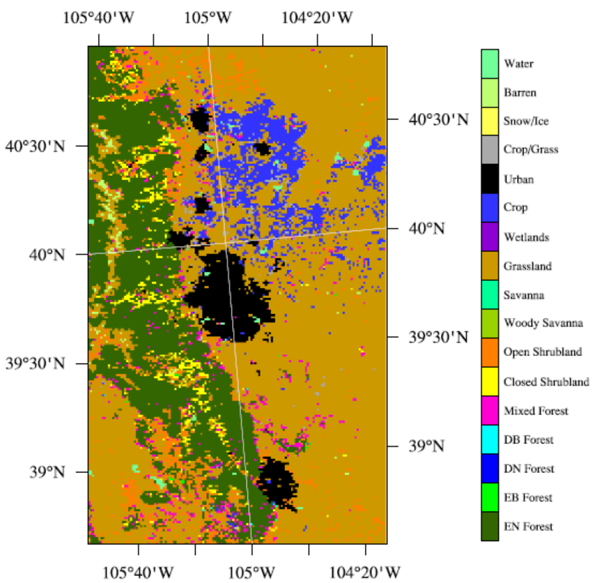

Figure 4: MODIS-derived map of FRONT domain land-use and land cover features.

As mentioned in Task 1, in FRONT-PORCH we propose to address the research issue of land-atmosphere coupling from observational and model diagnostic and prediction perspectives. This will be done by performing detailed model diagnostic experiments using the surface flux, lower troposphere and boundary layer observations collected during the experiment. To address issues of land use/land cover (LULC) variability successive coupled-model forecasts and hindcasts will be executed with varying degrees of LULC heterogeneity represented, the results of which will reveal what level of LULC specification and process representation is necessary to produce realistic thermodynamic and dynamic behavior surrounding the formation of diurnal convective events in the FRONT domain. The FRONT domain is particularly ideal for this sort of investigation as it possesses a large area that is directly impacted by intense irrigation throughout the summer or has succumbed to various degrees of urbanization (see Fig. 4). The complete FRONT-PORCH dataset will therefore provide an unprecedented opportunity to verify and evaluate the performance of coupled land-atmosphere prediction systems that have recently been enhanced to represent both irrigation and urbanization processes.

Task 3.3 Hydro-Nowcasting (Gochis)

For high impact weather produced by convective storms it is only on the nowcasting time and space scale (e.g., 0-60 min and a few km, respectively) that there is presently sufficient forecast skill, that people will take actions to save life, property, and human inconvenience. The prospect for such a capability by NWP models is still several years in the future and thus there remains significant importance on improving nowcasting techniques (Wilson et al. 2010). One goal of Task 3 will be to link the improved scientific understanding of convective storm growth and decay in the CFR to the establishment of nowcasting rules for storm growth and decay and of rainfall amount. Central to successful convective storm nowcasting is high resolution (few km) frequently updated (5-15 min) 3-dimensional observations of precipitation, wind, temperature and moisture. The VDRAS provides an excellent tool in that it assimilates available observations (radar, surface stations, sounding, GPS moisture, refractivity moisture, and others) into a numerical model which then provides a field of winds and temperature perturbations that are physically balanced. These kinds of analysis fields have proven to be of particularly high quality in the Front Range (Wilson et al. 1994).

The proposed expert system for generating the nowcasts of convective storm intensity is the NCAR AutoNowcaster (Mueller et al. 2003). The AutoNowcaster (ANC) is unique in its ability to nowcast storm initiation. Important forecast variables for the ANC include the location of boundary layer convergence lines, magnitude of the convergence, satellite observation of cumulus cloud evolution, radar detection of non-precipitating cumulus clouds, relative motion of convergence lines and cumulus clouds and stability fields (see Fig. 5). FRONT-PORCH will be an opportunity to develop new ANC predictors utilizing aforementioned VDRAS-assimilated wind and temperature fields. During FRONT-PORCH, the ANC will be set-up for quasi-real-time operations. Nowcasts of convective storm location and intensity and precipitation rate will be input directly into the real-time HRLDAS/NDHMS hydrologic prediction system described above for real-time streamflow prediction. We will make these products available to the local National Weather Service and the regional flood control districts for their use in issuing thunderstorm advisories and warnings and for flash flood guidance. [To this effect we have already established a working relationship with the local NWS Weather Service Forecast Office in Boulder and we have a long history of working successfully in a similar fashion with Weather Services worldwide.]

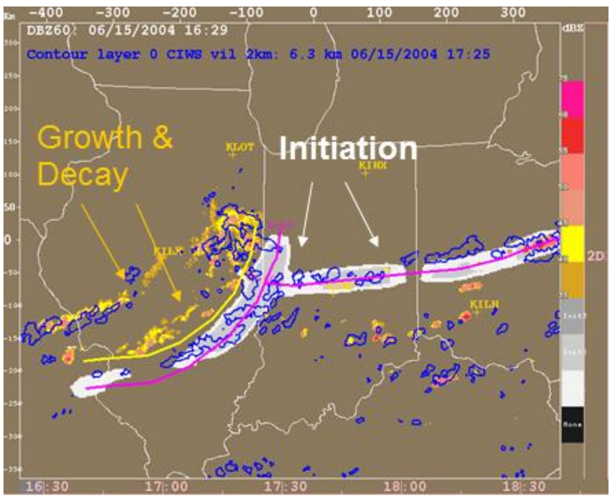

Fig 5: Example AutoNowcaster output for a 60 min nowcast. The white/gray regions are initiation nowcasts. The yellow/red cells are nowcast location and intensity for existing storms. The blue polygons show the location of 35-dBZ storms at verification time (60 min from now). The pink lines are nowcast locations of convergence lines.

Task 4: Collection of Radar Data Sets for Classroom Use (Yuter, Kennedy)

While radar data collection from NSF facilities for classroom use does occur intermittently, the experienced facility scientists and engineers who run the radars do not have the teaching expertise of faculty and vice versa. This task dedicates time and resources for focused collection of examples for classroom use and for the organization and publication of those examples on the web for use by the wider community. These types of real-world examples are crucial for the transition from traditional lecture-only based teaching to reformed learning practices that are revolutionizing Science Technology Engineering and Math (STEM) education. The goal of this task is to use high quality radar data sets to illustrate key aspects of what we currently know about storms. In classrooms and textbooks, we teach mesoscale concepts such as squall-line organization and Rotunno et al. (RKW; 1988) theory by using schematics and/or output from idealized models. While these simplified illustrations are important and useful, they fail to communicate the noisy and complex reality of these structures and their evolution in real storms. Additionally, models and illustrations are unable to do justice to the space and time scales that many of these storms occupy. The output of the proposed task will be modules on a website (hosted at NCAR, CSU or perhaps COMET) with sets of images and movies illustrating real-world examples of key mesoscale storm features. These examples would be used in the classroom as a focus for discussion of mesoscale kinematic and dynamical structures in conjunction with traditional schematics and idealized model output. The target audiences are senior-level undergraduates and graduate students. These materials would complement texts such as Markowski and Richardson's *Mesoscale Meteorology in Midlatitudes*, Houze's *Cloud Dynamics,* and Lamb and Verlinde's *Physics and Chemistry of Clouds*.

Listed in Appendix A is a set of weather scenarios that are desired for educational focus. Detailed data, such that the FRONT can provide for such events, will promote a rich learning experience for scientists, educators as well as students. There is substantial overlap between the data requirements for the education classroom modules and the science requirements so that both of these objectives can be met by FRONT-PORCH. As the season progresses, if integrated data collection is not satisfying the objectives of one of the four listed FRONT-PORCH Tasks (see the first page of this document), data collection strategies for that task will elevate in priority.

3. General Measurement Objectives

The FRONT-PORCH research plan centers on the deployment and continuous operation of a state-of-the-art observational network (See Fig. 6). In this section we summarize the instruments to be deployed and briefly describe their intended uses. Operational details of the can be found in the next section.

1. Radar Facilities: The CSU-CHILL, NCAR S-PolKa and X-band Doppler on Wheels (DOW) radars are being requested to facilitate research proposed under Tasks 1 and 2 of this research proposal which include a) convection initiation and evolution process studies, b) polarimetric radar validation and calibration for QPE, c) polarimetric signal interpretation, and d) multi-Doppler wind retrieval. Combined these radar facilities will provide a continuous three-dimensional depiction of cloud and hydrometeor structures as well as wind and, possibly, low-elevation moisture fields. Presently, the radars will be operated in a continuous PPI-volume and sector scan modes but for short experimental periods will be operated according to specific research objectives. The DOW radars will provide independent estimates of cloud, precipitation and wind fields to conduct additional process research, particularly in the mountain valleys where CHILL and S-PolKa observations are not possible and to further validate the stationary CHILL and S-Pol radars.
2. Supplemental soundings conducted under FRONT-PORCH will augment operational soundings in two ways. The first is to provide a mid-day sounding (near 11am LT) in order to better characterize the diurnal evolution of the Front Range thermodynamic environment and to assess the day-to-day variability in convective potential. Additional, mobile supplemental soundings will be launched every 3 hours during selected Intensive Observing Periods (IOPs) to provide a more rapid characterization of the diurnally evolving environment.
3. The 449-MHz wind profiler will be deployed to help assess the radar retrieved and data assimilation estimated wind fields throughout the project.
4. The surface flux stations will be deployed along two zonally oriented transects to characterize the topographic dependence of surface energy flux partitioning and their relationship to the diurnal thermal circulation regime. A comprehensive set of water and carbon isotope measurements will be made at selected sites. Streamflow data will be collected from existing operational networks.

4. Experiment Design

4.1 Location, time and instrumentation within the observational domain

The principal objective of the FRONT-PORCH 2013 field campaign is to make fundamental advances in understanding and prediction of diurnal, thermally-modulated convection in complex terrain through the utilization of state-of-the-art, lower atmosphere observing technology, real-time data assimilation and numerical modeling. The NSF FRONT facility offers a unique opportunity to explore our hypotheses and execute our four tasks given the location of existing polarimetric radars in relation to the steep escarpment of the CFR.

The three month experiment (15 May-15 August 2012) is subdivided into two observational periods (OPs), which are characterized by a) synoptically-linked, transient convective storms (OP I: 15 May – 15 June) and b) comparatively 'weakly-forced', diurnal convective storm events related to the onset of the North American Monsoon (OP II: 15 July – 15 August). Each observational period will have ~5 intensive observation periods (IOPs) of about 6-18 hours each, which accumulate to 10 IOPs (=180 hrs). An IOP will start 1-2 hours prior to the arrival or formation of precipitation in order to monitor the antecedent air temperature, humidity, wind and land surface hydrology conditions and will last until most of the precipitation has moved out of the S-PolKa and CHILL radar range.

Additions to the FRONT radar facilities are needed to address the comprehensive research objectives (Fig. 6):

- **MGAUS – Mobile GPS Advanced Upper Air System**: The mobile sounding system will be used to characterize the environmental and inflow region during IOPs starting 2 hours prior and every 2 hours during the precipitation event (research Tasks 1, 3 and 4). The mobility allows for targeted observations in the vicinity of the storm, which might not be optimally covered by the stationary instruments. The IOPs require a total of 120 soundings (18 hours = 11 soundings x 10 IOPs = 110 soundings + ~10% failure rate = 120 soundings). The MGAUS system will additionally be used to provide a daily mid-day sounding from the CSU-CHILL or S-PolKa site. This will be used in conjunction with existing microwave radiometers and the GPS network to assess stability profiles on the days in which convection formed and those when it did not. For the daily launch a total of 110 soundings (99 days = 99 soundings + ~10% failure soundings = 110 soundings). Thus the total sounding request is 230 sondes.
- **ISS-449 – Integrated Sounding System – 499 MHz wind profiler**: The system will be used to address research Task 2. Measurements of vertical velocities are necessary to validate the vertical velocities derived from multiple Doppler retrieval techniques. The **ISS-449** will be deployed on the CSU campus, which is within the dual-Doppler lobe between the CHILL and SPolKa radar.
- **ISFS – Integrated Surface Flux System**: The ISFS will be used to address research objectives in Tasks 1, 2 and 3, which require the measurement of local precipitation, sensible and latent heat fluxes, and soil moisture, temperature and heat flux. Specifically, an enhanced surface observing network will help improve a) ground-validation of quantitative precipitation measurements (Tasks 1 and 2), b) characterization of surface meteorological conditions (Tasks 1 and 3), and c) representation of the co-evolution of regional land-surface fluxes and convective precipitation (Task 1). A core network of surface meteorology and land surface flux instrumentation is already in place throughout the region. Modest enhancements to the existing surface observing network within the FRONT domain will help fill gaps in elevational sampling. The fully-automated **ISFS** stations will be deployed shortly before commencement of radar operations and will be arrayed in two longitudinal transects that broadly sample the regional scale surface topographic gradient. Emphasis will be placed on siting the ISFS stations where there is currently a lack of representative long-term measurements. In the FRONT domain, there are deficiencies in the foothill-pediment regions and in the eastern portions of the radar coverage umbrella. In total we propose to deploy 8 total energy and water flux stations and approximately 10 basic meteorological stations.
- **DOW – Doppler on Wheels radars**: The three mobile DOW radars (DOW6, DOW7, Rapid-scan DOW) will be deployed along the Foothills in an area with a concentration of hydrometeorological stations, which is not well covered by FRONT radars. The mobile radars will provide low-level wind fields and precipitation characteristics at foothill elevations ranging between 1600 – 3200 m. This facility will be used to address Tasks 1 and 2.
- The **Ka-band radar** of S-PolKa will be operated only during IOPs due to the limited lifetime of its transmitter.

The NSF FRONT facilities (CSU-CHILL, CSU-Pawnee, NCAR S-Pol) together with the ISS-449, ISFS, and partially MGAUS will be operated continuously throughout the experiment. Instrument operations, in particular the MGAUS and DOW radars, will be assisted by students from the North Carolina State U., Colorado State U., U. of Arizona, and U. of Colorado. Instruments will be maintained during regular office hours (Mo-Fr. 8am-4pm).

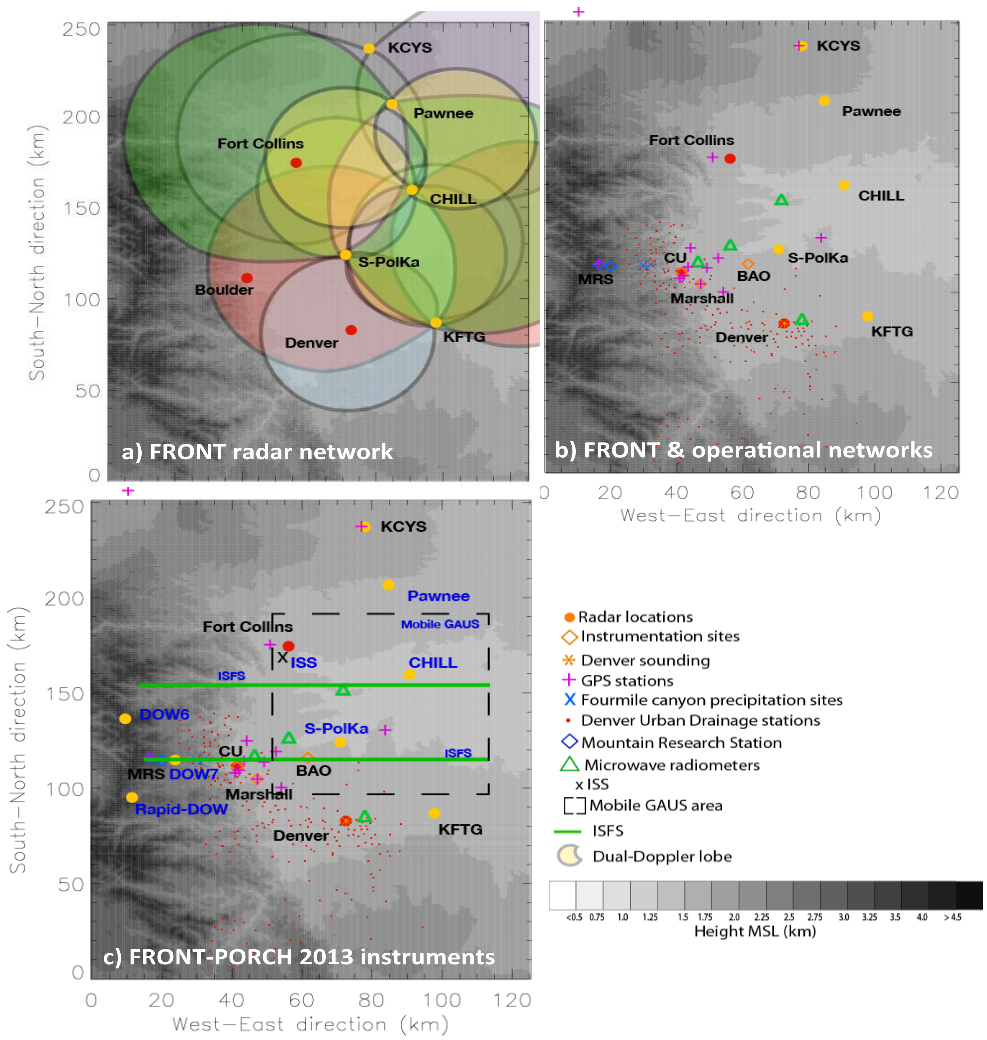

Figure 6: FRONT radar network and surface instruments for the FRONT-PORCH 2013 experiment. a) NSF FRONT radar network including the WSR-88D weather service radars at Denver, CO and Cheyenne, WY. Dual-Doppler lobes are indicated in color. b) FRONT and existing hydrometeorological and humidity stations in the CFR domain. c) FRONT-PORCH instrumentations with requested NSF facilities indicated in blue. The basic orientation of the surface instrument transects are shown with a green line.

4.2 Logistics and weather forecast during IOPs

Deployment and operation of FRONT-PORCH 2013 instruments will be coordinated during quasi-weekly and daily meeting by the project PIs and collaborators. The nominal timing of an IOP will be determined at daily planning meetings at an NCAR Operations Center the day before an IOP is expected to begin. Due to the episodic nature of active precipitation periods, decisions to stand-up or stand-down daily planning meetings will be made at quasi-weekly meetings or teleconferences. Besides operational model output, FRONT-PORCH will use nowcasting tools, described above, to guide 'within-IOP' activities (e.g., DOW locations).

5. Data Management Plan

Data management activities during and following the FRONT-PORCH 2013 project will be addressed in two ways. First, real-time operational and subsets FRONT-PORCH 2013 'project' or 'research' data will be made available to the NCAR FRONT field catalog. A template of this field catalog was established by the NCAR Earth Observing Laboratory (EOL) during the summer of 2011 and is progressively being populated with operational data sets and model output products (http://catalog1.eol.ucar.edu/front/). Example field data catalog datasets include satellite imagery, radar imagery, regional and local real-time hydrometeorological observing networks, operational sounding data, etc. The field data catalog will serve as the principal data portal for most operational as well as available research products and will be used in day-to-day mission decision-making such as the planning of intensive observing periods.

Additionally, a long-term project data archive will be coordinated by EOL as part of FRONT-PORCH 2013. The long-term archive will have NCAR-local and distributed (i.e., links to offsite locations) repositories. Internally at NCAR, EOL project data are primarily stored on the NCAR High Performance Storage System (HPSS) and accessed through the EOL Data Management System (EMDAC). EOL provides "one-stop shopping" for all centralized and related distributed project datasets through a web-based "Master Project Dataset List" that provides links to access all data and metadata. As such data repositories will be 'query-able', accessible via this common data portal which will contain basic dataset descriptions and pertinent, high-level (e.g., location, measurement description and periods of record) meta-data. The interfaces to the field data catalog and the long-term data archive will be supported through a separate NSF request by members of EOL (Steve Williams, personal communication) and will be coordinated with all NCAR-internal and external project investigators.

6. Education Plan

Several types of educational activities will be supported by the FRONT-PORCH field project. During the data collection phase, both graduate and undergraduate level students will gain direct hands-on experience in the operation of a variety of observing systems (i.e., sounding systems, research radars, etc.). Beyond basic instrument operations, students will participate in forecasting and operational planning meetings to expose them to the decision making processes that are critical to the successful collection of research-quality data. FRONT PORCH data sets are expected to provide the basis for many research efforts conducted by students at levels ranging from participants in a Research Experience for Undergraduate (REU), NCAR/UCAR Significant Opportunities in Atmospheric Research and Science (SOARS), the U. of Colorado Summer Multicultural Access to Research Training (SMART) programs through the MS and PhD levels. We expect between 10 to 15 students will be involved in data collection and analysis activities.

In addition to these traditional 'field experience' educational endeavors, FRONT-PORCH includes a task for data collection of high-quality case studies on mesoscale storm development and propagation. These case studies will be the centerpiece of education modules on key mesoscale structures (see Task 4 above). Both an education and facilities perspectives will be required to accomplish Task 4. As significant editing and annotation radar animations will be required, additional technical and web development resources will be needed to finalize and host the classroom radar data modules. The development of well-annotated time lapse data animations will be a central element in the educational case archive.

APPENDIX A: Case Study Template

Description of desired case study attributes for development into the North Carolina State education modules. Instructional materials developed from these case studies would complement traditional texts such as Markowski and Richardson's *Mesoscale Meteorology in Midlatitudes*, Houze's *Cloud Dynamics*, and Lamb and Verlinde's *Physics and Chemistry of Clouds*.

Description	**Radar scan types**	**Dual-Polarization and hydrometeor id**	**Dual-Doppler winds**	**Notes**
Cell replacement cycle in a squall line	PPI volume scan	required	required	Scan as fast as possible
Convective updraft with neighboring compensating downdrafts	PPI volume scan	helpful	required	Scan as fast as possible
"2D" squall line cross-sections (to compare to Houze's idealized cross-section)	RHI and PPI volume scans	required	required	
Development of hail in a multi-cell storm	RHI and PPI volume scans	required	required	Scan as fast as possible
Development of rear inflow within a squall line	PPI volume scans	required	required	Scan as fast as possible
RKW theory--Illustrations of convective cells, updrafts, cold pool and inflow for different environmental shear conditions	RHI and PPI volume scans	helpful	required	Upper air soundings needed
Radar data artifacts	RHI and PPI volume scans	required	helpful	

APPENDIX B: Estimated Deployment Budget

CHILL radar	$20k
S-PolKa	$30k
MGAUS*	$87.5k
ISFS	$30k
ISS-449	$10k
DOWs (DOW6, DOW7, rapid-scan DOW)	$70k
EST. TOTAL:	$247.5k

*Sounding Cost Breakdown: (IOPs: 18 hours = 11 soundings x 10 IOPs = 110 soundings + ~10% = 120 soundings x $500 = $60k; operational: 99 days = 99 soundings + ~10% = 110 soundings x $250 = $27,5k)

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RESULTS FROM PRIOR NSF SUPPORT:

Friedrich:

1) *PI on NSF AGS-093703: " A 10-yr climatology (1999-20009) on 4-dimensional precipitation characteristics using weather radar observations in the European Alps. $413,811, Jan 2010-Jan 2013. PI: Katja Friedrich*

A 9-year (2000-2008) analysis of precipitation characteristics for the European Alps has been generated from ground-based operational weather radar data provided by the Swiss radar network. The radar-based precipitation analysis focuses on the relationship between synoptic scale weather patterns and mesoscale precipitation distribution over complex alpine terrain. Daily synoptic scale weather patterns are associated with total daily precipitation and frequency of high precipitation rate to show that advective weather patterns with southerly mid-tropospheric flow result in the highest median for total daily precipitation. The summer (winter) season has the highest (lowest) total daily precipitation. Convective weather patterns result in elevated frequency of extreme precipitation rate events. Results of this work have been presented in Rudolph et al. (2011).

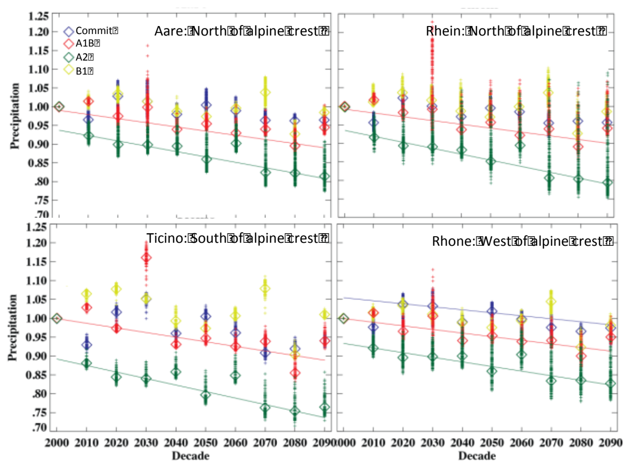

***Figure 1**: Prediction of 21st century precipitation combining GCM models (color coded: Commit, A1B, A2, B1) with radar-based precipitation maps for four major Swiss river basins: Aare, Rhein, Ticino and Rhone. Lines indicate that the decrease is significant.*

Projections of 21st century precipitation for seven Swiss river basins are generated by linking high resolution (2 x 2 km^2) radar-estimated precipitation observations to a global climate model (GCM) via synoptic weather patterns. The use of synoptic patterns characterizes the effect of changes in large-scale circulation, or dynamic effects, on expected precipitation. Identification of synoptic patterns from a global climate model for the 21st century shows an increasing frequency of anticyclonic synoptic patterns, decreasing frequency of cyclonic patterns, and constant frequency of advective patterns over Switzerland. When coupled with observed radar-estimated precipitation for each synoptic weather pattern, the changes in pattern frequencies result in an approximately 10-15% decrease in decadal precipitation over the course of the 21st century for seven Swiss river basins (Fig. 1). The lack of a trend in exceeding the 95th quantile of precipitation in combination with a decreasing trend in total precipitation provides evidence that dynamic effects will not result in increased frequency of heavy precipitation events, but that heavy precipitation will account for a greater proportion of total precipitation. Results of this work have been presented in Rudolph et al. (2012).

The three-dimensional precipitation structures and upstream conditions (moisture flux, static stability) of moderate and heavy precipitation in the European Alps are currently under investigation. The vertical structure of the precipitation will be analyzed according to the location of maximum rainfall rate, frequency of maximum rainfall rate, location of the melting layer, and maximum and average radar echo height. In particular, the change in precipitation type (snow versus rain, convective versus stratiform) will be investigated in great detail during winter storms with respect to annual snow amounts.

2) *PI on NSF ATM-0969172 "Analysis of Particle Size Distribution in Supercell Thunderstorm", $380,426, June 2010 – June 2013. PI: Katja Friedrich*

This grant has been dedicated to collect data of particle-size distributions within supercell thunderstorms during the VORTEX2 2010 field campaign, determining the influence of strong wind and turbulence on the accuracy of drop-size distribution measurements, and developing an automated quality-control algorithm. The research objectives focus on determining the characteristic of drop-size distribution (DSD) at the surface within convective thunderstorms and preparing disdrometer and radar data sets so that DSD can be related to dual-polarization observations to provide indication about the main microphysical processes. Mobile microphysical probes are very useful for targeted observations but need to be deployed with ground-based radars for valid interpretation of the data. Although the instruments are exposed to large hail and strong wind, none of the mobile disdrometers was severely damaged or destroyed during VORTEX2. However, the quality of the DSD measurements becomes very poor when wind speed exceeds ~10 m/s (Friedrich et al. 2012). Based on the VORTEX2 data set, the articulating disdrometers, i.e., the measurement area rotates into the wind, minimize the wind effects. Together with the U. of Florida we are currently setting up an experiment in the UF hurricane simulator to test the disdrometer accuracy under different wind conditions and different instrument configurations.
Preliminary results related to the characteristics of DSD at the surface within the supercell thunderstorm based on the VORTEX2 2009 and 2010 data set can be summarized as followed.

- Significant DSD variability occurs within less than minute (sharp edges between rain / no rain), which requires a high accumulation interval (e.g., 10 s) instead of 1 minute usually used for disdrometer measurements.
- Large raindrops $d > 4$ mm are common although only for short times (minutes); large drops are accompanied by small drops
- At the southern side of a supercell thunderstorm large and small drops were observed; Since most radar and airborne observations indicate the existence of large hydrometeors at higher elevations the increased in number of smaller drops at the surface measured by disdrometer could be related to break-up processes in a turbulent environment close to the surface
- Large number of small raindrops observed throughout the storm
- Precipitation modes (peak in number concentration for $d < 2$ mm ~1-3 minutes)
- Mean diameter ~2 mm most of the time (max mean d ~ 3 mm)
- Variations in drop size distribution parameters are strongly influenced by drop number density rather than microphysical processes. Therefore, only relative changes in DSD should be considered.

3) Co-PI on NSF DUE 0837388 "An Atmospheric Science Laboratory for Undergraduate Education", $144,359, Jan 2009 – Jan 2011. PI: Peter Pilewskie, Co-PIs: Katja Friedrich, A. Scott Kittelmann

This NSF funding was dedicated to improve undergraduate education by first establishing a precipitation and radiation instrumentation observatory and second, implementing these instruments, observations, and hands-on exercises into the ATOC undergraduate teaching curriculum. Continuous observations from *ATOC Skywatch Observatory*[1] have been made available via an open-source website. Two laboratory-exercises for 90-minutes labs were developed utilizing these instruments for hands-on experiments and data analysis[2]. These exercises have been implemented into undergraduate laboratory course in one out of two sections of the class. The assessment was preformed on the common learning goals and contained identical content questions for all sections. The overall score increased by 2.2 in the new labs compared to 0.8 for the old labs. The largest positive impact of the new lab exercises was found for students that had a low (>4) and medium (4-9) score prior to taking ATOC 1070. Results of this work have thus far been presented in LeBlanc et al. (2009), Kittelman (2010), and Trenbath et al. (2010).

[1] http://skywatch.colorado.edu/
[2] http://skywatch.colorado.edu/publications.html

References:

LeBlanc, S., P. Pilewskie, S. Kittelman, K. Friedrich, 2009: Summary of the Skywatch Suite of Instruments. ATOC Student Poster Conference, Boulder, CO (available online at http://skywatch.colorado.edu/publications.html).

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Gochis:

Dr. Gochis currently receives NSF support under Grant EAR-0910961. This proposal is aimed at understanding the impact of mountain pine beetle infestation on energy and water transfers in affected forests at stand and headwater catchment scales. He leads the project's tasks related to improving the representation of beetle-driven forest mortality in community land surface models supported by NCAR (e.g. the Community Land Model-CLM and Noah). To date three manuscripts from this project with contributions from Dr. Gochis have been submitted for publication (Edburg et al., 2011, Somor et al., 2011) or are in preparation (Duhl et al., 2012).

Weckwerth:

Weckwerth's past NSF funding is limited as she is a base-funded scientist at NCAR and does not receive NSF support from program funds. She was the co-lead for IHOP_2002 and her publications include Flamant et al. (2003), Weckwerth et al. (2004), Weckwerth and Parsons (2006); Cai et al. 2006; Demoz et al. (2006); and Weckwerth et al. (2008) and Bennett et al. (2010).

Hubbert:

Hubbert's past NSF funding is limited as he is a base-funded scientist at NCAR and does not receive NSF support from program funds.

Rutledge:

Grant: ATM-0002256, Shipboard Radar Observations of Precipitating Convection in EPIC

Period Covered: 3/1/2001-2/28/2004

Amount: $515,870

During September-October 2001, the East Pacific Investigation of Climate Processes in the Coupled Ocean-Atmosphere System (EPIC-2001) Inter-Tropical Convergence Zone (ITCZ) field campaign focused on studies of deep convection in the warm-pool region of the East Pacific. As part of the EPIC-2001 field phase, the NOAA research vessel Ronald H. Brown (RHB) was deployed at 10°N, 95°W in the east Pacific

ITCZ in order to study the nature of the convection and modulation by the passage of easterly waves. The RHB was equipped with a stabilized C-band Doppler radar as one of several instruments on board. The CSU Radar Meteorology Group led the radar and sounding operations on the RHB during EPIC. The C-band radar was operated 24 hr/day during the approximate 3-week period that the ship was on-station in the east Pacific ITCZ. Upper air soundings were launched 6 times per day.

A study by Petersen et al. (2003) integrated C-band Doppler radar, sounding, and surface heat flux data collected aboard the RHB during EPIC to describe the kinematic and thermodynamic states of the ITCZ environment, together with tendencies in convective structure, lightning, rainfall, and surface heat fluxes as a function of 3-5 day easterly wave phase. Three easterly waves were observed at the location of the RHB during EPIC-2001. Composites of radar, sounding, lightning and surface heat flux observations suggest the following systematic behavior as a function of wave phase: zero to-one quarter wavelength ahead of (behind) the wave trough in northerly (southerly) flow, larger (smaller) CAPE, lower (higher) CIN, weaker (stronger) tropospheric shear, larger (smaller) convective rain fractions, higher (lower) conditional mean rain rates, higher (lower) lightning flash densities, and more (less) robust convective vertical structure occurred. Larger areas of light convective and stratiform rain and slightly larger (10%) area averaged rain rates occurred in the vicinity of, and just behind, the trough axes in southerly and ridge flow. Other EPIC-based studies documented the detailed structure of convection in EPIC and contrasted to other tropical regions including Pereira and Rutledge (2006) and Cifelli et al. (2007) and Cifelli et al. (2008).

Publications

Convection and Easterly Wave Structure Observed in the Eastern Pacific Warm-Pool during EPIC-2001. Journal of Atmospheric Science, 60, 1754-1773. (Petersen, W. A., R. Cifelli, D. J. Boccippio, S. A. Rutledge, and C. Fairall). (2003)

Diurnal Cycle of Shallow and Deep Convection for a Tropical Land and an Ocean Environment and its Relationship to Synoptic Wind Regimes. Monthly Weather Review, 134, 2688-2701. (Pereira, L.G., and S.A. Rutledge). (2006)

Radar Characteristics of Precipitation Features in the EPIC and TEPPS Regions of the East Pacific. Monthly Weather Review, 135, 1576-1595. (Cifelli, R., S.W. Nesbitt, W.A. Petersen, S.A. Rutledge, and S. Yuter). (2007)

Diurnal Characteristics of Precipitation Features Over the Tropical East Pacific: A Comparison of the EPIC and TEPPS Regions. Journal of Climate, 21, 4068-4068. (R. Cifelli, S.W. Nesbitt, S.A. Rutledge, W.A. Petersen, and S. Yuter. (2008)

EPIC2001 and the Coupled Ocean-Atmosphere System of the Tropical East Pacific. Bull. Amer. Met. Soc., 85, 1341-1354. (D. A. Raymond, W. A. Petersen, R. Cifelli, et al.) (2004)

Grant: ATM-0733396, Studies of Convection in the North American Monsoon Experiment (NAME)
Period covered: 11/01/2007-10/31/2011
Amount: $619,088

Grant: ATM-0340544, Polarimetric Radar Operation in Support of the North American Monsoon Experiment (NAME)
Period covered: 01/13/2004-06/13/2006
Amount: $599,146

These two awards were made in support of NAME 2004 field experiment operations and subsequent scientific analysis. The PI co-directed the operations of the NCAR S-Pol radar during NAME, in collaboration with R. Carbone of NCAR. Data collection was done in July-August of 2004, documenting initial convection over the high terrain of the Sierra Madre Occidental (SMO) that then grew upscale to mesoscale proportions as systems approached the coastal plain near Mazatlan. Several studies were carried out to examine the vertical structure of convection as a function of terrain height and to investigate microphysical processes leading to frequent light rain over the SMO to very large rain rates over the coastal plain. Low-level warm rain production was found to be critical over the coastal plain, leading to intense rainfall. A strong diurnal cycle of precipitation over land was also documented, approximately 12 hours out of phase with the diurnal cycle over the waters of the Gulf of California. Convection was also classified as a function of wind regime. S-Pol polarimetric data were used to study changes in microphysics and drop size distribution parameters over water and land, the latter subdivided by terrain height. In addition to the publications listed below, one Ph.D. and three M.S. theses were completed in the CSU Radar Meteorology Group based on NAME data.

Publications

The NAME 2004 Field Campaign and Modeling Strategy. Bulletin of the American Meteorological Society, 87, 79-94. (Higgins, W., and co-authors). (2006)

Radar-Observed Characteristics of Precipitating systems during NAME 2004, Journal of Climate, 20, 1713-1733. (Lang, T.J., A. Ahijevych, S.W. Nesbitt, R.E. Carbone, S.A. Rutledge, and R. Cifelli). (2007)

Elevation-dependant trends in precipitation observed during NAME, Mon. Wea. Rev., 136, 4962-4979. (Rowe, A.K., S.A. Rutledge, T.J. Lang, P.E. Ciesielski, and S.M. Saleeby). (2008)

Vertical Structure of Convective Systems during NAME 2004. Mon. Wea. Rev., 138, 1695-1714. (D.G. Lerach, S.A. Rutledge, C.R. Williams and R. Cifelli). (2010)

Polarimetric Radar Observations of Convection in Northwestern Mexico During the North American Monsoon Experiment. Journal of Hydrometeorology, Special Collection, Precipitation Research. (T.J. Lang, S.A. Rutledge and R. Cifelli). (In press)

Investigation of Microphysical Processes in Isolated Convection in NAME. (A.K. Rowe, S.A. Rutledge and T. J. Lang). Mon. Wea. Rev. (Conditionally accepted)

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A. Professional Preparation

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University of Leipzig, Germany	Meteorology	M.S. 1999
Ludwig-Maximillians University, Munich, Germany	Physics	Ph.D. 2002

B. Appointments

2008 – present	**Assistant Professor**, Department of Atmospheric and Oceanic Sciences, University of Colorado at Boulder, CO
2005 – 2007	**Research Associate**, Swiss Weather Service, Locarno, Switzerland
2004 – 2005	**Research Associate,** Cooperative Institute for Research in Environmental Sciences, University of Colorado at Boulder, CO
2002 – 2004	**Research Associate**, Deutsches Zentrum für Luft- und Raumfahrt (DLR) Oberpfaffenhofen, Germany
1999 – 2002	**Research Assistance**, above named institute
1993 – 1999	**Research Assistance**, University of Leipzig, Germany

C. Recent publications closely related to the proposed project:

1. Friedrich, K., J. K. Lundquist, M. Aitken, E. A. Kalina, and R. F. Marshall, 2012: Stability and turbulence in the atmospheric boundary layer: A comparison of remote sensing and tower observations. *Geophys. Res. Lett., Vol. 39, No. 3, L03801, doi:10.1029/2011GL050413.*
2. Rudolph, J. V., K. Friedrich, and U. Germann, 2012: 21^{st} century precipitation trend for Swiss rive basins. *J. Climate* (in press).
3. Rudolph, J. V., K. Friedrich, and U. Germann, 2011: Relationship between radar-estimated precipitation and synoptic weather Patterns in the European Alps. *J. Appl. Meteor. Climatol.*, **50**, 944–957.
4. Dotzek, N., and K. Friedrich, 2009: Downburst-producing thunderstorms in southern Germany: Radar analysis and predictability. *Atmos. Res.*, **93,** 457-473.
5. Friedrich, K., D. E. Kingsmill, C. Flamant, H. V. Murphey, and R. M. Wakimoto, 2008: Kinematic and moisture characteristics of a nonprecipitating cold front observed during IHOP. Part I: Across-front structures. *Mon. Wea. Rev.,* **136**, 147-172.

D. Other significant publications:

1. Friedrich, K., S. Higgins, F. J. Masters, and C. R. Lopez, 2011: Effects of strong winds on PARSIVEL disdrometer measurements. *J. Atmos. Oceanic Technol.* (submitted).
2. Friedrich, K., U. Germann, and P. Tabary, 2009: Influence of ground clutter contamination on the accuracy of polarimetric quantities and rainfall rate. *J. Atmos. Oceanic Technol.,* **26**, 251-269.
3. Friedrich, K., U. Germann, J. J. Gourley, and P. Tabary, 2007: Effects of radar beam shielding on rainfall estimation for polarimetric C-band radar. *J. Atmos. Oceanic Technol.,* **24**, 1839-1859.
4. Friedrich, K., M. Hagen, and T. Einfalt, 2006: A quality control concept for radar reflectivity, polarimetric parameters, and Doppler velocity. *J. Atmos. Ocean Technol.*, **23**, 865-887.
5. Friedrich, K., D. E. Kingsmill, C. Flamant, H. V. Murphey, and R. M. Wakimoto, 2008: Kinematic and moisture characteristics of a nonprecipitating cold front observed during IHOP. Part I: Across-front structures. *Mon. Wea. Rev.,* **136**, 147-172.

E. Synergistic Activities

1. Field campaign participation: ASCII (2012), TOM (2011), ISPA (2010), SCOOP (2010-2012), VORTEX2 (2009, 2010), Gunnison Radar Project (2009, 2010), Hurricane Ike (2008), Hurricane Gustav (2008), ROTATE (2008), Radar France-Comte (2006, 2007) VERTIKATOR (2000); designing and maintaining the instruments deployed at the CU Mountain Research Site as part of SCOOP
2. Participation in preparing a high-profile interactive exhibit and the interactive video game *"Tornado Hunting"* at the Museum of Science and Industry in Chicago dedicated to the *Verification of the Origins of Rotation in Tornadoes Experiment 2 (VORTEX2)*.
3. Research and education advisors for many outreach programs, e.g., the NSF-funded 40-minute IMAX film *'Tornado Alley'*.
4. Maintaining precipitation instrumentations of the ATOC Skywatch Observatory (http://skywatch.colorado.edu) and developing lab exercises for ATOC 1070.
5. Participation in organizing the 2009 NCAR summer colloquium *Exploring the Atmosphere Observational Instruments and Techniques* giving students hands-on experience with major research facilities.

F. Collaborators and other Affiliations

Collaborators and Co-Editors (within the last 48 months)

V. N. Bringi, – Colorado State University, CO, (co-editor to *J. Atmos. Oceanic Technol.*); Dan Breed – NCAR, CO; Bertrand Calpini – Meteo Swiss, Payern, Switzerland; Bart Geerts – University of Wyoming; Urs Germann – MeteoSwiss, Locarno, Switzerland; David Gochis – NCAR, CO; Vanda Grubisic – NCAR, CO; Martin Hagen – Deutsches Zentrum für Luft- und Raumfahrt, Oberpfaffenhofen, Germany; David P. Jorgensen – NOAA/NSSL, Norman, Oklahoma, (co-editor to *Mon. Wea. Rev.*); David E. Kingsmill – University of Colorado, CIRES, Boulder, CO; Karen Kosiba – Center for Severe Weather Research, CO; Forrest Masters – U. of Florida, Gainesville, FL; Roy Rasmussen – NCAR, CO; Richard Rotunno – NCAR, CO; David Schultz – CIMMS and NOAA/NSSL, Norman, OK (co-editor to *Mon. Wea. Rev.*); Pierre Tabary – Météo-France, Centre de Météorologie Radar, Trappes, France; Steve Vasiloff – NOAA/NSSL, Norman, OK; Roger M. Wakimoto – NCAR, CO; Tammy Weckwerth – NCAR, CO; Joshua Wurman – Center for Severe Weather Research, CO; Sandra Yuter – North Carolina State University, NC

Graduate and postdoctoral Advisors

Nicole Moelders (Graduate Advisor) University of Alaska, Fairbanks, AL

Gerd Tetzlaff (Graduate Advisor) University of Leipzig, Germany
Ulrich Schumann (Ph.D. Advisor) DLR, Oberpfaffenhofen, Germany
Roger Smith (Ph.D. Advisor) Ludwig-Maximillians University, Munich, Germany
David E. Kingsmill (Postdoctoral Advisor) University of Colorado, CIRES, Boulder, CO

Thesis Advisor and Post-Graduate Scholar Sponsor
Rachel Humphrey, ATOC MS, 2008-2009
Scott Ellis, ATOC Ph.D., 2005-2010 (co-advisor)
Rosie Polkinghorne, ATOC Ph.D., 2005-2010 (co-advisor)
Evan Kalina, ATOC Ph.D. candidate, 2009-present
James Rudolph, ATOC Ph.D. candidate, 2008-present
Stephanie Higgins, U. of Colorado, PhD candidate, 2008-present, co-advisor
Carlos Lopez, U. of Florida Ph.D. candidate, 2009-present, co-advisor
Marcus van Lier-Walqui, U. of Florida Ph.D. candidate, 2008-present, co-advisor

DAVID J. GOCHIS
Curriculum Vitae

Address: National Center for Atmospheric Research
3450 Mitchell Lane, Boulder, Co 80307
Phone: +1 303 497 2809
Fax: +1 303 497 8401
E-mail: gochis@rap.ucar.edu

A. Professional Preparation

University of Arizona, USA	Ph.D.	2002
Oregon State University, USA	MS	1998
University of Kansas, USA	BS (w/ Honors)	1994

B. Appointments

2011-present	Scientist III, National Center for Atmospheric Research, Boulder, CO
2007-2011	Scientist-II, National Center for Atmospheric Research, Boulder, CO
2004-2007	Scientist-I, National Center for Atmospheric Research, Boulder, CO
2002–2004	Postdoctoral Research Associate, National Center for Atmospheric Research, Advanced Study Program, Research Applications Program (RAP), Boulder CO,
1998-2002	Research Assistant/Associate, University of Arizona, USA
1998	Consulting Engineer, CH2M Hill, Portland, Oregon, USA
1995-1998	Research Assistant, Oregon State University, USA

C. Relevant Peer-Reviewed Scientific Publications:

1. **Gochis, D.J.**, E.R. Vivoni, and C.J. Watts, 2010: The impact of soil depth on land surface energy and water fluxes in the North American Monsoon region. *J. Arid Environments*, **74**, 564-571.

2. Barlage, M., F. Chen, M. Tewari, K. Ikeda, **D. Gochis**, J. Dudhia, R. Rasmussen, B. Livneh, M. Ek, and K. Mitchell, 2011: Noah Land Surface Model Modifications to Improve Snowpack Prediction in the Colorado Rocky Mountains. In press, *J. Hydrometeorology*.

3. Rasmussen, R., C. Liu, K. Ikeda, **D.J. Gochis**, D. Yates, F. Chen, M. Tewari, M. Barlage, J. Dudhia, W. Yu, K. Miller, K. Arsenault, V. Grubišić, G. Thompson, E. Gutmann, 2011: High-Resolution Coupled Climate Runoff Simulations of Seasonal Snowfall over Colorado: A Process Study of Current and Warmer Climate. In Press to *J. Climate*.

4. Wood, E.F., J.K. Roundy, T.J. Troy, R. van Beek, M. Bierkens, E. Blyth, A. de Roo, P. Döll, M. Ek, J. Famiglietti, **D. Gochis**, N. van de Giesen, P. Houser, P.R. Jaffé, S. Kollet, B. Lehner, D.P. Lettenmaier, C. Peters-Lidard, M. Sivapalan, J. Sheffield, A. Wade, P. Whitehead, 2011: Hyper-Resolution Global Land Surface Modeling: Meeting a Grand Challenge for Monitoring Earth's Terrestrial Water. In press, *Water Resources Research*.

5. Gutmann, E., R. Rasmussen, C. Liu, **D.J. Gochis**, M. Clark, 2011: A Comparison of Statistical and Dynamical Downscaling of Winter Precipitation Over Complex Terrain. In press, *J. of Climate*.

D. Advisory Appointments and Synergistic Activities:

2011-present:	Associate editor, Journal of Hydrology
2010-2012:	National Research Council (NRC) Panel Member, Assessment of the U.S. National Weather Service Modernization Program
2010-2013:	Co-chair of International CLIVAR Variability of American Monsoon Systems (VAMOS) Panel
2008-2010	NOAA Climate Change Prediction Program for the Americas (CPPA) Advisory Panel Member
2007-present:	CLIVAR Variability of American Monsoon Systems (VAMOS) Panel member
2007-present:	NSF-NCAR-BEACHON (Bio-hydro-atmosphere interactions of Energy Aerosols, Carbon, H2O, Organics & Nitrogen) Science Working Group
2008-2009:	Water Cycle Science Steering Group to inform the Water Cycle Inter-Agency Working Group of the U.S. Climate Change Science Program (CCSP)
2006-2010:	Chair North American Monsoon Experiment (NAME) Science Working Group
2004-2010:	Member NAME Science Working Group
2004-2006:	Member of the Consortium of Universities for the Advancement of Hydrological Sciences, Inc. (CUAHSI) Science Advisory Team

Student Advisory Committees:

2012-present:	Scott Landolt (PhD), U. of Colorado, Main advisor – John Cassano
2011-present:	Tiantian Xiang (PhD), Arizona State University, Main Advisor - Enrique Vivoni
2008-present:	Hernan Moreno (PhD), Arizona State University, Main Advisor - Enrique Vivoni
2011:	Wei Yu (PhD), U. of Colorado, Main Advisor – Weiqiu Wang
2008:	Michael Barnes, U. of Arizona, NOAA Hollingsworth Summer Fellowship
2008:	Kazungu Maitaria (PhD), U. Arizona, Main advisor – Jim Shuttleworth
2007:	Chunmei Zhu (PhD), U. Washington, Main advisor – Dennis Lettenmaier
2007:	Angela Rowe (MS), Colorado State University, Main advisor – Steve Rutledge

E. Significant Collaborations (within last 4 years):

Enrique Vivoni, New Mexico Institute of Mining and Technology; Fei Chen, NCAR/RAP; Brent Ewers, U. Wyoming; Brian Cosgrove, NOAA-OHD; Christopher J. Watts, IMADES, Sonora, Mexico; Jaime Garatuza-Payan, ITSON, Sonora, Mexico; Steve Nesbitt, U. Illinois; David Yates, NCAR/RAP ; Ismail Yucel, Hampton U.; Bob Kuligowski, NOAA-NESDIS ; Yang Hong, U. Oklahoma ; Zong-Liang Yang, U. Texas at Austin; David Maidment, U. Texas at Austin; Peter Troch, U. Arizona; Paul Brooks, U. Arizona; Steve Nesbitt, U. Illinois; Xubin Zeng, U. Arizona; Steve Vasiloff, NOAA-NSSL; Steve Rutledge, Col. State University; Rob Cifelli, NOAA-ESRL; Jeff Hicke, U. Idaho; Reed Maxwell, Col. School of Mines; Hugo Berbery, U. of Maryland; Harald Kunstmann, Karlsruhe Insitut of Technology-Germany; Christa Peters-Lidard, NASA-GSFC; Peter Troch, U. Arizona; Martyn Clark, NCAR/RAP

Past Advisors

Jim Shuttleworth (U. Arizona) , PhD; Richard Cuenca (Oregon State University), MS

Tammy M. Weckwerth

Professional Preparation

Cornell College, Mt. Vernon, IA	Mathematics and Physics	B.A., 1988
University of California - Los Angeles	Atmospheric Sciences	M.S., 1991
University of California - Los Angeles	Atmospheric Sciences	Ph.D., 1995

Appointments

Scientist III, Earth Observing Laboratory, NCAR, Boulder, CO 2006-present
i) EOL project management for ELDORA and S-Pol, ii) Research in mesoscale meterology, iii) Deputy Manager of Remote Sensing Facility

Scientist II, Atmospheric Technology Division, NCAR, Boulder, CO 2001-2006
i) ATD project management for ELDORA and S-Pol, ii) Research in mesoscale meteorology, iii) Co-Chair of Scientific Steering Committee for IHOP_2002

Scientist I, Atmospheric Technology Division, NCAR, Boulder CO 1997-2001
i) ATD project management for ELDORA and S-Pol, ii) Research in mesoscale meteorology

Post-doc, Advanced Study Program, NCAR, Boulder, CO 1995-1997
i) Multi-platform SCMS data analysis of the evolution of boundary-layer convection, ii) Multi-platform Flatland/LIFT comparisons of instrument capabilities in mesoscale meteorology, iii) Modeling study of waves behind cold-air outflows.

Graduate research assistant, UCLA, Los Angeles, CA 1988-1995
Ph.D. research: Multi-platform CaPE data analysis and modeling study of horizontal convective rolls. M.S. research: Multi-platform MIST data analysis of convection initiation associated with a gust front.

Teaching assistant, Dept. of Atmos. Sci., UCLA, Los Angeles, CA 1990
Taught general meteorology course for non-science majors.

Student research participant, Argonne National Laboratory, Chicago, IL 1987
Participated in collection and analysis of rainfall data from minisodar.

5 Publications Relevant to this Proposal

Weckwerth, T. M., J. W. Wilson, M. Hagen, T.J. Emerson, J.O. Pinto, D.L. Rife and L. Grebe, 2011: Radar climatology of the COPS region. *Q. J. Roy. Meteor. Soc.*, **137**, 31-41, DOI: 10.1002/qj.747.

Weckwerth, T. M., H. V. Murphey, C. Flamant, J. Goldstein and C. R. Pettet, 2008: An observational study of convection initiation on 12 June 2002 during IHOP_2002. *Mon. Wea. Rev*., **136**, 2283-2304.

Bennett, L. J., T. M. Weckwerth, A. M. Blyth, B. Geerts, Q. Miao and Y. P. Richardson, 2010: Observations of the evolution of the nocturnal and convective boundary layers and the structure of open-celled convection on 14 June 2002. *Mon. Wea. Rev*., **138**, 2589-2607 doi:10.1175/2010MWR3200.1.

Weckwerth. T. M., and D. B. Parsons, 2006: A review of convection initiation and motivation for IHOP_2002. *Mon. Wea. Rev*., **134**, 5-22.

Weckwerth, T. M., C. R. Pettet, F. Fabry, S. Park and J. W. Wilson, 2005: Radar refractivity retrieval: Validation and application to short-term forecasting. *J. Appl. Meteor.*, **44**, 285-300.

5 Other Significant Publications

Weckwerth, T. M., 2000: The effect of small-scale moisture variability on thunderstorm initiation. *Mon. Wea. Rev*., **128**, 4017-4030.

Weckwerth, T. M., T. W. Horst and J. W. Wilson, 1999: An observational study of the evolution of horizontal convective rolls. *Mon. Wea. Rev*.,**127**, 2160-2179.

Weckwerth, T. M., J. W. Wilson, R. M. Wakimoto, and N. A. Crook, 1997: Horizontal convective rolls: Determining the environmental conditions supporting their existence and characteristics. *Mon. Wea. Rev*., **125**, 505-526.

Weckwerth, T. M., J. W. Wilson and R. M. Wakimoto, 1996: Thermodynamic variability within the boundary layer due to horizontal convective rolls. *Mon. Wea. Rev*., **124**, 769-784.

Wilson, J. W., T. M. Weckwerth, J. Vivekanandan, R. M. Wakimoto, and R. W. Russell, 1994: Boundary layer clear-air radar echoes: origin of echoes and accuracy of derived winds. *J. Atmos. Oceanic Tech*., **11**, 1184-1206.

Synergistic Activities

1) Project management for EOL-supported instruments (ELDORA and S-Pol) in field projects
2) Subject Matter Editor of *Bulletin of the American Meteorological Society,* 2005-present
3) Co-Scientific Lead of IHOP_2002 field campaign

Recent Collaborators

Lindsay Bennett – U. of Leeds, UK; Alan Blyth – U. of Leeds, UK; Cyrille Flamant – CNRS/UPMC/UVSQ, France; Katja Friedrich – U. of Colorado-Boulder; John Marsham – U. of Leeds, UK; Yvette Richardson – PSU; Steve Sherwood – U. New South Wales, Australia; Joel Van Baelen, U. Clermont-Ferrand, France; Jim Wilson - NCAR/EOL/RAL; Volker Wulfmeyer – U. of Hohenheim, Stuttgart, Germany; Joshua Wurman – CSWR, Inc.
Co-Editor (BAMS): Jeff Waldstreicher – NWS

Graduate and Postdoctoral Advisor

R. Wakimoto, NCAR, M.S. & Ph.D. Thesis Advisor
J. Wilson, NCAR, Ph.D. Thesis Co-Advisor and Postdoctoral Advisor

JOHN C. HUBBERT

Telephone: (303) 497-2041 e-mail: hubbert@ucar.edu

EDUCATION

Ph.D. Electrical Engineering, May 1992, Colorado State University, Fort Collins, Colorado. Advisors: V.N. Bringi and V. Chandrasekar.

M.S. Electrical Engineering, May 1985, Colorado State University, Fort Collins, Colorado. Advisor: Aram Budak.

B.A. Mathematics, May 1974, Cum Laude, University of Vermont, Burlington, Vermont.

WORK EXPERIENCE

PROJECT SCIENTIST III: National Center for Atmospheric Research, Boulder, Colorado. July 2005-present. Leader/Manager of the NEXRAD Data Quality Project.

PROJECT SCIENTIST II: National Center for Atmospheric Research, Boulder, Colorado. 2002-2005. Leader/Manager of the NEXRAD Data Quality Project.

AFFILIATE PROFESSOR at COLORADO STATE UNIVERSITY: Have served on several students' committees and collaborate with Dr. Chandrasekar. 2003 to present.

RESEARCH ASSOCIATE: Department of Electrical Engineering, Colorado State University. 1996-2002. Modeling, analysis of polarimetric weather radar data.

PUBLICATIONS

Closely Related

1. J.C. Hubbert, S.M. Ellis, M. Dixon, and G. Meymaris, Modeling, Error Analysis and Evaluation of Dual Polarization Variables Obtained from Simultaneous Horizontal and Vertical Polarization Transmit Radar. Part I: Modeling and Antenna Errors., J. Atmos. & Oceanic Technol., Oct. 2010.
2. J.C. Hubbert, S.M.ellis, M. Dixon, and G. Meymaris, Modeling, Error Analysis and Evaluation of Dual Polarization Variables Obtained from Simultaneous Horizontal and Vertical Polarization Transmit Radar. Part II: Experimental Data., J. Atmos. & Oceanic Technol., Oct. 2010.
3. J.C. Hubbert, M. Dixon, S.M. Ellis and G.Meymaris, "Weather Radar Ground Clutter, Part I: Identification, Modeling and Simulation", *J. Atmos. & Oceanic Technol.* , V26, July 2009, pp. 1165-1180
4. J.C. Hubbert, M. Dixon, and S.M. Ellis, "Weather Radar Ground Clutter, Part II: Real Time Identification and Filtering", *J. Atmos. & Oceanic Technol.* ,Volume 26, July 2009, pp. 1181-1197
5. Patent, 2010: "Methods and Apparatus for Clutter Filtering Staggered Pulse Repetition Time Signals", Patent no. 7,728,765 B1. This is a ground clutter mitigation scheme for radars that employ staggered transmitted pulses.

Significant

1. Patent, 2006: "Radar Systems", Patent no. 7,053,813. This radar pulsing scheme for range-velocity ambiguity mitigation was developed in conjunction with Dr. Chandrasekar of Colorado State University.
2. E. Ruzanski, J.C. Hubbert and V. Chandrasekar, "Evaluation of the simultaneous multiple pulse repetition frequency algorithm for weather radar" *J. Atmos. & Oceanic Technol.*, pp11661181, July, 2008 .

3. J.C. Hubbert, V.N. Bringi and D. Brunkow, " Studies of the Polarimetric Covariance Matrix, Part I: Calibration Methodology", *J. Atmos. & Oceanic Technol.*, V.60, pp 696-706, May, 2003.
4. J.C. Hubbert and V.N. Bringi, "Studies of the Polarimetric Covariance Matrix, Part II: Modeling and Polarization Errors", *J. Atmos. & Oceanic Technol.*, V.60, pp 1011-1022, July, 2003.
5. J. Hubbert, V.N. Bringi, L.D. Carey and S. Bolen "CSU-CHILL Polarimetric Radar Measurements from a Severe Hail Storm in Eastern Colorado", *J. of App. Meteor.*, V.37, pp749-775, 1998.

SYNERGISTIC ACTIVITIES

1. Project manager of the group that created the radar ground clutter mitigation algorithm, CMD (Clutter Mitigation Decision) that is now deployed on the NEXRAD network. This work received the NCAR Technical Achievement award in 2010.
2. Invited Speaker: RADMON Workshop, at the ERAD 2010 conference in Sibiu, Romania. Topic: Antenna polarization errors and biases in dual polarization variables.
3. Invited speaker Earth Systems Science Center, University of Alabama in Huntsville. Topics: Radar clutter mitigation and Antenna polarization errors
4. Invite Member of the International Organizing Committee (IOC) for the Radar Quality Control and Quantitative Precipitation Intercomparison (RQQI). WMO supported.
5. Regular Speaker at NEXRAD Technical Advisory Committee (TAC) meetings in Norman, OK, 2003, 2004, 2005. (See http://www.roc.noaa.gov/app/TAC/members/membership.asp for TAC details)

COLLABORATORS and OTHER AFFILIATIONS

Graduate Advisors:
V. Chandrasekar and V. N. Bringi, Colorado State University, CO

M. Dixon - NCAR/RAL, Boulder, CO

S. Ellis -NCAR/EOL, Boulder, CO

G. Meymaris -NCAR/EOL, Boulder CO

M. Politovich -NCAR/RAL, Boulder CO

S. Rutledge, Colorado State University, CO

Paul Joe -Environment Canada, Downsview, Ontario Canada

R. Ice - Radar Operations Center/Air Force Weather Agency, Norman, OK

D. Saxion - Radar Operations Center/Air Force Weather Agency, Norman, OK

N. Bharadwaj -ARM, Pacific Northwest National Laboratory, Richland, WA

J. Gerlach - Atmospheric Sciences Research Facility at the NASA Wallops Island

Earle Williams –MIT Lincoln Laboratory

D. Smalley - MIT Lincoln Laboratory

D. S. Zrnic, - NSSL, Norman , OK

S. M. Torres, -CIMMS/Univ. OK, Norman ,OK

D. Warde, -CIMMS/Univ. OK, Norman ,OK

Tim Crum, NWS/Radar Operation Center, Norman, OK

G. S. Cate - NOAA?NWS NEXRAD Product Improvement Program, Norman, OK

B. Bumgarner - Aviation Weather Services Group, SAIC, Wash. DC

Steven A. Rutledge, Ph.D.

Present Position	Professor Department of Atmospheric Science Colorado State University Ft. Collins, CO 80523 (970) 491-8283	Scientific Director CSU-CHILL National Radar Facility

Professional Preparation

B.S. (1978) -	Physics, University of Missouri - St. Louis, St. Louis, Missouri
Ph.D. (1983) -	Atmospheric Science, University of Washington, Seattle, Washington

Appointments

1994 -	Professor of Atmospheric Science, Colorado State University
1999 -2006	Head, Department of Atmospheric Science, Colorado State University
1990-1994	Associate Professor, Colorado State University
1988-1990	Assistant Professor, Colorado State University
1983-1988	Assistant Professor, Oregon State University
1978-1983	Graduate Research Assistant, University of Washington

Dr. Rutledge's interests are in mesoscale meteorology, atmospheric electricity, radar meteorology and cloud physics. He is a member of the NASA PMM Science Team. He was Co-chair for the MCTEX Experiment and the STERAO-A Deep Convection Experiment. He was the Lead Scientist for the TRMM-LBA Field Campaign in Brazil and Co-PI for STEPS in 2000. He was Co-PI for the NAME field experiment radar campaign in 2004. He is a Co-PI for the Deep Convection, Clouds and Chemistry Experiment (DC3) and a PI and member of the Steering Committee for DYNAMO and PI for the shipboard radar component. He also serves as the Scientific Director of the CSU-CHILL National Radar Facility. He recently completed terms as Editor for J. Atmos. Sci., member of the UCAR Board of Trustees and Councilor of the AMS. He is a Fellow of the AMS.

Five relevant publications

S-Band Dual-Polarization Observations of Winter Storms. *J. of Appl. Meteor. and Climatology.* (P. Kennedy and S.A. Rutledge) In press.

Using CASA IP1 to Diagnose Kinematic and Microphysical Interactions in a Convective Storm. *Mon. Wea. Rev*., **138,** 1613-1634. (B. Dolan and S.A. Rutledge).

A Theory-Based Hydrometeor Identification Algorithm for X-band Polarimetric Radars. *Journal of Atmospheric & Oceanic Technology***, 46**, 1196-113. (B. Dolan, and S.A. Rutledge).

Observations of Quasi-Symmetric Echo Patterns in Clear Air with the CSU-CHILL Polarimetric Radar. *Journal of Atmospheric and Oceanic Technology*, **21**, 1182-1189. (Lang, T. J., S. A. Rutledge, and J. L. Stith).

Polarimetric Observations of Hail Formation, *Journal of Applied Meteorology*, **40**, 1347-1366. (P. C. Kennedy, S. A. Rutledge, W. A. Petersen, and V. N. Bringi).

Other related publications

Potential Role of Dual Polarization Radar in Validation of Satellite Precipitation Measurements: Rationale and Opportunities, *Bulletin of the American Meteorological Society*, **89,** 1127-1145. (Chandrasekar, V., A. Hou, E. Smith, V.N. Bringi, S.A. Rutledge, and E. Gorgucci)

A Description of the CSU-CHILL Radar Facility. *Journal of Atmospheric and Oceanic Technology*, **17**, 1596-1608. (D. Brunkow, V. N. Bringi, P. C. Kennedy, S. A. Rutledge, V. Chandrasekar, E. A. Mueller, and R. K. Bowie).

Correcting Propagation Effects in C-band Polarimetric Radar Observations of Tropical Convection Using Differential Propagation Phase. *Journal of Applied Meteorology*, **39**, 1405-1433. (L. D. Carey, S. A. Rutledge, and D. A. Ahijevych).

Synergistic Activities

As Director of CSU-CHILL Radar Facility, promote science-related outreach activities with the broader community (K-12 students, volunteer weather observers, other science and engineering academic programs outside of CSU)

Co-PI for the 2009 Remote Sensing NCAR ASP Symposium, which attracted 29 national and international graduate students to Boulder. The CSU-CHILL Facility was a key platform for this project.

Recent Collaborators & Other Affiliations
Paul Krehbiel, New Mexico Institute of Mining and Technology
Donald MacGorman, NSSL
David Rust, NSSL
Earle Williams, MIT
Edward Zipser, University of Utah
Walt Petersen, MSFC/UAH
Ph.D. Advisor Prof. Peter V. Hobbs, University of Washington (deceased, 2005)

Graduate students advised: 50 total graduate advisees. A list of advisees for the last 5 years follows.

Sarah Tessendorf, Ph.D., 2006; David Lerach, M.S., 2006; Kyoko Ikeda, M.S., 2007; Cristina Kalb, M.S., 2007; Angela Rowe, M.S., 2007; Kristin George, M.S., 2008; Richard Cullin, M.S., 2008; L. G. Pereira, Ph.D., 2008; Brenda Dolan, Ph.D., 2009

PI: Sandra E. Yuter

a. Professional Preparation

Brown University	Geology-Physics/Mathematics	B. S., 1983
University of Washington	Atmospheric Sciences	Ph. D., 1996

b. Appointments

2011-	Professor, Department of Marine, Earth, and Atmospheric Sciences, North Carolina State University, Raleigh, NC
2007-11	Associate Professor, Department of Marine, Earth, and Atmospheric Sciences, North Carolina State University, Raleigh, NC
2005-07	Assistant Professor, Department of Marine, Earth, and Atmospheric Sciences, North Carolina State University, Raleigh, NC
2004-05	Research Associate Professor, Department of Atmospheric Sciences, University of Washington, Seattle, WA
1999-04	Research Assistant Professor, Department of Atmospheric Sciences, University of Washington, Seattle, WA
1996-99	Research Scientist, Mesoscale Group, Department of Atmospheric Sciences, University of Washington, Seattle, WA
1988-90	Software Engineer III, Research Data Program, National Center for Atmospheric Research, Boulder, CO
1986-88	Technical Marketing Engineer, Graphics Division, Symbolics Inc., Los Angeles, CA
1983-86	Member of Technical Staff, Data Systems Laboratory, TRW Defense Group, Redondo Beach, CA

c. Publications

(i) Recent

Allen, G., G. Vaughan, T. Toniazzo, H. Coe, P. Connolly, S. E**.** Yuter**,** C. D. Burleyson, P. Minnis, and J. K. Ayers, 2012: Gravity wave--induced perturbations in marine stratocumulus, *Q. J. Roy. Met. Soc.*, conditionally accepted.

Biasutti, M., S. E. Yuter, C. D. Burleyson, and A. H. Sobel, 2011: Very high resolution rainfall patterns measured by TRMM Precipitation Radar*. Climate Dynamics*. 1-20, doi: 10.1007/s00382-011-1146-6

Holder, C. T., S. E. Yuter, A. H. Sobel, and A. Aiyyer, 2008: The mesoscale characteristics of tropical oceanic precipitation during Kelvin waves and mixed-Rossby gravity waves. *Mon. Wea. Rev*., **9**, 3446-3464.

McConnell, D. A., S. E. Yuter, C. D. Burleyson, N. R. Hardin, K. Ryker and J. A. Stempien, 2011: Building successful self-regulated learners: What 2000+ students have to tell us. *Abstracts, 2011 GSA Annual Meeting*, 9–12 October 2011, Minneapolis, MN.

Mechem, D. B., S. E. Yuter, and S. P. deSzoeke, 2012: Thermodynamic and aerosol controls in Southeast Pacific stratocumulus*. J. Atmos. Sci*., in press.

Miller, M. A., and S. E. Yuter, 2008: Lack of correlation between chlorophyll a and cloud droplet effective radius in shallow marine clouds. *Geophys. Res. Lett*., 35, L13807, doi:10.1029/2008GL034354.

Smith, B. L., S. E. Yuter, P. J. Neiman, and D. E. Kingsmill, 2010: Water vapor fluxes and orographic precipitation over Northern California associated with a land-falling atmospheric river. *Mon. Wea. Rev*., **138**, 74-100.

Sobel, A. H., C. D. Burleyson, and S. E. Yuter, 2011: Rainfall on small tropical islands. *J. Geophysical Research,* **116**, D08102, doi:10.1029/2010JD014695.

Sukovich, E. M., D. E. Kingsmill, and S. E. Yuter, 2009: Variability of graupel and ice crystal aggregates observed in tropical oceanic convection by aircraft during TRMM KWAJEX. *J. Appl. Meteor. Clim*., 48, 185-198.

Yuter, S. E., D. A. Stark, J. A. Crouch, M. J. Payne and B. A. Colle, 2011: The impact of varying environmental conditions on the spatial and temporal patterns of orographic precipitation over the Pacific Northwest near Portland, Oregon. *J. Hydrometeorology*, **12**, 329-351.

d. Synergistic Activities

Courses taught: Graduate level: Atmospheric Convection (even numbered years), Dynamics of Mesoscale Precipitation Systems (odd numbered years); Undergraduate level: Introduction to Atmospheric Sciences I (every year), Introduction to Meteorological Remote Sensing (every year).

Involvement of undergraduates in research activities: PI trains and supervises 1-3 undergraduate research assistants a year to work on field studies and observational data processing and analysis. Undergraduate students supervised to date include 6 women and 1 disabled student.

Recent field project experience: (winter 2011-12) The Wasatch Hydrometeor Aggregation and Riming Experiment: Alta, Utah; (2010) ISPA: Steamboat Springs, CO, (2008) VOCALS Rex: Southeastern Pacific.

e. Collaborators and Other Affiliations

(i) Collaborators

G. Allen	U. Manchester
J. K. Ayers	NASA
M. Biasutti	Columbia
J. Blaes	NWS
A. Brewer	NOAA ESRL
C. D. Burleyson	NCSU
H. Coe	U. Manchester
B. A. Colle	Stonybrook U.
P. Connolly	U. Manchester
J. Cunningham	NCSU
S. deSzoeke	Oregon State
S. Ellis	NCAR
C. Fairall	NOAA ESRL
D. Freeman	NCSU
K. Friedrich	U. Colorado
T. Garrett	U. Utah
A.M. Hall	NCSU
N. Hardin	NCSU
M. Hughes	NOAA ESRL
D. Kingsmill	NOAA ESRL
D. Leon	U. Wyoming
Y. Lin	GFDL
D. McConnell	NCSU
D. Mechem	U. Kansas
M. Miller	Rutgers U.
M.A. Miller	NCSU
P. Minnis	NASA
B. Moore	NOAA ESRL
P. Neiman	NOAA ESRL
K. Ryker	NCSU
B. L. Smith	NWS
A. Sobel	Columbia
D.A. Stark	StonybrookU.
J.A. Stempien	U. Colorado
E. Sukovich	NOAA ESRL
T. Toniazzo	U. Reading
G. Vaughan	U. Manchester
D. Waliser	JPL
C. White	NCSU
M. Wilbanks	NCSU
R. Wood	U. Washington
P. Zuidema	U. Miami

(ii) Graduate Advisor: Robert Houze, University of Washington

(iii) Thesis Advisor: 13 graduate student advised. University of Washington: Kimberly Comstock (Ph.D. 2006, Global Energy Concepts), NCSU: Justin Crouch (M.S.2009), Christopher Holder (M.S. 2007, ICF International), Matthew Miller (M.S. 2007, Ph.D.2010), M. Jordan Payne (M.S. 2007, Weather Inc.), Kate Rowjowsky (M.S 2010), Barrett Smith (M.S. 2007, NWS), current students: Casey Burleyson (Ph.D), Jeff Cunningham (Ph.D.), Margaret Grey (M.S.), Andrew Hall (M.S), Nathan Hardin (Ph.D), Matthew Wilbanks (M.S.)

CURRENT AND PENDING:

Katja Friedrich

Supporting Agency	Project Title	Total Award	Period Covered	Academic Months	Summer Months	Location
Current						
NSF	A 10-yr climatology (1999-2009) on 4-dimensional precipitation characteristics in the European Alps	$413,811	01/01/2010-12/31/2012	0	2	CU Boulder
NSF	Analysis of Particle Size Distribution in Supercell Thunderstorm	$380,426	06/15/2010-06/14/2013	0	0.5	CU Boulder
Pending						
None						
This submission						
NSF	Front Range Radar Observing Network Testbed - Precipitation Observations and Research on Convection and Hydrometeorolog	$0	05/15/2013-08/15/2013	0	0	NCAR

David Gochis:

Current and Pending Support

Investigator: David Gochis	Other agencies (including NSF) to which this proposal has been/will be submitted.

Support: ☒Current ☐Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: Development of Hybrid 3-D Hydrological Modeling for the NCAR Community Earth System Model (CESM)

Source of Support: Department of Energy

Total Award Amount: $180,000 Total Award Period Covered: 11/1/2011-10/31/2014

Location of Project: Boulder, Colorado

Person-Months Per Year Committed to the Project. Cal: .36 Acad: Sumr:

Support: ☒Current ☐Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: Improved Hydrometeorological Forecasting Through Physically-Based Distributed Models

Source of Support: Arizona State University

Total Award Amount: $44,307 Total Award Period Covered: 5/1/2009-4/30/2012

Location of Project: Boulder, Colorado

Person-Months Per Year Committed to the Project. Cal: .12 Acad: Sumr:

Support: ☒Current ☐Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: Fusing NASA Remote Sensing Products, NWP Models and Distributed Hydrological Models to Improve Probabilistic Flash Flood Decision Making

Source of Support: NASA

Total Award Amount: $304,734 Total Award Period Covered: 1/1/2010-12/31/2012

Location of Project: Boulder, Colorado

Person-Months Per Year Committed to the Project. Cal: .36 Acad: Sumr:

Support: ☒Current ☐Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: Sensitivity of Hydrologic Impacts Assessment to Downscaling Methodology and Spatial Resolution

Source of Support: Department of the Interior

Total Award Amount: $480,148 Total Award Period Covered: 10/1/2010-9/30/2013

Location of Project: Boulder, Colorado

Person-Months Per Year Committed to the Project. Cal: 1.32 Acad: Sumr:

Current and Pending Support

Investigator: David Gochis (page 2)	Other agencies (including NSF) to which this proposal has been/will be submitted.

Support ☒Current ☐Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: The Role of Land Surface Physics in Controlling Intraseasonal Precipitation Variability over Complex Terrain

Source of Support: Arizona State University

Total Award Amount: $153,662 Total Award Period Covered: 1/1/2010-12/31/2012

Location of Project: Boulder, Colorado

Person-Months Per Year Committed to the Project. Cal: .96 Acad: Sumr:

Support ☒Current ☐Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: Improved Seasonal Streamflow Forecasts in the Rio Sonora Basin

Source of Support: Arizona State University

Total Award Amount: $36,973 Total Award Period Covered: 5/1/2009-7/31/2012

Location of Project: Boulder, Colorado

Person-Months Per Year Committed to the Project. Cal: .96 Acad: Sumr:

Support ☒Current ☐Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: ETBC: Collaborative Research: Quantifying the Effects of Large-Scale Vegetation Change on Coupled Water, Carbon and Nutrient Cycles: Beetle Kill in Western Montane Forests

Source of Support: NSF - Geosciences

Total Award Amount: $189,379 Total Award Period Covered: 8/1/2009-7/31/2012

Location of Project: Boulder, Colorado

Person-Months Per Year Committed to the Project. Cal: .96 Acad: Sumr:

Support ☐Current ☒Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: Collaborative Research: Processes and Patterns in the North American Monsoon Macrosystem

Source of Support: University of Arizona

Total Award Amount: $96,745 Total Award Period Covered: 4/1/2011-3/31/2016

Location of Project: Boulder, Colorado

Person-Months Per Year Committed to the Project. Cal: .6 Acad: Sumr:

Current and Pending Support

Investigator: David Gochis (page 3)	Other agencies (including NSF) to which this proposal has been/will be submitted.

Support: ☐ Current ☒ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: Distributed Research Infrastructure for Hydro-Meteorology – United States of America

Source of Support: European Union

Total Award Amount: $0 (NSF co-sponsorship) Total Award Period Covered: 2/1/2012-1/31/2015

Location of Project: Boulder, Colorado

Person-Months Per Year Committed to the Project. Cal: .6 Acad: Sumr:

Support: ☐ Current ☒ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: Evapotranspiration Partitioning Across the North American Monsoon Region using Isotopic Measurements and the Noah-MP Land Surface Model

Source of Support: University of Arizona

Total Award Amount: $0 (NSF co-sponsorship) Total Award Period Covered: 8/1/2012-7/31/2015

Location of Project: Boulder, Colorado

Person-Months Per Year Committed to the Project. Cal: .6 Acad: Sumr:

Support: ☐ Current ☒ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: Collaborative Research: Developing Cyberinfrastructure Standards for Hydrometeorology

Source of Support: NSF

Total Award Amount: $346,705 Total Award Period Covered: 16/1/2012-5/31/2015

Location of Project: Boulder, Colorado

Person-Months Per Year Committed to the Project. Cal: 1.2 Acad: Sumr:

Support: ☐ Current ☒ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: WSC – Category 3: Collaborative Research: Snowpack and Ecosystem Dynamics: The Sustainability of Inter-Basin Water Transfers under a Changing Climate

Source of Support: NSF

Total Award Amount: $482,803 Total Award Period Covered: 6/1/2012-5/31/2016

Location of Project: Boulder, Colorado

Person-Months Per Year Committed to the Project. Cal: .6 Acad: Sumr:

Steve Rutledge:

Current Support for Steven A. Rutledge

Supporting Agency	Point of Contact	Project Title	Award Amount	Role	Period of Project	PI Months
NSF Subcontract from University of Massachusetts		ERC: The Center for Collaborative Adaptive Sensing of the Atmosphere	$358,646 Additional funding expected	Co-PI	10/1/03 - 08/31/11	0.5 academic
National Science Foundation	Jim Huning (703) 292-000 jhuning@nsf.gov	The CSU-CHILL Radar Facility	$3,687,210	PI	09/01/07 - 08/31/12 (NCE)	1.5 academic
National Science Foundation	Alex Pszenny (703) 292-8522 apszenny@nsf.gov	Collaborative Proposal: Deep Convective Clouds and Chemistry (DC3). Science Program Overview.	$19,933	PI	09/15/2010 – 08/31/2012	0.5 academic
National Aeronautics and Space Administration	Matt Schwaller (301) 614-5382 Mathew.schwaller@nasa.gov	GPM Ground Validation Studies at Colorado State University.	$70,922	PI	11/26/2010 – 11/25/2012 (NCE)	0.0
National Aeronautics and Space Administration	Dr. Ramesh Kakar (202) 358-0240 ramesh.kakar@nasa.gov	Studies of Convection and Precipitation Physics Under PMM	$550,000	PI	03/19/10 – 03/18/13	0.5 Summer 0.5 academic
Defense Advanced Research Projects Agency (DARPA)	Steven Cummer (919) 660-5256 cummer@ee.duke.edu	Physical Origins of Coupling to the Upper Atmosphere from Lightning (PhOCAL)	$305,256	Co-PI	07/01/2010 – 05/31/2013	0.5 Summer
National Science Foundation	Nicholas Anderson (703) 292-4715 nanderso@nsf.gov	Electrification and Lightning in Convective and Mesoscale Precipitation	$818,017	PI	09/01/2010 – 08/31/2013	1.0 academic
National Science Foundation	Steve Nelson (703) 292-8524 snelson@nsf.gov	Ship and Island Based Radar Observations in DYNAMO	$1,171,889	PI	05/01/2011 – 04/30/2014	1.0 Academic
Department of Energy (DOE)	Ashley Williamson (301) 903-3120 Ashley.williamson@science.doe.gov	Use of DOE SGP Radars in Support of ASR Modeling Activities.	$526,520	PI	09/15/2011 – 09/14/2014	1.0 Summer
National Science Foundation	Jim Huning (703) 292-0000 jhuning@nsf.gov	The CSU-CHILL National Facility	$2,829,384	PI	11/15/11 – 10/31/14	1.5 academic

Pending Support for Steven A. Rutledge

National Aeronautics and Space Administration		GPM Ground Validation Studies at Colorado State University.	$70,000	PI	01/01/2012 – 12/31/2012	0.0

Current and Pending Support:
Sandra E. Yuter, North Carolina State University

Current

Title: Collaborative Research: Ship-based Observations of air-sea interactions and stratocumulus cloud-aerosol-drizzle processes in VOCALS
Source of support: NOAA
Total amount of award: $298,764
Award period: 7/1/2008 – 6/30/12
Location of project: North Carolina State University, Summer salary/year: 0.5 months

Title: Collaborative Research: Intermittent and steady state processes in orographic precipitation
Source of support: National Science Foundation
Total award amount: $345,879
Award period: 9/1/2009- 8/31/12
Location of project: North Carolina State University, Summer salary/year: 0.5 months

Title: NASA Earth and Space Science Fellowship (NESSF) Program—Casey Burleyson
Source of support: NASA
Total amount of award: $60,000
Award period: 9/1/2010-8/31/2012
Location of project: North Carolina State University, Summer salary/year: 0 months

Title: Global characteristics of marine stratocumulus clouds and drizzle
Source of support: NASA
Total amount of award: $337,985
Award period: 02/08/2011-02/07/2014
Location of project: North Carolina State University, Summary salary/year: 0.5 months in Yr1, 1 month in Yrs 2 and 3

Title: Collaborative Research: Cloudiness transitions within shallow marine clouds near the Azores
Source of support: DOE
Total amount of award: $510,182
Award period: 10/01/2011-09/30/14
Location of project: North Carolina State University, Summary salary/year: 0.75 months in Yr1, 1 month in Yrs 2 and 3

Title: Spatio-temporal patterns of precipitation and winds in California
Source of support: NOAA
Total amount of award: $60,705
Award period: 7/01/2011 – 6/30/13
Location of project: North Carolina State University, Summer salary/year: 0.5 months

Title: Collaborative Research: The Wasatch Hydrometeor Aggregation and Riming Experiment
Source of support: National Science Foundation
Total award amount: $129,546
Award period: 9/1/2011- 8/31/2014
Location of project: North Carolina State University, Summer salary/year: 0.5 months in yr 1, 0.25 in yrs 2 and 3

Pending

Title: Simulation of the MJO using the Navy global model: Impacts of Stochastic Cumulus Parameterizations
Source of support: Office of Naval Research
Total award amount: $123,105
Award period: pending
Location of project: North Carolina State University, Summer salary/year: 0.25 months in each of three years.