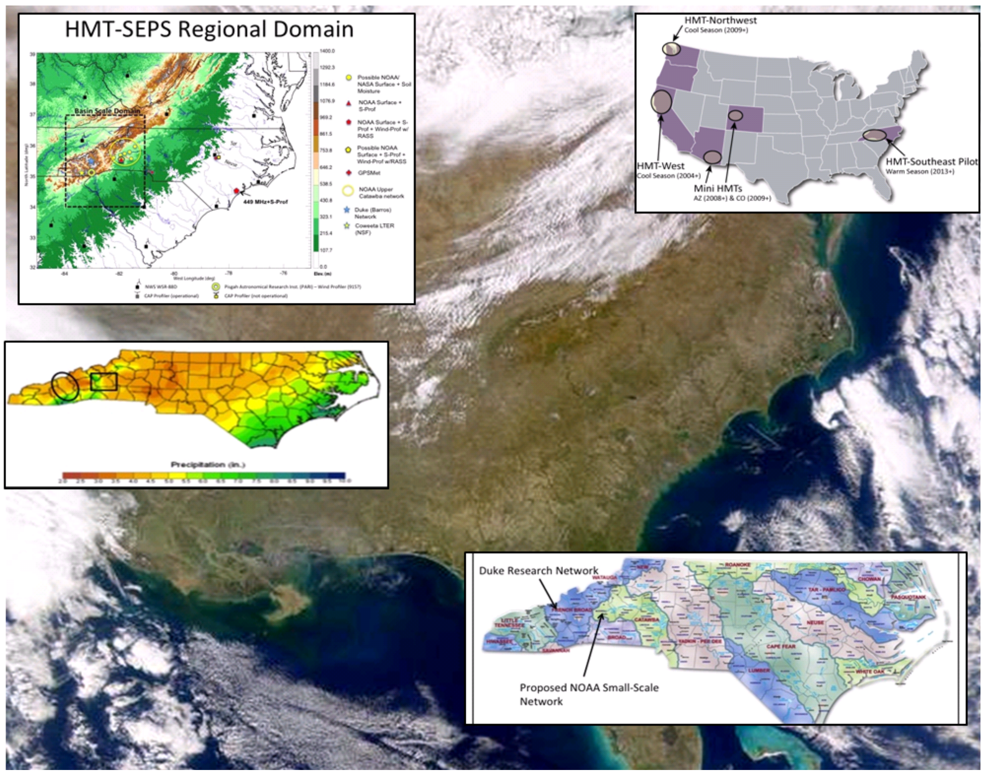
NOAA HMT-SE Science Plan: 2013-2014 Pilot Study



Rob Cifelli
Kelly Mahoney
Ellen Sukovich
Ben Moore
Lynn Johnson
Ana Barros
Walt Peterson

Updated April 2013

NOAA HMT-SE Science Plan: 2013-2014 Pilot Study

Rob Cifelli[1], Kelly Mahoney[2], Ellen Sukovich[2], Ben Moore[2], Lynn Johnson[3], Ana Barros[4], and Walt Petersen[5]

Executive Summary

The HMT-SE Pilot Study (HMT-SEPS) is a field project planned for May 2013 – October 2014 in western North Carolina. The project represents an initial step toward addressing the scientific questions articulated by earlier planning efforts in 2009 to define a fuller-scope HMT-SE research agenda (Schneider 2009a, b). HMT-SEPS will be largely focused on quantitative precipitation estimation (QPE) and Quantitative Precipitation Forecasting (QPF) in western portions of North Carolina, but some instrumentation in central and eastern North Carolina will allow for HMT-related study across a wider region as well. Complementary research on southeast U.S. extreme precipitation events and improved characterization of moisture sources and transport will also be conducted, with a particular focus on gaps and opportunities for improvement in the QPF of such events. The combined efforts of the HMT-SEPS field project and the accompanying QPF-related research efforts will together run from spring 2012 through spring 2015.

For the HMT-SEPS field project, NOAA will bring a number of instrument assets to the region and leverage additional assets from the NASA ground validation campaign occurring in the same vicinity. Instruments from existing operational and academic institutions (e.g., Duke University) will also be used. The combined infrastructure will provide an opportunity to evaluate the baseline skill of existing QPE systems, improve algorithms, and test new technologies within HMT's overall QPE activities. NOAA assets that will be brought to the campaign include:

- Four wind-profiling radar sites (including 915-MHz and 449-MHz vertically-pointing S-band radars for diagnosis of both wind field and precipitation vertical structure);
- Six surface sites with standard meteorology sensors (temperature, relative humidity, pressure, wind, and redundant precipitation-measuring instruments) as well as soil moisture and soil temperature (5-levels) sensors; and
- Repair of the Raleigh, NC 915-MHz Cooperative Agency Profiler (CAP) profiler and an upgrade to the software of the both Raleigh, NC and the existing Charlotte, NC CAP to improve clutter mitigation and melting level detection.

The full scope of HMT-SEPS (~$500k from NOAA HMT) will include the deployment of instrumentation and data collection in May 2013 through October 2014, as well as QPE-QPF analysis extending into spring 2015. This science plan outlines objectives and deployment plans for HMT-SEPS, as well as additional research directions focused on improved understanding of regional heavy precipitation events and associated QPF challenges in the southeast U.S. Opportunities for growing these preliminary efforts upscale via collaboration with interested partners to enhance the HMT-SEPS project are also discussed.

It is envisioned that the efforts outlined here will result in both technical documentation and peer-reviewed publication of QPE and QPF-related study findings. Archival of precipitation data sets in standard formats is anticipated; these data would be available to academic and other researchers. Cross-sector collaboration via academic, private, and government partnerships will help to ensure that operational utility is gained from these initial efforts, and such collaboration may be critical in laying the foundation for ongoing work and support for establishing a long-term presence in the southeast.

[1] NOAA ESRL
[2] CIRES/University of Colorado/NOAA ESRL
[3] CIRA/Colorado State University/NOAA-ESRL
[4] Duke University
[5] NASA MSFC

Organization

I. Introduction

The NOAA Hydrometeorology Testbed (HMT) conducts research on precipitation and weather conditions that can lead to flooding and flash flooding, and fosters transition of scientific advances and new tools into forecasting operations. The HMT concept consists of a series of demonstration projects in different geographical regions to enhance understanding of region-specific processes related to precipitation. HMT-West is the first regional demonstration of the HMT implementation strategy, with activities beginning in 2004 (Fig. 1).

In an effort to broaden the impact of HMT's research findings and test existing and new hypotheses related to orographic precipitation in different regions, HMT is planning to conduct operations in the southeast U.S. (hereafter referred to as HMT-SE). An HMT-SE Pilot Study (HMT-SEPS) is planned as an extended field project May 2013 – October 2014 focused in western North Carolina. The project represents an initial step toward addressing the scientific questions articulated by earlier planning efforts in 2009 to define a fuller-scope HMT-SE research agenda (Schneider 2009 a, b). Although a longer-term presence in the southeast is desirable, current budget constraints limit the overall scope of effort that can be achieved at present. It is hoped that the pilot project will provide an initial step towards long operations in the southeast region, similar to the way HMT-West was started in California (see http://hmt.noaa.gov/field_programs/hmt-west/).

HMT-SEPS will be largely focused on quantitative precipitation estimation (QPE), one of HMT's five major activity areas. In particular, the effort will consist of baseline evaluations of QPE systems as well as an opportunity to improve QPE algorithms toward developing the best possible QPE forcing to operational users, including the National Water Center, as described in HMT's QPE work plan (HMT 2011). Complementary research on southeast US extreme precipitation events and improved characterization of moisture sources and transport will also be conducted, with a particular focus on knowledge gaps and opportunities for improvement in the QPF of such events. The pilot project could also include an effort dedicated to hydrologic applications and surface processes (HASP), which would complement the QPE effort; however, the scope of HASP activities would depend on securing additional funds for the overall pilot project effort.

HMT-SEPS will complement a similar effort by NASA to validate precipitation retrieval algorithms in the same region of North Carolina from the Global Precipitation Measurement (GPM) satellite constellation (Barros et al. 2011). The NASA field campaign is referred to as the GPM Integrated Precipitation and Hydrology Experiment (IPHEX). In fact, NASA's motivation for leading a validation campaign in the southeast is driven primarily by the desire to partner with NOAA HMT in precipitation research activities. In turn, the majority of HMT-SEPS instrumentation will be focused in the complex terrain region of western North Carolina to leverage NASA's on-going ground validation (GV) activities in an area of orographic terrain where an existing network of ground based sensors currently exists (Barros et al. 2011). IPHEX will involve NASA, NOAA (ESRL, NSSL, OHD), and academic partners (University of Iowa, Duke University, and others). HMT-SEPS is also intended to serve an important role as part of NOAA's GPM Proving Ground, where algorithms that utilize GPM data can be developed, improved, and evaluated prior to implementation in NOAA operations.

NOAA, NASA, and academic partners will bring a number of instrument assets to HMT-SEPS so that significant leveraging of resources can occur; these connections are described in Sec. VI and VII. Although NOAA's emphasis will be on basin scale QPE processes in the Appalachian mountain region, instrumentation is also planned in selected locations across the state (i.e.,the piedmont and coastal plain), toward providing a larger-scale network that extends from the Appalachian Mountain region to the Atlantic coast. Archival of precipitation data sets in standard formats is also anticipated; these data would be available to academic and other researchers for additional/future research.

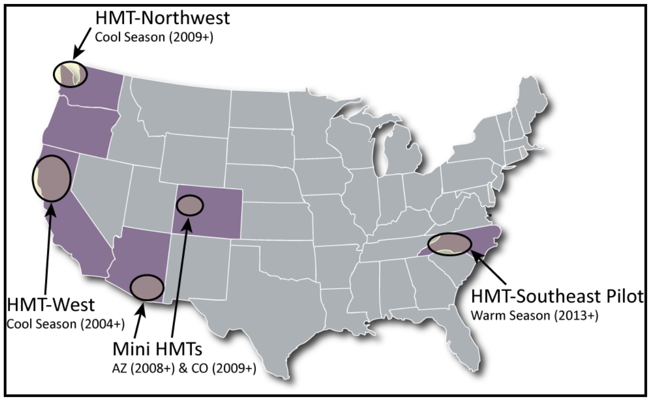


Figure 1. Location of current and future HMT activities.

II. NOAA Requirements, Objectives, and Deliverables for HMT-SEPS

NOAA's requirements for HMT-SEPS are primarily focused on QPE, with some funding available for research focusing on QPF and heavy precipitation processes. If additional funding is acquired, the project scope may be expanded to include more work on QPF-related research, as well as the impact of QPE and QPF on hydrologic applications and surface processes (HASP; HASP objectives are documented in Appendix A.) Together, QPE, QPF, and HASP constitute 3 of the 5 major activity areas for HMT (see hmt.noaa.gov).

The objectives defined below stem from one of the grand science challenges identified by the NOAA Science Workshop Committee 2010:

"*Improve understanding of the water cycle at global to local scales to improve our ability to forecast weather, climate, water resources and ecosystem health.*"

Many of the specific QPE and QPF objectives were identified in the HMT-SE Operational Needs and Requirements Workshop (Schneider 2009a) and are identified in blue text.

QPE

QPE objectives to be addressed in HMT-SEPS include:

- Support the National Weather Service (NWS) adaptation and use of polarimetric algorithms for the impending upgrade of the WSR-88D radar network (e.g., evaluate the NWS radar-rainfall algorithms and participate in training to share experience with dual polarimetric radar); and
- Evaluate and improve QPE systems (Multisensor Precipitation Estimates (MPE), Multiple-Radar/ Multiple-Sensor (MRMS), Stage IV, and others as appropriate) in terrain regions extending from the Appalachian mountains to the piedmont to coastal plain. Planned research topics in this area include:
  - intelligent integration of multi-sensor QPE information for gauges, radars, and satellite;
  - infrared (IR) and microwave satellite QPE products (CMORPH, SCaMPR, Hydro-Estimator, TRMM 2A25 and 3B42) with ground-based QPE;
  - 4-D structure of precipitation and variability of the drop size distribution (DSD) with resulting impact on QPE systems (e.g., appropriate Z-R (selection); and
  - impact of gap-filling radars on QPE systems

QPF

QPF objectives to be addressed in HMT-SEPS include:

- Improve the understanding of region-specific physical processes impacting QPF, e.g.,
  - moisture transport from multiple moisture source regions
  - interaction of pre-existing precipitation systems with terrain and/or with topographically-driven thermal boundaries
- Analyze climatology and event classification toward improving understanding of large-scale dynamics and mesoscale processes associated with extreme precipitation;
- Facilitate researcher and forecaster collaboration to
  - (i) clarify fundamental physical processes/environmental parameters affecting regional precipitation patterns and extreme precipitation;
  - (ii) identify human and model QPF challenges; and
  - (iii) identify new or improved tools, definitions and classifications to connect relevant research findings to benefit operational forecasting;

- Evaluate impact of observations from the HMT-SEPS NOAA and NASA instrument networks on data assimilation and resulting QPF [pending regional applicability of HMT-SEPS and collaboration with larger modeling efforts]

Planned deliverables

By May 2015, it is anticipated that HMT-SEPS activities will result in:

- technical documentation and peer-reviewed publication of QPE and QPF-related study findings
- workshop and conference presentations on significant project findings
- archival of precipitation data sets in standard formats for use by academic and other researchers
- strategies for continuing HMT-SE beyond HMT-SEPS and fostering ongoing operations-to-research-to-operations ("O2R2O") partnerships

The ultimate scope of this project is largely dependent upon the fruition of partnerships and collaborations to maximize the limited NOAA HMT budget. The above set of deliverables is conservative based on the current level of funding and personnel available in NOAA HMT. Leveraging the interest, experience, and resources of other groups may allow the outcomes and scope of this work to grow considerably.

III. Rationale for HMT-SEPS Selected Study Area

The HMT-SEPS field study is designed to study primarily QPE in a region of complex terrain and moderate orography (elevations < 2000m). The domain region of western North Carolina was chosen for the HMT-SEPS field study region for several reasons, including:

- it is a region where known QPE and QPF biases occur;
- a variety of precipitation regimes occur in the region; and
- there exists an infrastructure of precipitation and hydrologic instrumentation to leverage for examination of orographic hydrologic processes.

Orographic precipitation in the Appalachians has been shown to present major challenges for QPE and QPF. Prat and Barros (2010) reported an overall bias of TRMM PR 2A25 against measurements from a high-density rain gauge network in the Smoky Mountains of up to 60% for heavy precipitation events in this region, whereas 80% of missed rainfall corresponds to the light rainfall category (< 2mm hr^{-1}). Numerous studies have documented specific QPF challenges for the region, encompassing all seasons and weather system types (e.g., Keeter et al. 1995; Bailey et al. 2003; Gaffin et al. 2003; Green 2005; Atallah and Bosart 2007; Mahoney and Lackmann 2007; Keighton et al. 2009; Srock and Bosart 2009; Letkewicz and Parker 2010; Miller 2012).

Over the Southern Appalachians, precipitation patterns are largely dependent upon the track of both tropical and extratropical synoptic-scale systems, as well as smaller-scale features associated with the terrain itself (e.g., Appalachian cold-air damming, wedge fronts, lee troughs, etc.). Extratropical synoptic-scale systems typically approach the region from the west/northwest or the south, while tropical cyclones often approach from the south or the east. As a system approaches the southern Appalachian mountains, the interaction of the moist low-level flow associated with the system and the terrain generally determines the location of precipitation maxima. In the far southwestern corner of North Carolina, the annual average precipitation is more than 90 inches, often resulting from moist southerly winds associated with either extratropical or tropical systems being forced upward over the mountainous terrain. When an easterly component of the low-level winds increases, the orographic precipitation is focused further to the east, resulting in enhanced precipitation in the Catawba river basin (Fig. 2). While moist, easterly, upslope winds determine a significant portion of warm-season precipitation in the HMT-SEPS field study region, existing precipitation systems also enter the region from the west, as often occurs with mesoscale convective systems (MCSs) and even warm-season cold fronts. An additional factor affecting the regional meteorological variability is the source of moisture, as the Gulf of Mexico, Atlantic Ocean, Caribbean Sea, and even the tropical Pacific Ocean (e.g., Moore et al. 2012) can serve as major contributors of moisture, with the relative role of each largely determined by the synoptic-scale pattern, the tracks of individual weather systems, and the resulting low-level wind field. The potential to have precipitation under varied large-scale set-ups provides considerable forecast and observational challenges, and underscores the motivation for examining this complex region in further detail.

Despite a noteworthy body of scientific literature devoted to the meteorology of this region, fundamental questions persist regarding the impact of the Appalachian Mountains on regional rainfall patterns, processes, and amounts. For example, determining the maintenance of precipitation systems crossing the Appalachians (e.g., Letkewicz and Parker 2009) as well as where and why precipitation initiates within the region remain challenging questions. A nocturnal low level jet (LLJ) that may occur on either or both the east/west sides of the southern Appalachians is yet another feature that may play an important role in the diurnal cycle of rainfall on analysis of profile observations in the Mid-Atlantic states but is not well-understood (Zhang et al. 2006; Parker and Ahijevych 2007).

While this region faces precipitation measurement and forecasting challenges year-round in both the cold and warm season, the warm season is selected as the focus for HMT-SEPS. A large variety of precipitation regimes will thus be examined, including: extratropical baroclinic systems; MCSs, tropical systems, in addition to less organized, relatively-isolated convective precipitation events. However, as instruments will remain in the field between the 2013 and 2104 warm seasons, measurements will be made during the cold season as well, and those data will also be made available to interested groups.

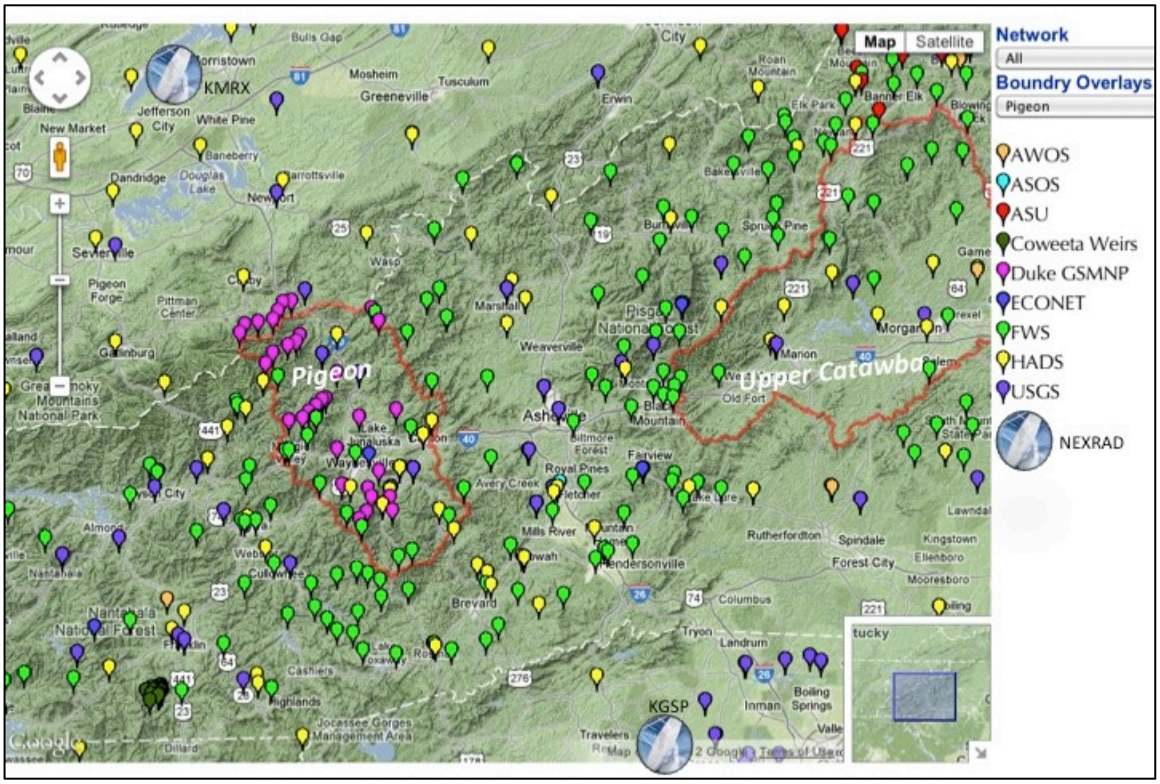


Figure 2. Location of select existing instrumentation in western North Carolina for hydrometeorological research. Pigeon and Upper Catawba watersheds are outlined in red. Marker colors refer to different networks as indicated in the legend ("Duke GSMNP" are NASA PMM rain gauge locations). Network data courtesy of Ana Barros.

IV. Proposed Timeline of HMT-SEPS (2012 – 2015)

The overall timeline for HMT-SEPS begins in 2012 and is currently planned through the first quarter of 2015. Figure 3 illustrates the three main task areas (Instrument Deployment, QPE Analysis based on HMT-SEPS data, and QPF analysis). Planning and preparation for the HMT-SEPS instrument deployment will begin in the summer of 2012, and the official data collection period will span May 2013 – October 2014. NASA's IPHEX campaign will last approximately six weeks, with an intended May 2014 start date. QPE analysis will be performed as the HMT-SEPS data is collected, and these efforts will continue through May of 2015. QPF research efforts are underway as of January 2012, and will continue at a relatively steady effort level through the spring of 2015.

During this time, engagement of interested regional partners will be solicited. Such synergistic efforts could range from simply the use of the HMT-SEPS data collected, to full-fledged university research projects, and/or focused operational testing and integration efforts. Particularly as the HMT-SEPS pilot study and initial research efforts get underway, there could also be ideal opportunities for those well-poised to address specific O2R2O-type challenges (e.g., the CSTAR program). As research goes forth, if a focus on O2R2O-type challenges emerges as an area of desired emphasis for ongoing work, efforts could include forecast simulation experiments similar to those carried out by NCEP's Weather Prediction Center (WPC)'s Winter Weather Experiment, NSSL's Spring Experiment, the Atmospheric River Retrospective Forecasting Experiment (ARRFE; conducted by HMT and WPC in the Fall of 2012), and the Flash Flood and Intense Rainfall (FFaIR) experiment planned by WPC for July 2013.

Beyond the spring of 2015, NOAA's funding environment and regional partner interest will largely determine the ongoing scope and longevity of HMT-SE. It is anticipated that HMT-SE (i.e., the larger entity beyond the 16-month HMT-SEPS endeavor) will be reassessed and re-scoped as new resources are identified.

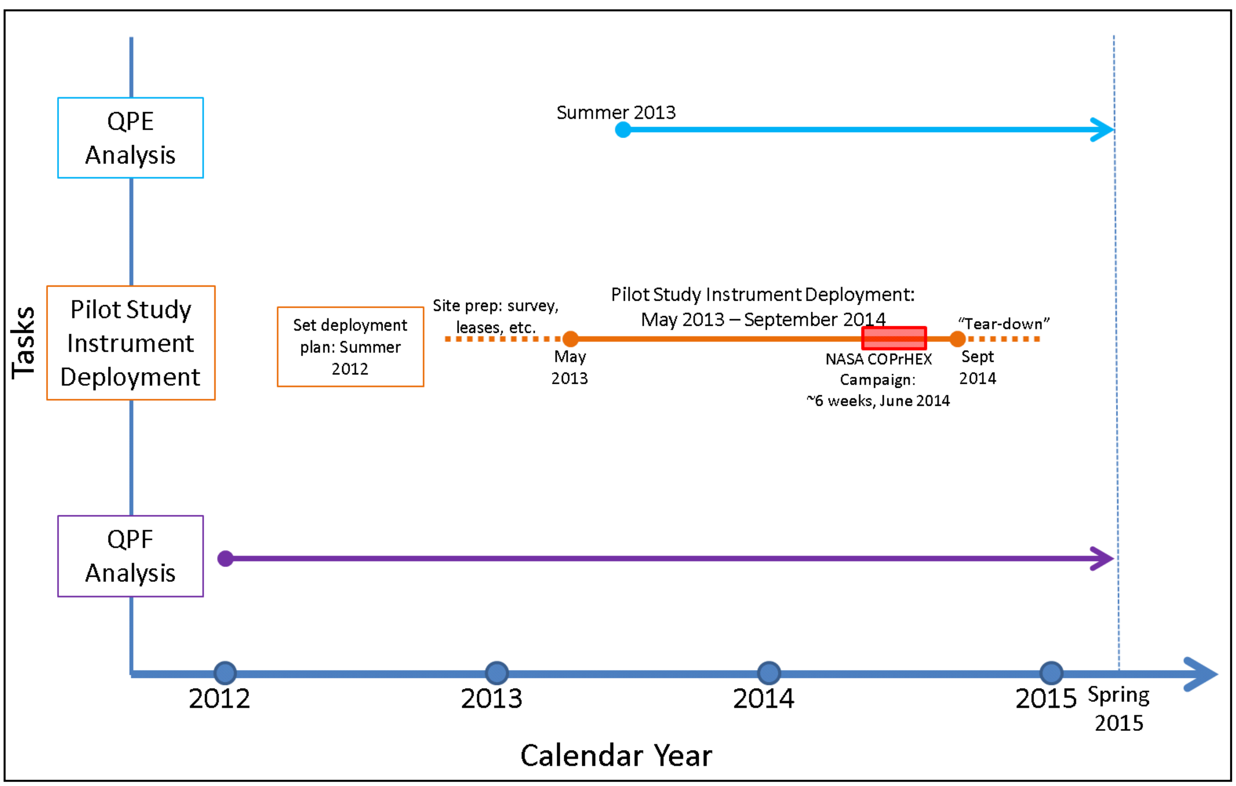


Figure 3: Proposed timeline for HMT-SEPS analysis and research efforts.

V. QPE Summary and Science Questions

Robust information regarding both the magnitude and uncertainty of QPE is required by operational forecasters in order to produce skillful hydrologic simulations of stream discharge, to issue flood warnings to the public, and improve overall situational awareness (Ciach et al. 2007). This is especially true in mountainous regions, where the combination of steep terrain and heavy rainfall is conducive to flash flooding. Recent studies (e.g., Min et al. 2011) have shown that climate change may increase the occurrence of extreme precipitation events over time, further highlighting the need for reliable QPE. The situation over complex terrain is even more challenging, given the low density of observations, sharp, topographically-forced precipitation gradients, complex microphysical processes resulting from the interaction of precipitation producing processes with orography, and limitations in the existing operational NEXRAD radar network design (including areal coverage)

NOAA objectives for QPE within HMT-SEPS are described above in Sec. II and are intended to support the NOAA GPM Proving Ground concept (currently under development), which is a joint initiative across NOAA National Environmental Satellite Data and Information Service (NESDIS), NWS, and Oceanic and Atmospheric Research (OAR) to develop, improve, and evaluate QPE algorithms utilizing GPM data prior to implementation in NOAA operations. Barros et al. (2011) describe the relevant NASA activities targeted for IPHEX. These activities include both integrated validation and physical validation. Broadly speaking, "integrated validation" aims to improve understanding of the time and space scales where GPM satellite data are useful for hydrologic prediction, and "physical validation" refers to improvement in precipitation retrieval algorithms through error characterization and better understanding of precipitation microphysics. These NASA objectives are complementary to those of NOAA, and specific linkages are described in Appendix B.

QPE: Science questions

1. How can enhanced observations help to evaluate and improve NWS polarimetric algorithms developed as part of the upgrade of the WSR-88D radar network?
2. How can HMT-SEPS observations be used to increase understanding of microphysical processes and aid in evaluating and improving QPE systems such as MPE, MRMS, Stage IV, and others?
3. How can multi-sensor QPE information from gauges, radars, and satellite be optimally integrated?
4. How do infrared (IR) and microwave satellite QPE products compare with ground-based QPE?
5. What is the impact of 4-D precipitation data and drop size distribution (DSD) information on QPE systems (e.g., toward establishing the most appropriate Z-R relationship)?
6. What is the impact of gap-filling radars on QPE for this region?

Researchers in NOAA HMT will focus their attention on (1) and (2). The degree to which the remaining topics can be addressed is dependent on engagement with partners across NOAA, NASA and academic institutions. Additional information on QPE and the linkage of specific QPE objectives to the HMT-SEPS instrumentation strategy and deployment plan is provided in Section VII.

VI. QPF Summary and Science Questions

Warm-season quantitative precipitation forecasts (QPF) are often the least skillful area of forecast systems (e.g., Fritsch and Carbone 2004; WPC, personal communication), and extreme precipitation events represent an additional level of forecast complexity due to the infrequent, stochastic, and extraordinary nature of such events. The southeast U.S. experiences warm-season extreme precipitation from a number of different phenomena, making the improvement of overall QPF skill even more challenging. Observing and forecasting moisture sources and transport in this region is also a major challenge. Therefore, research complementary to the overall HMT-SEPS goals will be conducted on regional QPF challenges, with an emphasis on southeast U.S. extreme precipitation events, improved characterization of moisture sources and transport, and opportunities for improvement in the QPF of such events.

A number of factors challenge skillful QPF in this region. For example, numerical weather prediction (NWP) models often struggle with diabatic processes and effects resulting from strong moisture feeds and convective systems (e.g., Reeves and Lackmann 2004; Brennan and Lackmann 2005, 2006; Zhang et al. 2006; Mahoney and Lackmann 2006, 2007; Brennan et al. 2008). Variability in sources of moisture and methods of transport further complicate the predictability of extreme precipitation events in this region. For example, precipitation processes may be affected by frontal dynamics, diabatically-driven dynamics, pre-existing systems (as in predecessor rain events associated with tropical cyclones; Cote 2007; Moore 2010; Galarneau et al. 2010) or direct linkages to the Tropics, as with atmospheric rivers (e.g., Moore et al. 2011).

Additional factors such as the topography of the Appalachian Mountain system (e.g., Parker and Ahijevych 2007; Letkewicz and Parker 2010), as well as the relatively sparse nature of observations in space and time (e.g., Markowski et al. 2006; Tollerud et al. 2008), provide considerable forecast and observational challenges, and underscore the motivation for examining this complex region in further detail.

A first step in addressing questions related to moisture sources and transport in the region is to develop a climatology of heavy precipitation events. Once established, the climatological data will be analyzed according to weather system type, moisture source, transport mechanism, and other relevant environmental parameters. Differentiating, distinguishing, and stratifying sub-phenomena (e.g., distinguishing atmospheric rivers from more general low-level jet (LLJ) dynamics) during these events may also have a significant operational benefit (e.g., Bodner et al. 2011). Testing of specific scientific hypotheses as they emerge from the climatological study will be performed by case study analysis and model sensitivity tests. Analysis of the scientific questions posed below will utilize a combination of observational and reanalysis datasets, as well as numerical-model-based experiments, to investigate extreme precipitation events on both longer (seasonal, intra-seasonal) and shorter (in-depth event-based case studies) timescales.

The HMT-SE QPF-oriented questions listed below are broader in scope and geographical range than those addressed by HMT-SEPS. While the QPE and QPF efforts associated with HMT-SEPS and more generally HMT-SE are complementary and will take advantage of one another to the greatest extent possible, the QPF research will examine extreme precipitation events across the entire southeastern U.S., and not only in the HMT-SEPS intensive study region. Preliminary results from all of these activities, ideally combined with collaboration with and interest from regional partners, will shape future directions and help to determine the full scope of HMT-SE.

QPF: Science questions

1. What is the climatology of extreme precipitation events in the southeastern U.S.?
2. How do QPF errors -- in both “human” (e.g., WPC, WFOs) forecasts and NWP model forecasts relate to the largest observed precipitation events in this region?
3. What are the primary moisture sources and moisture transport mechanisms for extreme rainfall in the southeast U.S.?
4. Does the moisture source region systematically impact the intensity, distribution, and/or flood potential of extreme rainfall events?
    a. Specifically, how does the main moisture source region relate to:
        - Absolute measures of precipitation totals and/or atmospheric moisture content?
        - Spatial scale/coverage of extreme precipitation?
        - Climatological anomalies of resulting extreme events?
        - Types, intensities, or modes of precipitation/convection (e.g., shear and instability characteristics)?
        - QPF skill?
    b. To what extent are specific event characteristics differentiated by specific moisture source regions, particularly with respect to:
        - Mode of moisture transport (frontal, closed vs. open extratropical system, tropical system, AR, LLJ, surface-based, elevated, nocturnal)?
        - Vertical structure of moisture: How deep is the moist layer? Where (vertically) does moisture and moisture transport maximize?
        - Horizontal structure of moisture maxima; how wide is the moisture transport feature?
        - Evolution in space and time of moisture (How does moisture transport change over time? How long does moisture transport persist over a given area?)
5. How can high-resolution, probabilistic QPF generated from statistically post-processing the new ESRL/PSD reforecast dataset improve predictions of extreme precipitation in the southeast U.S.?
6. What can information gained from investigating the above science questions potentially provide in terms of improved forecasting of extreme precipitation, improved predictability of phenomena leading to extreme precipitation, and/or improved NWP model predictability?

VII. Deployment Strategy

In addition to existing operational sites, a core of instruments will be deployed for HMT-SEPS by NOAA from approximately May 2013 – mid-October, 2014 (see Fig. 4a,b). The instrument deployment will be supported by a combination of both NOAA and NASA GPM resources. As of April 2013, most of the instrumentation sites have been finalized, and instrumentation will include:

- Four NOAA profiling radar sites (including 449 MHz and 915 MHz for wind profiling with Radio Acoustic Sounding System -RASS for boundary layer temperature retrievals and S-band for precipitation vertical structure). Each profiler site will include a surface meteorological station to measure (temperature, relative humidity, pressure, wind, and precipitation and will include an optical (parsival) disdrometer for drop size distribution measurements);
- 6 NOAA surface sites in the Upper Catawba basin with standard meteorology sensors (temperature, relative humidity, pressure, wind, redundant precipitation measurements using a combination of NOAA and NASA gauges, and one or more NASA disdrometers) as well as soil moisture and temperature (5-levels);
- Repair of the Raleigh Cooperative Agency 915 MHz Profiler (CAP) as well as an upgrade of software to provide wind, melting layer, and water vapor flux (using nearby GPS data) information; and
- An upgrade to the Charlotte CAP 915 MHz profiler to provide improved clutter and melting level detection. A GPS receiver is located approximately 8 km from the Charlotte CAP profiler site to provide integrated water vapor measurements.

The NASA GPM program will also deploy a significant amount of instrumentation as part of IPHEX.

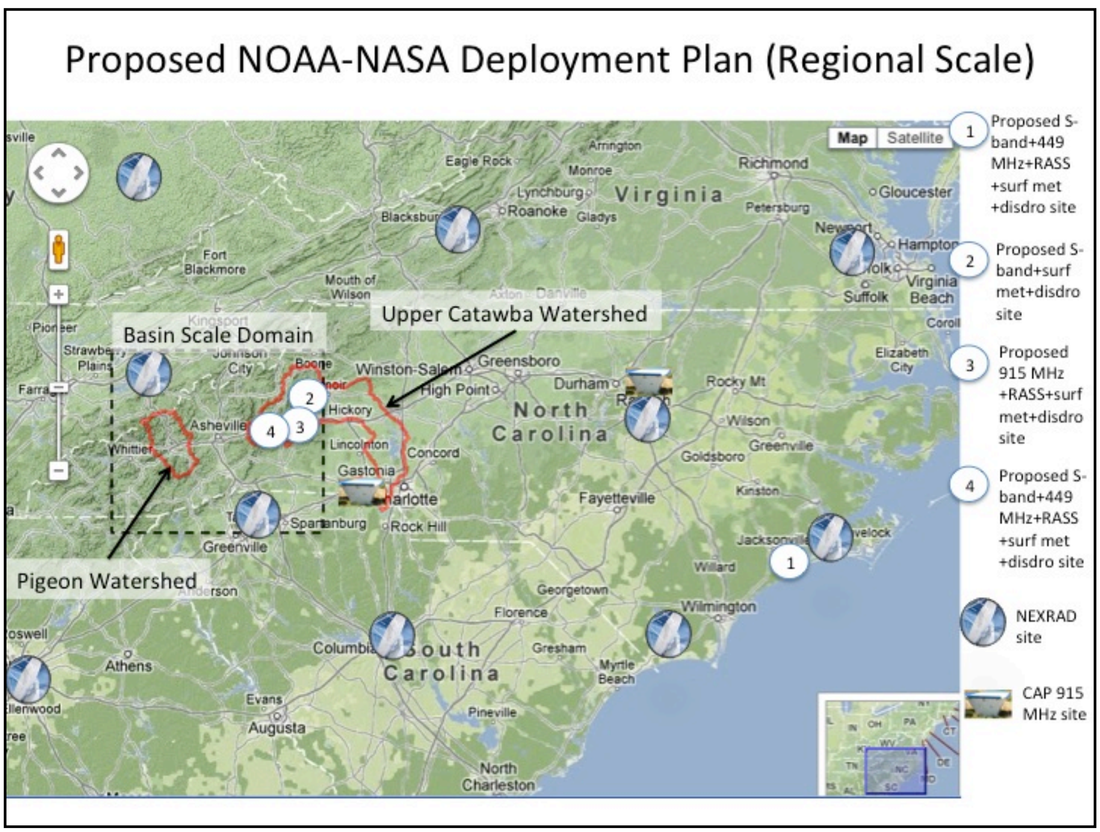
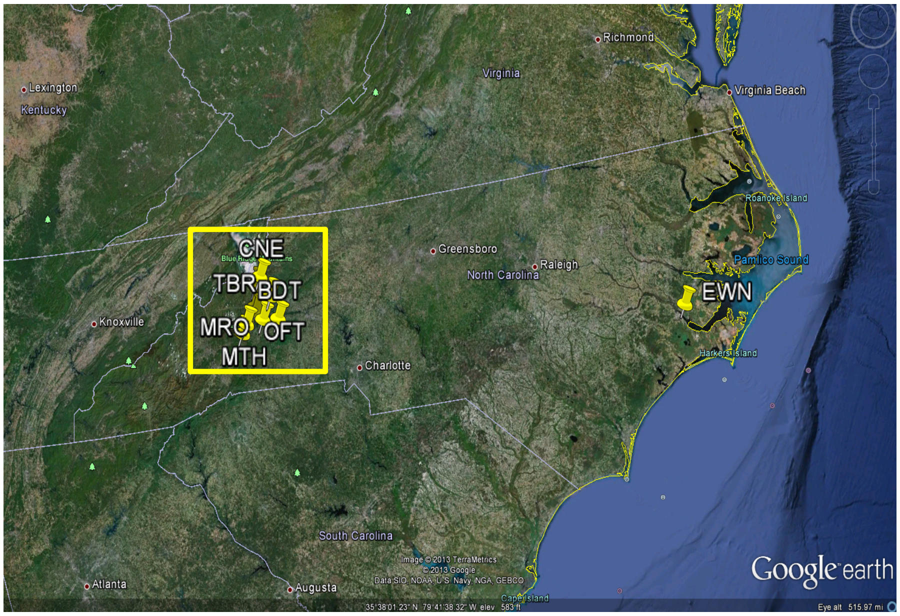


Figure 4a. Regional view of HMT-SEPS instrumentation (Summer 2012 planning map; locations approximate).



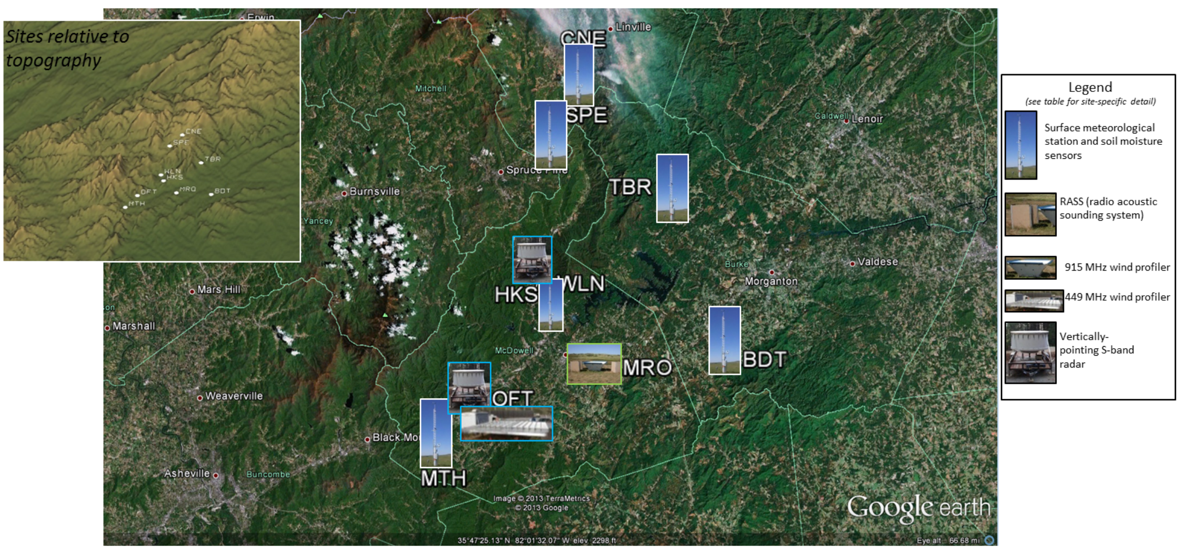


Figure 4b. Location of regional-scale (top) and basin-scale (bottom) NOAA HMT-specific instrumentation in HMT-SEPS (as of Spring 2013).

The combination of wind/precipitation profiling radars and surface meteorological instrumentation will obtain precipitation information principally for QPE science objectives. However, the observations may also support QPF and HASP science objectives. . As shown in Fig. 4, the deployment strategy will involve a combination of large-scale and small-scale networks. Profiling over the large-scale domain will provide general perspective on the evolution of weather systems as they move through the region, and boundary conditions for regional modeling and diagnostic studies. A nested, concentrated network will provide data to support detailed QPE (VPR correction, DSD variability, etc.) and HASP (sensitivity of hydrologic models to QPE, etc.) objectives and will complement NASA physical validation and integrated validation objectives as discussed in Sec. III.

The basin selected for the small-scale network is the upper Catawba (Figs. 4b and 5). This basin was chosen for the following reasons:

- proximity to the Barros Research Network in French Broad River Basin allows for scanning radar coverage of both areas;
- the upper Catawba represents an area of moderate terrain compared to the steeper terrain of the Barros Research Network – the combined region would allow for an examination of precipitation variability (DSDs, VPR, etc) for MCSs that traverse the mountains from WSW->ENE;
- the upper Catawba is relatively un-regulated in terms of dams and diversions and therefore provides a relatively "natural" hydrologic basin to simulate;
- the upper Catawba appears to offer a large enough basin area to examine spatial variability of QPE and its representation in GPM/NOAA satellite retrievals and small enough to adequately network for detailed hydrologic modeling and response; and
- the upper Catawba is located in a relative precipitation maximum zone (Fig. 6)

The NOAA assets will complement NASA GPM, Duke University, University of Iowa, and other instrumentation for HMT-SEPS/IPHEX as shown in Table 1. As noted above the NASA GPM GV instrumentation will likely be deployed for ~6 weeks (May – June 2014). Moreover, HMT-SEPS/IPHEX will leverage existing operational instrumentation (rain and stream gauges, Charlotte and Raleigh 915 MHz profilers – see Figs. 2 and 4) that is currently in place.

The existing instrumentation in the proposed IPHEX/HMT-SEPS region includes a combined network of NASA sensors (32 rain gauges and one meteorological tower) to examine the vertical structure and spatial variability of precipitation in the southern Appalachians (Pigeon River Basin with the larger French Broad Basin) as well as a network operational rain gauges for flood warning and stream gauges (see Figs. 2 and 4b). The IPHEX domain also includes one USGS hydrologic benchmark watershed within the area sampled by the NASA rain gauge network, the NSF Long Term Ecological Research station (LTER) at Coweeta, several USFS and national park service research stations, as well as several carefully monitored river basins, including the Yadkin and the Catawba near the core IPHEX area and Tar-Pamlico and the Neuse watersheds in the Piedmont and Coastal areas. The existing instrumentation, together with NASA and NOAA deployments slated for the pilot study (described below), will provide an unprecedented opportunity to baseline and improve QPE.

As described above, NOAA has repaired the Raleigh 915 MHz CAP profiler (Fig. 4a), and it will be operational in spring 2013 (legal and funding constraints permitting). The profiler data will be useful to NWS operations and will provide a cross-state (from the mountains to the coastline) transect and allow for studies of boundary layer evolution for QPF.

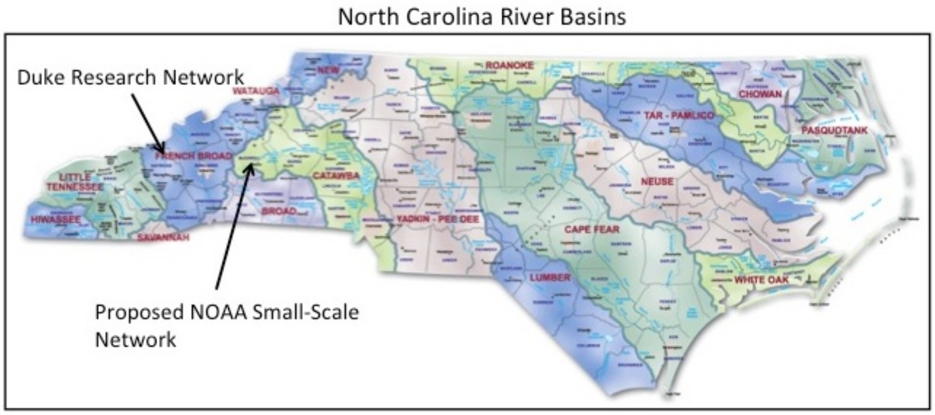


Figure 5. North Carolina river basins. Image from
http://www.eenorthcarolina.org/public/ecoaddress/riverbasins/riverbasinmapinteractive.htm

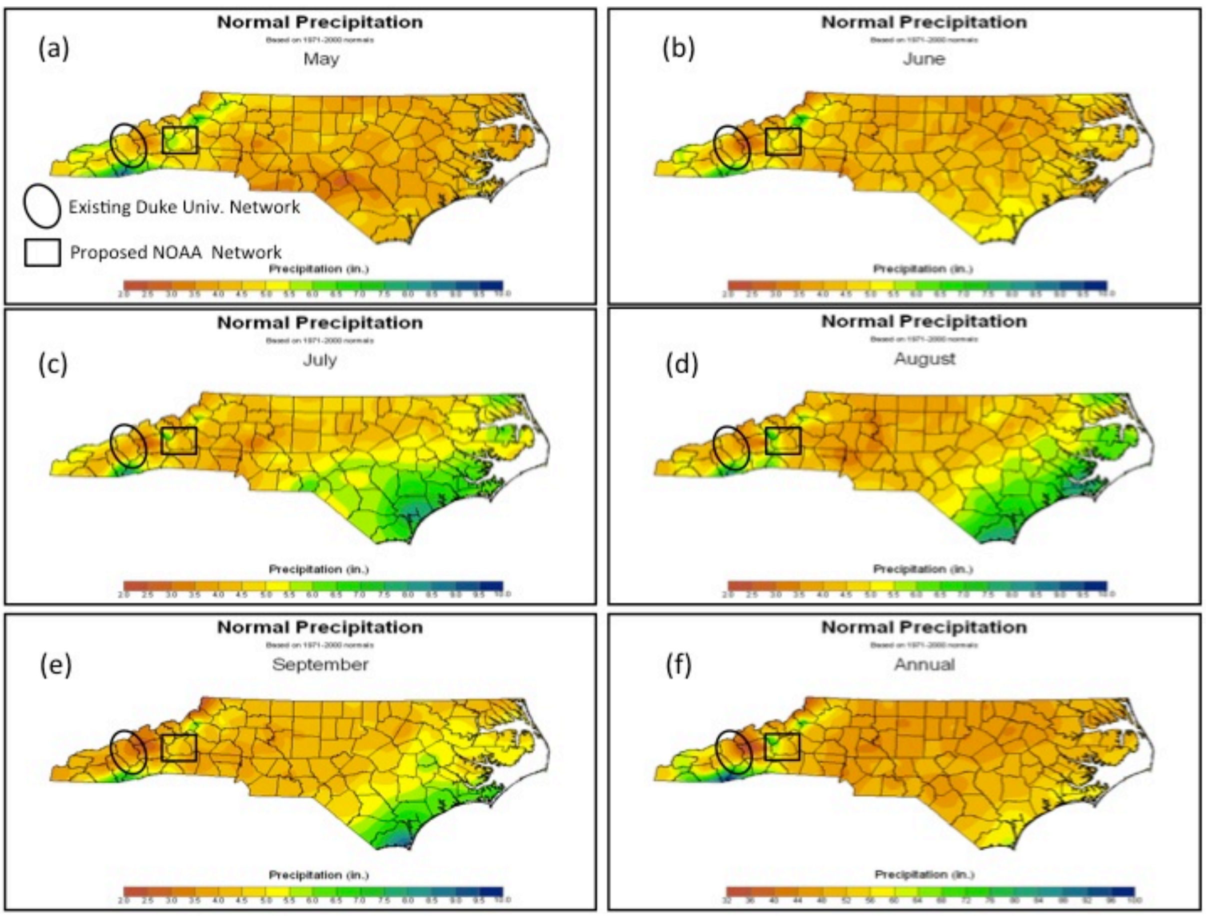


Figure 6. Average monthly and annual precipitation in North Carolina (in), based on 1971-2000 data. Panels a-e show May-September average precipitation, respectively. (f) shows average annual precipitation. Oval and rectangle represent approximate locations of the Duke University network and the proposed NOAA small-scale network, respectively. Image from the State Climate Office of North Carolina
http://www.nc-climate.ncsu.edu/climate/monthlyprecip.html

Table 1. List of instrument assets and their relationship to HMT-SEPS/IPHEX objectives.

Instrument	**Quantity Measured**	**Organization**	**Science Objective(s)**	**Notes**
449 MHz wind profiler w/ RASS	Vertical air motion in precipitation up to ~4 km, horizontal wind in all conditions up to ~4 km	NOAA PSD	**QPE** (DSD retrievals, VPR correction) **Physical validation**	When co-located with S-prof, can retrieved vertical profile of DSDs. When co-located with GPS-met, can estimate horizontal moisture flux.
S-band precipitation profiler (S-prof)	Reflectivity, radial velocity and spectrum width of precipitation	NOAA PSD	**QPE** (DSD retrievals; VPR) **Phys validation**	Resolve vertical structure of precipitation. When co-located with 449-MHz profiler, can retrieved vertical profile of DSDs.
Surface sites co-located with profilers	Tripod tower with pressure, temperature, humidity, wind speed and direction, rain rate, and disdrometer	NOAA PSD	**QPE** (DSD retrievals, rain rate) **HASP** (surface forcing) **Phys validation** **IH validation**	Battery powered, no shelter needed,
Separate Surface/Subsurface Sites	Surface: Tripod tower with pressure, temperature, humidity, wind speed & direction, rain rate, and disdrometer Sub-Surface: soil moisture at 5 depths	NOAA PSD and NASA	**QPE** (DSD retrievals, rain rate) **HASP** (surface forcing) **Phys validation** **IH validation**	Battery powered, no shelter needed, and redundant rain gauges. Requires a pit to be dug to install sub-surface probes.
NOAA Parisvel disdrometer	Surface raindrop size distribution, rain rate and equivalent radar reflectivity	NOAA PSD	**QPE** (DSD retrievals; VPR) **Phys validation**	Provides absolute calibration reference for 915 MHz and S-prof radars. Requires AC power and shelter.
N-Pol, S-band polarimetric scanning radar	Reflectivity, radial velocity and polarimetric signatures	NASA	**QPE** (precip vertical structure, DSD retrievals, rain rate) **HASP** (QPE forcing) **Phys validation** **IH validation**	Provides spatial structure of precipitation.

Ku-Ka band scanning radar	Reflectivity, radial velocity and polarimetric signatures at 13- and 35-GHz.	NASA	**Phys validation**	D3R – frequencies match GPM DPR
NASA Parsival disdrometer	Surface raindrop size distribution, rain rate and equivalent radar reflectivity	NASA	**QPE** (DSD retrievals, rain rate) **HASP** (QPE forcing) **Phys validation** **IH validation**	Array of disdrometers to characterize the spatial distribution of DSDs. Each unit is self contained with solar and battery power. NASA has ~20 units.
2D video disdrometer	Surface raindrop size distribution, rain rate equivalent radar reflectivity, and raindrop oblateness	NASA	**QPE** (DSD retrievals, rain rate) **HASP** (QPE forcing) **Phys validation** **IH validation**	2-dimension viewing for verifying polarimetric retrieval assumptions. NASA has ~4 units.
Aircraft	ER-2 and UND Citation	NASA	**Phys validation**	TBD
Rain gauge network	Surface rain rate and accumulation	NASA	**QPE** (rain rate) **HASP** (QPE forcing) **Phys validation** **IH validation**	Array of redundant rain gauges to verify spatial rain rate variability.
Rain gauge network	Surface rain rate and accumulation	Duke University	**QPE** (rain rate) **HASP** (QPE forcing) **Phys validation** **IH validation**	Barros Research Network has ~32 rain gauge sites

In order to determine the number field sites that NOAA PSD can deploy, Table 2 lists the instrument combinations that were initially planned as NOAA HMT-SE field sites. Descriptions of the instruments and their measurements are given in Table 1. Table 2 represents a best estimate of the current NOAA PSD instrument inventory available for HMT-SE. If future funding is available, more sites can be added to Table 2.

Table 2. NOAA's assets for HMT-SEPS listed by each site as of April 2013.

Site Name	Site ID	Latitude	Longitude	Elev (m)	449	915	RASS	S-band	Met	Soil Moisture	GPS	Parsivel
Brindletown	BDT	35.6424	-81.7810	355					X	X		X
Crossnore	CNE	36.0148	-81.9300	1008					X	X		X
Hankins	HKS	35.7310	-82.0271	379				X	X			X
Marion	MRO	35.6547	-81.9609	384		X	X		X			X
Mount Hebron	MTH	35.5677	-82.2248	519					X	X		X
New Bern	EWN	35.0874	-77.0455	3	X			X	X		X	X
Old Fort	OFT	35.6406	-82.1616	421	X			X	X		X	X
Spruce Pine	SPE	35.9473	-81.9950	833					X	X		X
Table Rock	TBR	35.8397	-81.3320	356					X	X		X
Woodlawn	WLN	35.7678	-82.0399	523					X	X		X

References

Atallah, E., L. F. Bosart, and A. Aiyyer 2007: Precipitation Distribution Associated with Landfalling Tropical Cyclones over the Eastern United States. *Mon. Wea. Rev*., **135**, 2185-2206.

Bailey, Christopher M., Gail Hartfield, Gary M. Lackmann, Kermit Keeter, Scott Sharp, 2003: An Objective Climatology, Classification Scheme, and Assessment of Sensible Weather Impacts for Appalachian Cold-Air Damming. *Wea. Forecasting*, **18**, 641–661.

Baker, A. K., and G. M. Lackmann, 2009: Convection and Appalachian cold-air damming. 23rd Conf. on Weather Analysis and Forecasting, Omaha, NE, Amer. Meteor. Soc., 1-6. http://ams.confex.com/ams/23WAF19NWP/techprogram/session_23128.htm

Barros, A.P., W. Petersen., W. Krajewski, Emanouil Anosgnostou, Marshall Shepherd, James Smith, Timothy Schneider, Robert Cifelli, Douglas Miller, Eyal Amitai, Ali Tokai, 2011: COPrHEX. White paper.

Bergeron T., 1965: On the low-level redistribution of atmospheric water caused by orography. *Proc. Int. Conf. on Cloud Physics,* Tokyo, Japan, IAMAP/WMO, 96–100.

Bodner, M.J., N.W. Junker, R.H. Grumm, R.S. Schumacher, 2011: Comparison of Atmospheric Circulation Patterns during the 2008 and 1993 Historic Midwest Floods. *Nat. Wea. Dig*. 35, 103 – 120.

Ciach, G. J., W. F. Krajewski, and G. Villarini, 2007: Product-Error-Driven Uncertainty Model for Probabilistic Quantitative Precipitation Estimation with NEXRAD Data. J. Hydrometeor, 8, 1325–1347.

Fuhrman,C.M., Konrad, and Band., L., 2008: Climatologial Perspectives on the Rainfall Characteristics Associated With Landslides in Western North Carolina. *Physical Geography*, 2008, **29**, 4, pp. 289-305.

Gaffin, David M., Stephen S. Parker, Paul D. Kirkwood, 2003: An Unexpectedly Heavy and Complex Snowfall Event across the Southern Appalachian Region. *Wea. Forecasting*, **18**, 224–235.

Galarneau, T. J., Jr., L. F. Bosart, and R. S. Schumacher, 2010: Predecessor rain events ahead of tropical cyclones. *Mon. Wea. Rev.,* **138,** 3272–3297.

Green, T. A., 2005: Cold Air Damming Erosion and Associated Precipitation in the Southeastern United States. M.S. thesis, Dept. of Marine, Earth, and Atmospheric Sciences, North Carolina State University, 270pp. (Available online at:http://www.lib.ncsu.edu/theses/available/etd-01022006 235238/unrestricted/etd.pdf).

Hamill, T. M., and J. S. Whitaker, 2006: Probabilistic quantitative precipitation forecasts based on reforecast analogs: Theory and application. *Mon. Wea. Rev.*, **134**, 3209–3229. 10.1175/MWR3237.1

Keeter, Kermit K., Steven Businger, Laurence G. Lee, Jeff S. Waldstreicher, 1995: Winter Weather Forecasting throughout the Eastern United States. Part III: The Effects of Topography and the Variability of Winter Weather in the Carolinas and Virginia. *Wea. Forecasting*, **10**, 42–60.

Keighton, Steve, and Coauthors, 2009: A Collaborative Approach to Study Northwest Flow Snow in The Southern Appalachians. *Bull. Amer. Meteor. Soc.*, **90**, 979–991.

Letkewicz, C. E., and M. D. Parker, 2010: Forecasting the maintenance of mesoscale convective systems crossing the Appalachian Mountains. *Wea. Forecasting*, **25**, 1179-1195.

Lundquist, J. D., J. R. Minder, P. J. Neiman, and E. Sukovich, 2010: Relationships between barrier jet heights, orographic precipitation gradients, and streamflow in the Northern Sierra Nevada. *J. Hydrometeor*, **11**, 1141-1156.

Mahoney, K. M., and G. M. Lackmann, 2006. The sensitivity of coastal cyclogenesis forecasts to convective parameterization: A case study of the 17 February 2004 East coast cyclone. *Wea. Forecasting*, **21**, 465-488.

Mahoney, K. M., and G. M. Lackmann, 2007: The effects of upstream convection on downstream precipitation. *Wea. Forecasting*, **22**, 255–277.

Miller, D. M., 2012: Near-term effects of the lower atmosphere in simulated northwest flow snowfall forced over the southern Appalachians. *Wea. Forecasting*, http://dx.doi.org/10.1175/WAF-D-11-00103.1.

Min, S.K., X. Zhang, F.W. Zwiers, and G.C. Hegerl, 2011: Human contribution to more-intense precipitation extremes. *Nature*, **470**, 378-381, 10.1038/nature09763.

Moore, Benjamin J., Paul J. Neiman, F. Martin Ralph, Faye E. Barthold, 2012: Physical Processes Associated with Heavy Flooding Rainfall in Nashville, Tennessee, and Vicinity during 1–2 May 2010: The Role of an Atmospheric River and Mesoscale Convective Systems*. *Mon. Wea. Rev.*, **140**, 358–378.

National Weather Service, Office of Hydrologic Development, 2010: MPE Editor Users Guide January 7, 2010 Build 9.2. Report, Report, National Weather Service, Office of Hydrologic Development, available at https://ocwws.weather.gov/intranet/whfs/.

NOAA Science Workshop Program Committee, 2010: Strengthening NOAA science., Findings from the NOAA Science Workshop, April 20-22, 2010, Co-Chairs: Dr. Paul Sandifer and Dr. Randall Dole, http://www.nrc.noaa.gov/plans_docs/2010/Science_Workshop_WP_FINAL.pdf.

Parker, M.D. and D.A. Ahijevych, 2007: Convective episodes in the east-central United States. *Mon. Wea. Rev.*, **135**, 3707-3727.

Prat, O., and Barros, A.P., 2010: Assessing satellite-based precipitation estimates in the Southern Appalachian Mountains using rain gauges and TRMM PR. *Adv. Geosci.*, 25, 143–153.

Schaake, J., A. Henkel., and S. Cong, 2004: Application of PRISM Climatologies for Hydrologic Modeling and Forecasting in the Western U.S., Preprint, 18th Conf. on Hydrology, Amer. Meteor. Soc. 84th Annual Meeting, Seattle, WA, 7p.

Moneypenny, M., and D. Schneider, 2002: The mesoscale seeder-feeder mechanism: Its forecast implications. *Nat. Wea . Dig.* **26**: 1, 2, 45-52.

Schneider, T. 2009a: Report on the NOAA Hydrometeorology Testbed–Southeast (HMT-SE) Operational Needs & Requirements Workshop, February 3-5, 2009, Chapel Hill, North Carolina. http://hmt.noaa.gov/resources/pdf/Report_on_HMT-SE_Workshop1_Final.pdf

Schneider, T. 2009b: Report on the NOAA Hydrometeorology Testbed–Southeast (HMT--SE) Research Planning Workshop, June 15--17, 2009, Chapel Hill, North Carolina. http://hmt.noaa.gov/resources/pdf/Report_on_HMT-SE_Workshop2_Final.pdf

Srock, Alan F., Lance F. Bosart, 2009: Heavy Precipitation Associated with Southern Appalachian Cold-Air Damming and Carolina Coastal Frontogenesis in Advance of Weak Landfalling Tropical Storm Marco (1990). *Mon. Wea. Rev.*, **137**, 2448–2470.

White, A.B., P.J. Neiman, F.M. Ralph, D.E. Kingsmill, and P.O.G. Persson, 2003: Coastal orographic rainfall processes observed by radar during the California Land-Falling Jets Experiment. *J. Hydrometeor*., **4**, 264–282.

Zhang, D.-L., Zhang, S., and Weaver, S., 2006: Low-level jets over the Mid-Atlantic States: Warm-season climatology and a case-study. *J. Appl. Meteo. and Climat.,* **45**, 194-209.

Zhang, J., and Y. Qi, 2010: A Real-Time Algorithm for the Correction of Brightband Effects in Radar-Derived QPE. *J. Hydrometeor*, **11**, 1157–1171.

Zhang, Jian, and Coauthors, 2011: National Mosaic and Multi-Sensor QPE (NMQ) System: Description, Results, and Future Plans. *Bull. Amer. Meteor. Soc.*, **92**, 1321–1338.

Appendix A:

Additional HMT-SE potential study areas (contingent on additional funding, and interest, time, and resources of regional partners)

1. Hydrologic applications and surface processes (HASP)

NOAA's requirements for HMT-SEPS are primarily focused on QPE and QPF. If additional funding is acquired and/or partner organizations can participate, the project scope may be expanded to include work on the impact of QPE and QPF on hydrologic applications and surface processes (HASP).

HASP objectives are documented here in the event that additional funding is acquired to support these activities. Many of the specific HASP objectives were identified in the HMT-SE Operational Needs and Requirements Workshop (Schneider 2009a) and are identified in blue text.

Overarching goals of HASP research would be (i) to test and explore the coupling of atmospheric and hydrologic models, (ii) to examine and prototype ensemble approaches to hydrologic prediction, and (iii) to explore and develop quantification strategies for expressing predictive uncertainty. *Pending additional resources and/or collaborators*, possible HMT-SE HASP objectives may also include:

- Use HMT-SEPS observational data to validate National Water Center (NWC) experimental hydrologic "forcing" data;
- Use methodology developed from QPF error climatology to compare NWC "forcing" data to observational data as well as WPC QPF products to benchmark data with other products;
- Quantify the impact of both QPE and QPF uncertainty on hydrologic flood simulations as well as for water budgets of the basin;
- Quantify the impact of microphysics, storm dynamics and evolution, barrier jets, etc. on uncertainty in QPE and QPF products and subsequent hydrologic products;
- Develop size criteria for watershed basins or sub-basins such that they are large to be relevant to NASA GPM objectives and small enough to instrument accurately;
- For a specific location in the HMT-SEPS domain, evaluate performance of lumped vs. distributed hydrologic model simulations (e.g., Hydrology Laboratory – Research Distributed Hydrologic Model, HL-RDHM); and
- Improve quantification of streamflow predictability at a given specific location

(Appendix A will remain dynamic to allow for easy updating of developing partnerships and collaboration opportunities.)

Appendix B. Linkages Between NOAA HMT-SEPS and NASA IPHEX Science Objectives

The NOAA objectives for QPE within HMT-SEPS are described in Secs. II and V. Barros et al. (2011) describe the relevant NASA activities targeted for IPHEX. These include integrated validation and physical validation. Broadly speaking, the former relate to improved understanding of the time and space scales where GPM satellite data are useful for hydrologic prediction and the latter refer to improvement in precipitation retrieval algorithms through error characterization and better understanding of microphysics. Specific NASA objectives for IPHEX will contribute to both integrated and physical validation. As described below, these NASA objectives are complementary to NOAA (linkages to NOAA science objectives are indicated in *blue italics*).

1. **GPM Rainfall Retrieval Algorithms** (physical validation)
   - 4-D variability of rainfall structure: IPHEX observations will be used to examine the microphysical properties of various precipitation regimes. This will include characterization of the space-time variability of the drop size distribution (DSD), including terrain impacts. *Improved understanding of the vertical structure of radar reflectivity and the DSD will support NOAA's goal to improve QPE via optimization of Z-R relations and VPR corrections as a function of precipitation regime and terrain.*
   - Space-time characterization of radar reflectivity attenuation (Ku and Ka-band) at low-levels.
   - Variability of surface emissivity: This includes characterization of soil moisture, surface temperature, vegetation characteristics, etc. An important issue to address is the impact of thick fog on radiometric signatures. *A description of soil moisture complements NOAA's effort to characterize the sensitivity of hydrologic models to soil moisture forcing in the HMT-SE (see below)*.
   - Contribution of light rain to total water budget: Previous work indicates that light rain (< 5 mm hr^{-1}) contributes 60-65% of total the total water budget in this region and that shallow layers of terrain-anchored fog/rain are important for seeder-feeder orographic precipitation enhancement. IPHEX will provide an opportunity to examine the contribution of different rainfall regimes to the total water budget in a comprehensive fashion. *The impact of seeder-feeder processes on QPE in the southern Appalachians will be compared to similar processes observed in HMT-West, where White et al. (2003) showed that nearly 50% of cold season rain volume in the California coast range was shown to be associated with "hybrid" rain (i.e., situations where a radar bright band signature is present and the radar reflectivity profile shows an increase in radar reflectivity with decreasing height at low levels. This structure implies a microphysical process consistent with the "seeder-feeder" mechanism (Bergeron 1965; Schneider and Moneypenny 2002), where ice crystals fall into a moisture rich environment to enhance collision-coalescence of liquid drops).*
2. **GPM Hydrology** (integrated validation)
   - Improved understanding of the coupling between rainfall regime and surface runoff vs. ground water recharge: This includes down-scaling of satellite precipitation products and an assessment of QPE uncertainty across time and space scales. This objective also includes assessing the performance of satellite rainfall products in hydrological application over a range of medium size basin scales (150-2000 km^2). This activity requires synergistic measurements of a number of hydro-meteorological variables at watershed scale. *This effort is complementary to NOAA HMT's goal to better understand the sensitivity of hydrologic models, including the NOAA RDHM, to various hydrologic forcing parameters (QPE, soil moisture, snow level, etc.) as well as to examine the utility of providing ensemble stream flow*

forecasts using a WRF ensemble for input forcing. IPHEX would provide an opportunity to expand HMT hydrologic research from the west coast to watersheds in the southeast and would highly complement similar efforts of NASA GPM investigators.

- Methods to integrate satellite information into the operational environment: This includes an analysis of the appropriate time and space scales where satellite data can show the most benefit to QPE/hydro system. *This effort will complement similar efforts at NOAA. In particular, HMT researchers will use the precipitation measurements collected during IPHEX (gauge, radar, and satellite) to improve understanding of microphysical processes in the region and evaluate the performance of selected QPE algorithms, including Mountain Mapper (Schaake et al. 2004), Multi-sensor Precipitation Estimator (MPE; National Weather Service 2010) and NMQ Q2 (Zhang and Qi 2010; Zhang et al. 2011). If collaborations with partner organizations can be established, this effort will also include a quantitative assessment of the added value of satellite data for QPE, as well as "intelligent" integration of ground and satellite QPE, and is part of a larger HMT goal to determine the "best possible" QPE in regions of complex terrain, ultimately resulting in improved hydrologic forcing guidance for NOAA's National Water Center (NWC).*
- Determination of the best methods to utilize numerical model-integrated QPE: This includes an assessment of coupled cloud resolving model (e.g., WRF)-land surface model performance in warm-season environments. The sensitivity of assimilation at different spatial and temporal scales and the resulting impact on QPE will also be explored. *NOAA HMT researchers also will be conducting data assimilation experiments with high-resolution forecast models that will assimilate the IPHEX datasets.*
- Creation of a dataset framework to enable broad community engagement for testing and improving hydrologic applications and capabilities. *If funding and collaborative efforts can be established, hydrologic prediction systems such as Community Hydrologic Prediction System (CHPS) will be used to both inter-compare different prediction systems and also to facilitate interoperability of hydrologic information with the NOAA Office of Hydrologic Development (OHD) and NWS forecast offices and river forecast centers. Tools such as CHPS provide a framework to allow HMT researchers to perform hydrologic simulations and exchange data with partner organizations across NOAA and the academic community.*