MESOSCALE AND MICROSCALE METEOROLOGY LABORATORY

STRATEGIC PLAN (2013-2018)

National Center for Atmospheric Research
Boulder, Colorado

Revised April 2015

The mission of the Mesoscale and Microscale Meteorology Laboratory is to advance the understanding of the meso- and microscale aspects of weather and climate, and to apply this knowledge to benefit society.

Table of Contents

SUMMARY

Since its inception over 27 years ago, the Mesoscale and Microscale Meteorology Laboratory (MMM) has excelled in fundamental research covering the dynamics and physics of mesoscale (1 – 1000 km) and microscale (10^{-6} – 1000m) atmospheric flows and processes. This work continues, but through time increasing emphasis has been placed on the modeling and prediction of these phenomena. MMM builds upon and leverages collaborations within NCAR and throughout the community to achieve more accurate mesoscale weather forecasts and climate prediction and projections.

The principal tool for atmospheric prediction is the numerical weather prediction (NWP) model. The accuracy of the NWP model depends on the discrete representation of the continuous equations believed to be governing atmospheric motion, the representation of unresolved small-scale motions (e.g., boundary-layer turbulence and cloud microphysics) that have important effects on the resolved larger-scale motion, and the data-ingest systems used for model initialization and forecast verification. Thus to advance the science of atmospheric prediction, MMM has endeavored to produce the most accurate and computationally efficient numerical models, more effective systems of data assimilation, and better representations of processes not currently resolved in present-day NWP models. The result of our efforts, with extensive external contributions, is the WRF[1] model, now serving a global community.

As advanced as WRF is, demand for forecast accuracy continues to be ahead of supply. For example, there is a growing demand for mesoscale predictions on climatic time scales. This demand has been the motivation behind the extensive NRCM simulation research and the growth of a hybrid statistical-dynamical prediction approach. It is also one of the forces behind the recent development of MPAS, with a priority objective to bridge the weather and climate divide and enable predictions of regional climate and high-impact weather statistics on decadal time scales. This regional-climate focus will leverage development efforts from both the climate-prediction and weather-prediction communities, and promote a wide range of collaborative activities with academic, government, industry, societal, and local government groups. Recognizing that prediction is interpreted by users within their own frameworks of risk perception and action, MMM strives to adapt our research and our predictions in ways that improve the usability of use of weather and climate information. Over the last five years, MMM has built a core interdisciplinary program with expertise in communication and use of weather-related information.

The improvement of NCAR community models depends critically on the feedback from forecasters and climate-model users. MMM has led the way with WRF for the first experimental real-time high-resolution (4km grid size in 2003) forecasts over the continental U.S. in summer (when convection poses a particularly significant challenge to any forecast model) and the recent

[1] Acronyms used in this document are defined in the list starting on p. 26.

NRCM climate simulation also at 4km resolution. These efforts continue today at higher resolution and over larger domains, experimenting with new data-assimilation strategies and forecast-verification techniques. They go hand-in-hand with field experiments (e.g., MPEX planned for 2013) providing high-resolution data sets that help check on the fidelity of the model forecasts. Since 2004, MMM has also led the way with experimental real-time high-resolution forecasts of tropical cyclones. Again, field programs (e.g., PREDICT, GRIP, 2010) and new data-assimilation strategies have been critical components of the forecast-system development.

The small-scale meteorological processes that most affect the accuracy of weather and climate predictions are: the physics of *clouds and precipitation*, the effects of *turbulence and surface exchange*, and how these processes act in combination. Hence MMM has continued to place emphasis on boundary-layer and cloud-microphysics research. For example, the importance of air-sea interaction and water and ice latent heating on tropical cyclones has been appreciated for decades, but due to the extreme conditions at the sea surface and in clouds, only recently has progress been made both through observations and advanced numerical simulations. MMM scientists have played leading roles in this research and have partnered with university colleagues, other NCAR laboratories, and outside agencies to address these issues and to meet new demands for boundary-layer information coming from the renewable-energy industry.

The ability to predict cloud effects continues to be a weak link in weather and climate models. The effects of clouds run the gamut from the NWP problem of the timing, location, amount and type of precipitation expected, to the climate problem in which the distribution and nature of clouds play a critical role in future-climate projections, to evaluation of active remote sensing (lidar, radar) from spaceborne instruments (CloudSat, CALIPSO). For these reasons, MMM continues a robust research effort on the microphysics of clouds, including the effects of aerosols, ice nuclei (ICE-T), and dust.

In summary the fundamental research conducted in MMM is essential to weather- and climate-model development both in the improvement of current models and for providing the necessary groundwork for future models. Based on extensive consultation with staff and the community at large, the following pages describe recent progress and future plans for advancement in these areas.

1. Mesoscale Numerical Weather and Climate Prediction

Demand for weather-forecast precision continues to be ahead of our ability to supply it. The reasons for this are partly due to inherent limitations on the ability to forecast with arbitrary accuracy any fluid system with many scales of motion and partly due to technological gaps yet to be filled. Our research program continually seeks to improve our technological capacities up to the inherent limits of atmospheric predictability. As the latter limits are not precisely known, the search for better methods of atmospheric prediction follows multiple paths looking for solutions with the largest ratios of benefit to cost.

Since its early beginnings in the 1950s, numerical weather prediction has followed a steady path of improvement through the strategy of improved modeling technology, higher resolution, better representations of unresolved processes, and improved methods of data collection and assimilation. The early models covered the entire the globe so increases in grid resolution were dictated by increases in the speed of computers. By the late 1960s, a new generation of models focused on limited areas of the globe (e.g., the contiguous United States) were able to vastly increase resolution, but at the expense of theoretical and computational challenges involved in representing conditions at the fictitious boundaries of a limited-area domain. This trade-off between the inherent uncertainty in limited-area modeling (or grid nesting) and the gain in accuracy made possible with higher resolution, is a challenge that runs through all of mesoscale atmospheric prediction and will be encountered in various forms throughout this strategic plan. To mention just a few of the challenges: optimal modeling strategies for resolution refinement, physics suitable for medium-range (a week or longer) forecasts and climate simulations, and physics that can adjust appropriately to the surrounding grid resolution in variable-resolution modeling. These challenges are not unique to mesoscale prediction and we expect they will be met by the combined efforts of NCAR Laboratories, as well as by collaboration with the wider community.

1.1 The Weather Research and Forecasting Model (WRF)

Background

MMM has throughout its history supported community limited-area modeling systems (e.g., MM4, MM5). Well over a decade ago planning began within NCAR for a significantly improved approach to limited-area modeling taking into account advances in software engineering, a wide range of computing platforms, and needs of a much more diverse user base. This planning in collaboration with university and agency partners led to the development of the WRF model.

Since its first public release in 2000, the WRF modeling system has experienced a continual growth in popularity. The WRF registered-user base is now over 20,000. The popularity of the annual WRF Users' Workshop has made it a week-long event providing a modeling lecture series, working-group meetings, general presentation and discussion sessions, and mini-tutorials on WRF-related capabilities. The workshop most recently attracted approximately 240 attendees. The map shown in Fig. 1 indicates that WRF is a worldwide resource used in 151 countries, with 20 of those utilizing real-time applications of WRF for operational forecasting.

The WRF system has further matured and expanded over the past few years. Detailed on WRF web pages (http://www.mmm.ucar.edu/wrf/users/wrfv3.4/updates-3.4.1.html) and in documentation, the number of physics packages and options has increased to provide researchers with new capacities for better simulating the atmosphere and probing processes. This development confirms WRF as truly a community model, with the growth in large part due to users' interests in contributing to the system. The WRF data assimilation system (WRFDA) has matured to encompass the ingestion of an extensive array of observation types, especially in the area of satellite-derived measurements. WRFDA now also offers ensemble data assimilation approaches. Detailed updates can be found at the above-cited link.

A strong direction that has emerged in the WRF effort has been that of using the model as a regional climate research tool. As a result of the explosive interest in this application, the Regional Climate Research Section (RCRS) was created within MMM (Section 1.5). Whether for regional climate or weather studies, however, the increased interest and application of WRF over the past few years has increased the demand on MMM for user support, and NSF has responded by increasing base funding for personnel in this vital area.

Figure 1 Map illustrating countries with WRF registered users and countries with operational or real-time forecasting applications.

Plans

1) The MMM effort will strive to achieve its continuing goal of maintaining a high level of community support of the WRF system. This support will cover providing assistance to users in their WRF applications and providing training through semi-annual WRF tutorials at NCAR, as well as tutorials abroad as resources allow. In addition, MMM will serve the community by leading and hosting the annual WRF Users' Workshop.

2) MMM will continue with its management and oversight of the WRF repository and of WRF public releases. These functions remain two of the core responsibilities that MMM has assumed with respect to WRF.

3) MMM and collaborators will pursue development of the WRF system (including WRFDA; see Section 1.2) to build new capabilities, accommodate changing computer

technologies and platforms, and respond to user needs. As in the past, the specific physics and software additions to be addressed will mostly reflect the application goals of WRF users.

4) The RCRS will advance our experience and understanding of WRF for regional climate modeling. As it has experienced in the NWP context, WRF is positioned for significant worldwide user growth in high-resolution climate modeling (Section 1.5).

1.2 Data Assimilation

Background

Data assimilation provides initial conditions for forecasts and thus is an essential component of any forecasting system. Because it routinely and systematically compares model predictions to large and diverse observational data sets, data assimilation also has a central role in the continued improvement and refinement of the forecast model, for example by identifying model biases. Moreover it can inform improvements to the observational network through observing-system simulation experiments. MMM is recognized for its unique expertise in modeling, assimilation and observing of mesoscale and convective processes and for advancing high-resolution prediction.

Since the last Strategic Plan (2008), MMM has continued developing advanced data-assimilation techniques for WRF (Section 1.1), suited to high-resolution analysis and prediction, including a four-dimensional variational scheme (4D-Var), an Ensemble Kalman Filter (EnKF) and "hybrid" approaches that incorporate elements of both variational and ensemble techniques. The variational and hybrid schemes are available to the community through the WRFDA system, while the EnKF is implemented through WRF/DART, which employs the Data Assimilation Research Testbed (DART) and was jointly developed with CISL/IMAGe. MMM also made progress toward a single, unified system encompassing all these techniques; for example, observation operators from WRFDA may be utilized in WRF/DART assimilation.

While there is room for ample improvement, MMM data-assimilation systems have matured significantly over the last five years. Assimilation of satellite radiances is now routine in several applications. In addition, the EnKF system provides initial conditions for MMM's real-time forecasts of both tropical cyclones and springtime convection and in the process has identified important biases in WRF forecasts, as described in Section 1.3. MMM has achieved these capabilities through leveraged research and development for AFWA (see Fig. 2 for an example), AMPS, CWB, and AirDat among other entities. This research has also led to considerable expertise in the Gridpoint Statistical Interpolation (GSI) system used for assimilation at NCEP.

Finally MMM has helped to make the field of data assimilation accessible to graduate/ postgraduate students and scientists active in other research areas through its development of the WRFDA community facility encompassing email support, tutorials and workshops in conjunction with the WRF activities. WRF/DART is also available to, and widely used by, the community.

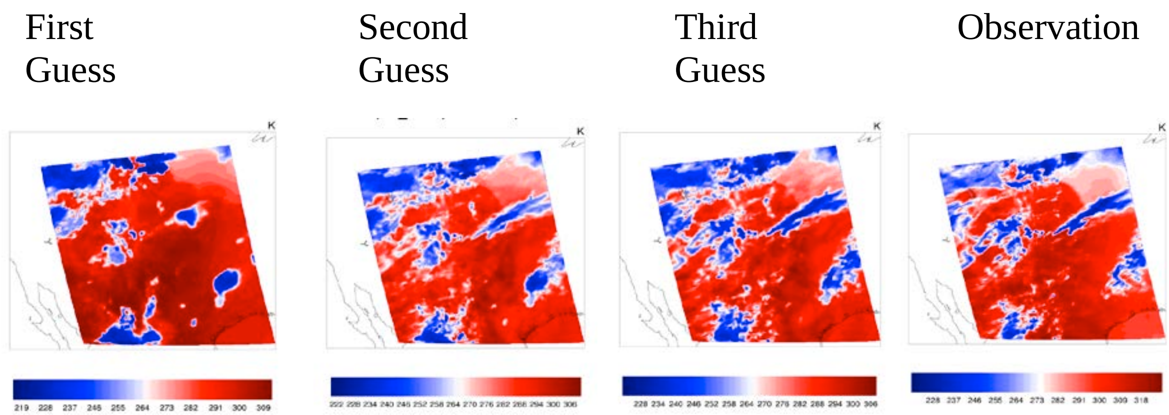


Figure 2 AFWA Coupled Analysis and Prediction System (ACAPS) showing successive corrections to brightness temperature in channel #787 of NASA/AIRS in a WRF-model analysis showing changes in cloud liquid water and ice.

Plans

1) MMM will continue development and support of data-assimilation systems for community use. Support efforts will focus on WRF. Development will emphasize unified ensemble-variational systems for WRF (including WRF-Chem) and MPAS (Section 1.4).

2) MMM will apply data assimilation to scientific problems of particular interest. Efforts will continue in mesoscale data assimilation for real-time forecast experiments with WRF, and soon with MPAS; in cloud analysis; and in assimilation of Doppler-radar observations and satellite radiances for convective-scale motions. MMM will also participate in and support field programs, with the goals of using data assimilation to improve forecasts of mesoscale phenomena and to evaluate novel observation sets. New applications will include assimilation for the prediction of atmospheric aerosols (cloud condensation nuclei, ice nuclei and dust) and coupled land-atmosphere and ocean-atmosphere problems relevant to weather and regional-climate prediction.

3) Data assimilation will be more closely integrated with model development. MMM will use data assimilation to increase understanding of physical processes represented in WRF and MPAS and to accelerate improvements to those representations, by comparing model solutions against diverse observational datasets over long periods.

4) MMM will continue fundamental research in data assimilation. This will include techniques that account for nonlinearity and non-Gaussianity, that provide bias correction and parameter estimation, and that account for forecast-model error.

1.3 Experimental Forecasting with WRF

To both test and take advantage of the unique capabilities of the WRF modeling and DA system, three major experimental forecasting efforts have been undertaken at MMM: hurricane prediction; summertime convective weather over the continental U. S.; and, weather over the Antarctic.

1.3.1 Hurricane Prediction

Background

The first experimental, hurricane-specific forecasts using WRF-ARW were conducted for hurricane Isabel in 2003. This model is referred to as the Advanced Hurricane WRF (AHW). The purpose of these forecasts was to see if the same model used for mesoscale weather prediction was also capable of predicting hurricanes. Encouraging results led to more extensive and comprehensive hurricane-prediction work each year since then, building toward a reliable quasi-operational system that could also be used for research. Developments for hurricane applications were tested and, if found helpful, were folded back into the community version of WRF-ARW so that the hurricane version of the model was never far from the community version.

In 2008, the Hurricane Forecast Improvement Program (HFIP) was just starting. Part of that project focused on development, retrospective testing and real-time testing of several regional hurricane models. MMM developed a strong collaboration with the University at Albany-SUNY to implement improved data assimilation and improve our capability to perform vastly more testing and evaluation of the forecasts. This extensive testing allowed the model to be selected by HFIP to run in a quasi-operational configuration and it has done so each of the last three hurricane seasons (2010-2012). Figure 3 shows results of the retrospective testing from 2012, from which it can be seen that hundreds of hurricane track and intensity forecasts were evaluated, the model is competitive with operational models, and there has been measurable improvement between 2011 (orange) and 2012 (red). The current configuration of the model takes advantage of two concentric moving nests, with an innermost-grid spacing of 4km. A columnar ocean model predicts the cooling of the ocean surface from wind-driven mixing. Initial conditions are provided by a cycling EnKF, which among other advantages, allows one to notice systematic errors. Much of the recent work has been to improve the physics of the model regarding shallow and deep convection, thus improving both the data assimilation and forecasts. In the process of doing real-time forecasts over the last several years, numerous science studies have arisen that use datasets created from these real-time simulations. These include published studies of vortex resilience in shear, introduction of new methods to evaluate model errors, and the effect of various physical processes in the model on storm track. Output from real-time forecasts are archived for the community and made available to anyone interested.

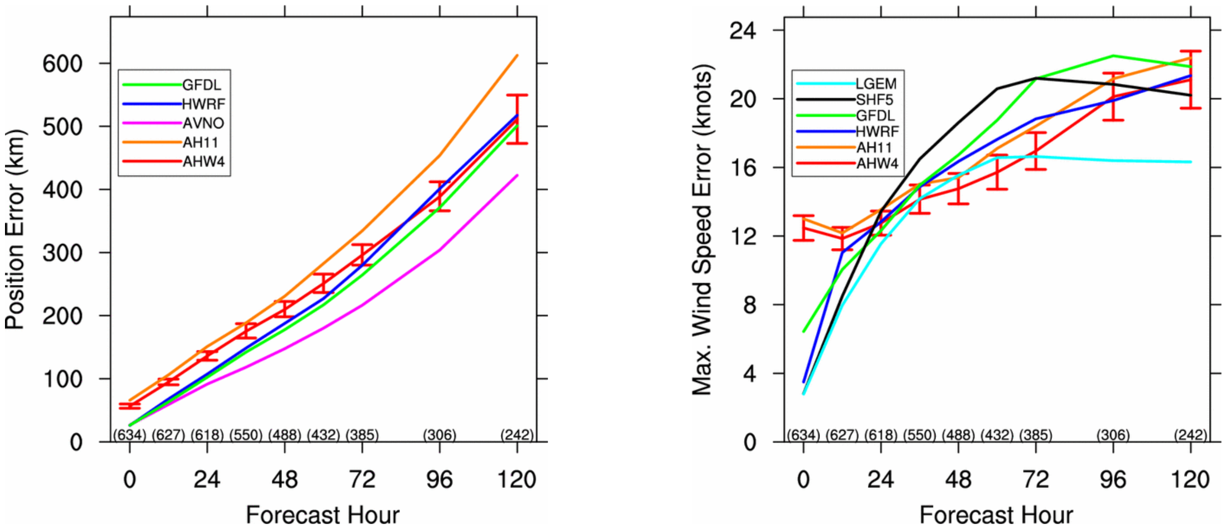


Figure 3 Position mean absolute errors (left) and intensity errors (right) for Atlantic tropical cyclones from the 2009-2011 hurricane seasons. The number of forecasts in parentheses at each lead time is shown along the bottom of each graph. (AH11 is the AHW version in 2011; AHW4 is the version run in 2012; AVNO is the GFS model; SHF5 and LGEM are statistical models used only for intensity prediction.)

Plans

1) MMM will conduct further analysis of systematic model errors using techniques recently developed. This work will continue to identify and fix systematic errors in model physics. Many of the physical processes of note involve shallow convection and effects of Saharan air layers (as suggested in the field studies ICE-T, NAMMA and to be further examined in ICE-D) on storm track and intensity. The focus on physical parameterizations, especially the treatment of tropical convection, is expected to improve the performance of MPAS (Section 1.4).

2) MMM intends testing the AHW in all ocean basins in order to improve the performance of the system for the benefit of users in all parts of the world. During the 2012 hurricane season, AHW is running quasi-operationally in both the Atlantic and Eastern Pacific ocean basins.

3) Long-term upgrades to the system will include changes to the data-assimilation system, perhaps moving to a “hybrid” system (see Section 1.2). The addition of ocean and wave models to AHW is currently being explored. Eventually MMM plans to examine the prediction of tropical cyclones with the MPAS model, thereby alleviating restrictions from limited-area domains.

1.3.2   Convective Weather Prediction

Background

An important component of WRF development has been experimental explicit convective weather forecasts (3km grid resolution, extending to forecast lead times of 48h) covering much of the continental U.S., to better establish the capabilities and limitations of such high-resolution numerical guidance. This activity has been undertaken in collaboration with the NOAA Hazardous Weather Testbed (HWT) Spring Program, but also has contributed to forecast efforts in support of the VORTEX-2 field campaign in 2010, the Deep Convective Clouds and Chemistry (DC3) trial period in May 2011 as well as the full DC3 field campaign in May and June 2012. An example of one of the better forecasts is presented in Fig. 4, demonstrating the ability of these high-resolution forecasts to accurately predict a swath of damaging surface winds over a 12-h period associated with a severe convective system (a derecho) in the northeast U.S. on 12 June 2012.

These forecast exercises have been instrumental in documenting forecast sensitivities and biases for the wide range of physics options generally applied for convective applications, and have also been helpful in identifying errors in the various physics schemes. However, one of the more consistent findings from these exercises is that such convective forecasts are more sensitive to the specification of initial conditions than model physics. As such, much of the effort has been focused on improving the representation of the initial atmospheric state. In 2009 and 2010, MMM scientists tested the use of the RUC 13km Diabatic Digital Filter Initialization (DDFI) procedure to incorporate ongoing convective activity into the initial conditions and to address spin-up issues associated with standard cold-start procedures. This technique proved to be very effective at reducing the spin-up period from roughly 6h to 3h without producing spurious convective activity.

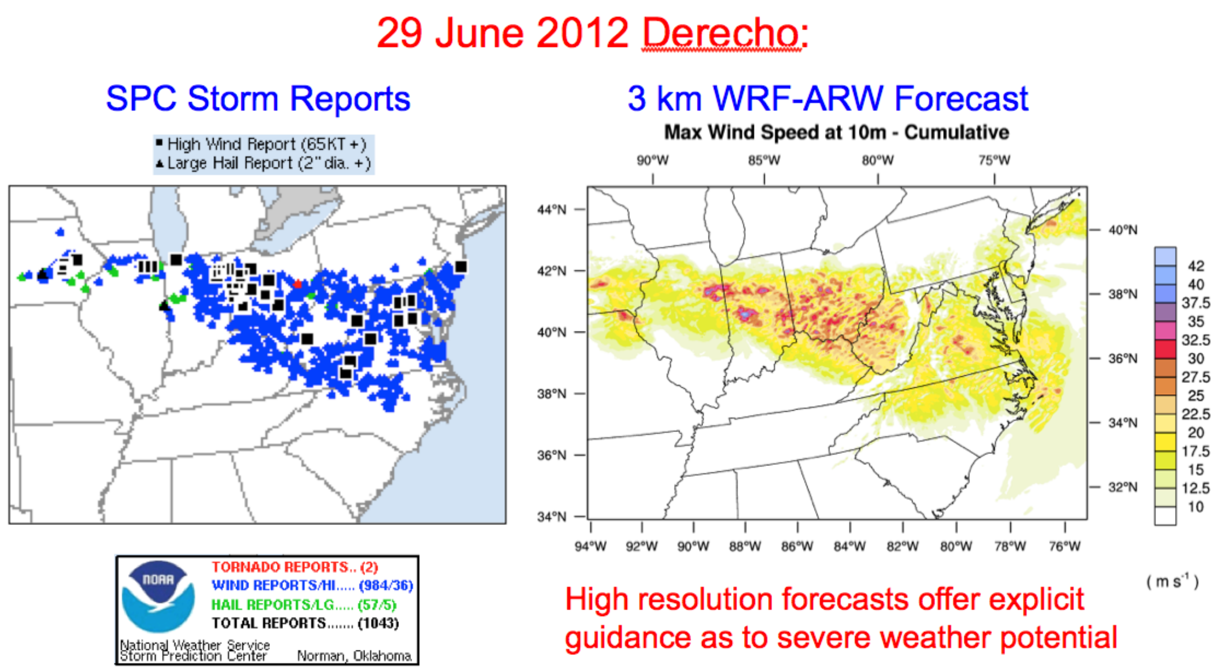


Figure 4 Comparison of high-wind reports (left panel) and a real-time WRF forecast of high winds for the same period with lead times ranging from 1h in the western part to 18h in the eastern part of the region shown.

Starting in 2011, initial and boundary conditions for these forecasts were drawn from an ensemble data assimilation system using the WRF/DART system. WRF-DART was used in a continuous cycling mode, with a 50-member ensemble providing a set of CONUS mesoscale (15km horizontal resolution) analyses every six hours over the duration of the forecast period. A single analysis was then selected from the ensemble to make a 48-h convection-resolving (3km horizontal resolution) forecast for the central U.S. This marked the first use of WRF-DART for real-time convective forecasting and several significant problems were uncovered related to the build up of model bias during the continuous cycling process. Based on this analysis, the DART system was reconfigured for the DC3 (2012) field campaign, producing a marked improvement in forecast skill that was highly valued by the DC3 PIs and other participants.

Given that initial condition uncertainty has been identified as a major contributor to significant convective forecast errors, planning proceeded for an observational field experiment named MPEX (Mesoscale Predictability EXperiment). MPEX is motivated by the basic question of whether experimental, sub-synoptic observations can extend the lead time of convective-scale predictions and/or otherwise enhance skill in regional numerical weather prediction over a roughly 6- to 24-h time span. The primary goal of this experiment is to use dropsondes and microwave temperature profiles (MTP) to enhance upstream subsynoptic-scale upper-air observations early in the morning, 6h to 18h prior to anticipated convective outbreaks. The target area for this experiment is the Intermountain and High Plains region of the U.S., with the goal of improving the forecast of severe convective outbreaks over the Central Plains and Midwest.

Plans

1) MMM will continue real-time explicit convective forecasting experiments, both to test the ongoing advancements and refinements to WRF-ARW as well as to offer forecast support for MPEX and FRONT-PORCH, or more generally, other field experiments with a need for targeted weather information. Emphasis will be on continued development and testing of WRF-DART EnKF techniques to produce an improved representation of the atmospheric state and its uncertainties for 0- to 48-h convective forecast applications. The anticipated new resources associated with the NCAR-Wyoming Supercomputing Center will also allow us to expand efforts to explore probabilistic forecast skill from such ensemble forecasts.

2) A critical component of the real-time convective forecasting effort is the analysis, verification and validation of the model forecasts. In this regard, MMM is interested in not only the basic timing and location of convective features, but also in verifying convective structure, intensity and evolution, as well as the aspects of the mesoscale environment responsible for convective triggering and resultant convective mode (see Section 2.4). Of particular importance is the analysis and documentation of the common modes of forecast failure for such convective applications.

3) The MPEX field program has been approved by NSF, and is currently scheduled for mid-May through mid-June 2013. The enhanced sub-synoptic data set acquired as part of MPEX (dropsondes and MTP profiles) will be used to produce enhanced synoptic and subsynoptic analyses for incorporation into explicit convective forecast models, for both real-time and retrospective studies. The potential benefits of the enhanced upstream tropospheric observations will be tested using a variety of data-assimilation techniques to conduct data-denial experiments.

1.3.3 Antarctic Mesoscale Prediction System

Background

The Antarctic Mesoscale Prediction System (AMPS) is an experimental, real-time, high-resolution numerical weather prediction capability that MMM runs over Antarctica in support of the United States Antarctic Program (USAP). The effort is funded by the NSF Office of Polar Programs and is a collaboration between NCAR and The Ohio State University. AMPS employs a polar-modified version of the ARW and produces twice-daily forecasts with a nested-grid setup with resolutions as high as 1.67 km. AMPS provides numerical guidance to the forecasters of the USAP, while also supporting NSF scientific and logistical activities across Antarctica. Over the years it has been a tool and database for researchers and graduate students for Antarctic meteorological and climatological research, as well as assisting in emergency situations and international Antarctic forecasting.

Since 2008 AMPS has improved and expanded its physics, forecasts, and services. It has increased its grid configuration from a 60-km/20-km/6.7-km/2.2-km nested setup to a 45-km/15-km/5-km/1.67-km nested setup. It has expanded the range of its product types based on forecaster feedback. Papers from the AMPS effort have addressed system performance and verification, data assimilation, event studies, and regional precipitation regimes. The system has served as a vehicle for the development, testing, and implementation of Polar WRF, a version of the model with modifications to better capture conditions over the high latitudes and extensive ice sheets. The popularity of AMPS use in the international Antarctic community has continued, and the program organized and hosted the 7th Antarctic Meteorological Observation, Modeling, and Forecasting Workshop at NCAR in 2012.

AMPS forecasts are made available to all through its web page, http://www.mmm.ucar.edu/rt/amps. This is a means for the USAP, for field-campaign investigators, and for international users to access AMPS's real-time NWP guidance. Figure 5 presents an example, a forecast plot for an Antarctic cruise of the NSF research vessel R/V Nathaniel B. Palmer. These types of plots follow the NSF ships and stay centered on their positions. The chart shows forecast sea-level pressure, surface winds, and 3-hourly precipitation and marks the location of the Palmer (labelled "NBP") in the Ross Sea. AMPS forecast products and gridded fields are also made available via a web server, e-mail, and the Antarctic IDD (Internet Data Distribution) capability, created as part of a collaboration with the University of Wisconsin and other Antarctic weather-community members.

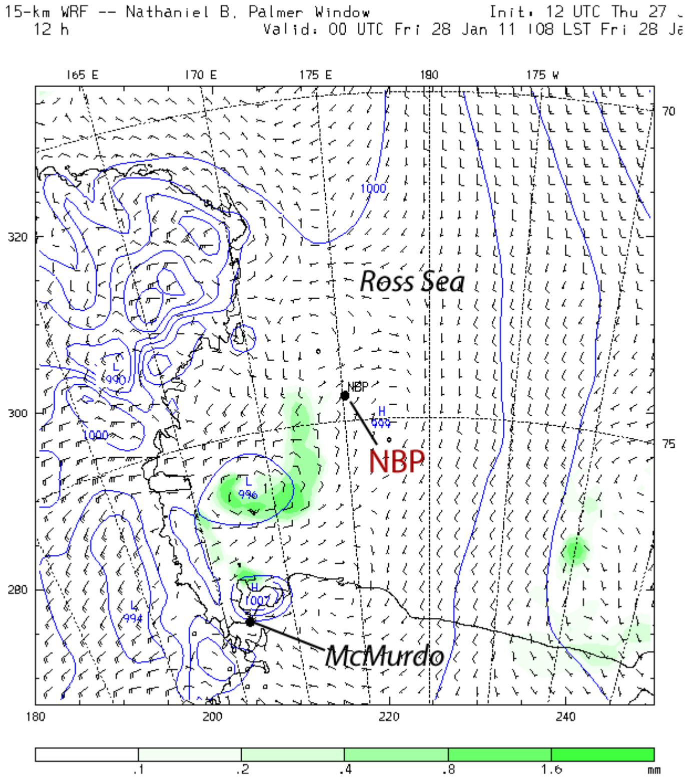


Figure 5 AMPS plotting window following the NSF *R/V Nathaniel B. Palmer* for a Ross Sea research cruise. 12-hr AMPS forecast of sea level pressure (interval= 2 hPa), surface winds (wind barbs, full barb= 10 kt), and precipitation (3-hourly accumulated precipitation shaded in green) in the vicinity of the *Palmer* (valid 0000 UTC 28 Jan 2011) with its location marked as "NBP".

Plans

1) MMM will work on the development and evaluation of polar physics modifications to WRF to improve high-latitude NWP. MMM will integrate these into the WRF repository for future model releases to the community.

2) To better support Antarctic atmospheric research, MMM will improve access to the AMPS archive—the database of AMPS model forecasts for Antarctica used in disciplines ranging from meteorology, to climatology, to glaciology—to those outside of NCAR.

3) MMM will expand real-time NWP support for USAP and NSF Antarctic field campaigns, logistical needs, and investigations through AMPS.

1.4 The Model for Prediction Across Scales (MPAS)

Background

With increasing computer capabilities, MMM has recognized a community need for a global nonhydrostatic atmospheric model for mesoscale and cloudscale research that can take advantage of emerging petascale computer architectures. MMM is collaborating with Los Alamos National Laboratory (LANL) to develop the Model for Prediction Across Scales (MPAS), which presently includes global atmosphere and ocean solvers. NCAR is responsible for the atmospheric component, LANL the ocean component, and the development of the infrastructure is shared between the two partners.

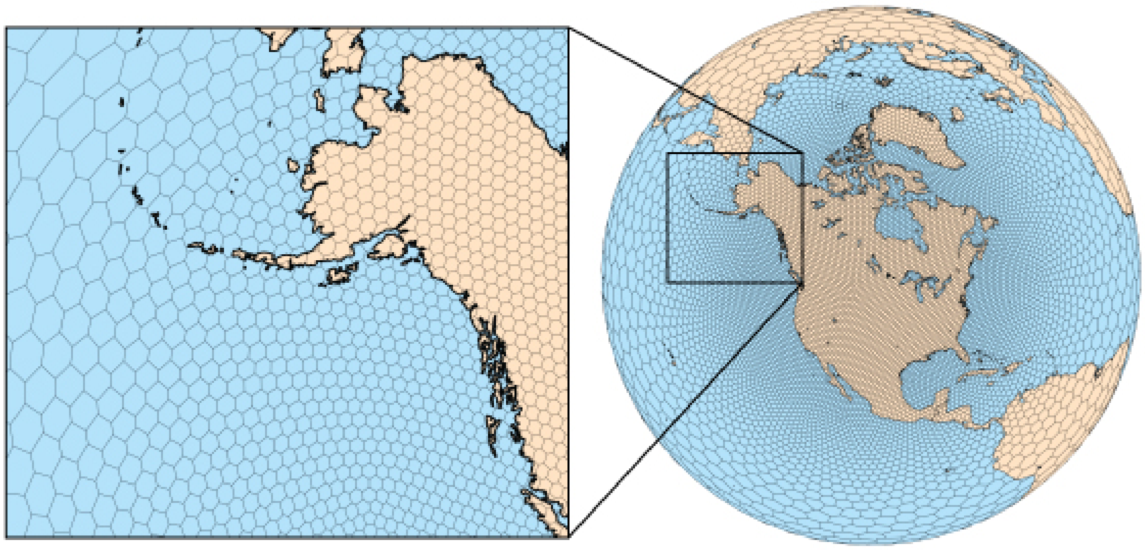


Figure 6 An MPAS variable-resolution mesh.

The MPAS solvers are based on spherical centroidal Voronoi meshes (nominally hexagons) that are unstructured, and allow for variable resolution meshes that seamlessly transition between fine and coarse mesh regions. The meshes are generated using a user-specified mesh-density function and allows great flexibility. An example of the Voronoi mesh is given in Fig 6.

MPAS development began in 2008; a prototype shallow-water equations solver for the sphere was completed in the summer of 2009, a hydrostatic atmospheric solver followed in early 2010, and a prototype nonhydrostatic solver in late 2010. The nonhydrostatic solver is based on the solver in ARW with extensions to allow for the Voronoi mesh in addition to upgrades from the existing ARW numerics. The MPAS nonhydrostatic atmospheric solver has been coupled with the NRCM atmospheric physics suite from ARW and is being tested for the NRCM regional climate work being undertaken in MMM. The nonhydrostatic MPAS is also being coupled to the DART for ensemble data-assimilation work. In collaboration with CGD, the hydrostatic MPAS solver has been implemented as a Community Atmosphere Model (CAM) core in the Community Earth System Model (CESM), with initial testing of MPAS variable-resolution meshes, using the full-CAM atmospheric physics. The MPAS nonhydrostatic solver will soon replace the MPAS hydrostatic solver within CAM. The infrastructure was developed in parallel with the solvers, and represents a major part of the development effort.

Plans

1) MMM will continue to develop the MPAS model for use in MMM's regional climate (Section 1.5) and weather applications. This includes MPAS use as a stand-alone system and its use as a core in other coupled-model systems such as CESM, and encompasses both the solver technology, infrastructure technology, and pre- and post-processing capabilities needed for our applications.

2) MMM, in partnership with LANL, will make the MPAS solvers available to the community, as both a stand-alone system and as components for other modeling systems such as CESM.

3) MMM and the larger research community recognize the need for physics that work seamlessly across model resolutions. MMM's primary focus will be to develop scale-aware physics parameterizations for MPAS (see also Sections 2.1 and 2.2) because of its variable-resolution mesh applications. Resources permitting, MMM will also provide support for chemistry-related scale-aware parameterizations, such as convective transport of chemical compounds, wet deposition, and production of nitrogen oxides by lightning.

1.5 Regional Climate Research

Background

Regional climate research is a new MMM activity that grew out of the frontier Nested Regional Climate Modeling (NRCM) program and became fully established in late 2012. The goal is to improve understanding, assessment, projection and prediction of regional climate and weather with emphasis on the two-way effects of climate variability and change on high-impact weather and the societal consequences, providing improved capacity for community investigations of regional climate and establishing new approaches to effective user communication.

There are many disciplines associated with regional climate and high-impact weather and the community interest in this area is growing in complexity and areas of interest. Thus, the regional climate program in MMM brings together a range of expertise and perspectives in a strongly interdisciplinary research activity, where an integrated group of physical-mathematical-social scientists are working to build a niche in interdisciplinary work at the intersection of weather extremes and regional climate, covering research, development and use of suitable tools (e.g. NRCM and MPAS, hybrid statistical-dynamical approaches, societal indices and specialized module approaches to assessing risk and impacts of importance to diverse users), working closely with societal and industry partners at both the research and development stages, and providing and maintaining regional climate modeling systems for community use.

The NRCM was developed by MMM and CGD as a test bed for regional climate research by utilizing a version of WRF embedded in the Community Climate System Model (CCSM). This has provided both valuable experience and initial regional climate predictions at resolutions as high as 4 km. The NRCM system is now available to the community and MMM has started regional climate tutorials aimed at introducing new users to the system and providing information on lessons learned and best practices for regional climate prediction. Collaborations with ACOM scientists have led to a version of NRCM coupled with chemistry, which is being used to study air quality in future climate for both the North American and southeast Asian regions.

A major effort has also been established to develop hybrid statistical-dynamical approaches to regional climate prediction and assessment. This includes using advanced statistics to extract information on high-impact weather from a combination of high- and low-resolution simulations, developing index approaches to directly assessing climate impacts, and developing new approaches to assessing and reducing uncertainty in regional-scale climate predictions of changes in extremes.

Making a prediction is only part of the way to a successful outcome, as the prediction is interpreted by users within their own frameworks of risk perception and action. MMM is thus working with a range of communities, from Native Americans to leading companies in industry and commerce, to adapt our research and our predictions in ways that improve the usability and use of weather and climate information.

Plans

1) With the full complement of regional climate staff now in place, the plan is to proceed with the goal of developing and utilizing an advanced regional climate research and prediction capacity and of maintaining this for community use. This will be a hybrid statistical-dynamical system based on MPAS, but including statistical approaches for modifying the output and assessing and reducing uncertainty. The system also is being developed with direct interaction with and feedback from a range of societal groups and will include a range of approaches to directly assessing impacts.

2) The fledgling community support established for NRCM will be expanded along the lines of the WRF support effort. This will include a help desk, national and international tutorials and workshops, and a structured process for community systems to be incorporated back into the system. MMM also plans to directly engage community and societal groups through a range of workshops, specialized sessions at international conferences and focus-group sessions.

3) The program on communicating science to society will continue with a focus on developing effective targeting and framing methodologies. This will include research on understanding the cultural mechanisms through which weather and climate risks are perceived, experienced, and addressed; and anthropological research on drought and water management perceptions and impacts. The goal here is to improve the capacity of society, commerce and industry to utilize weather and climate impacts information.

4) All these activities require an interdisciplinary research approach. MMM will strive to maintain core expertise in critical disciplines with the goal of developing and enhancing links to an international network of experts in these disciplines.

1.6 Communicating Weather- and Climate-Related Risk for Use in Decisions

Background

To ensure that MMM's weather and climate research benefits society, the resulting information must be communicated and used to improve societal outcomes. This information includes short-term forecasts and warnings derived from MMM's prediction-related research, as well as information about weather-related risk and its variations over longer timescales. Learning to communicate this information effectively requires research to understand how different types of users (such as members of the public, public officials, and others) perceive weather-related risk, interpret weather risk information, and make weather-related decisions. The resulting understanding can then be applied to develop and evaluate different communication mechanisms, incorporating knowledge about hydrometeorological prediction capabilities and systems. Findings can also motivate research to help develop new types of hydrometeorological predictions to better serve societal needs.

Until recently, expertise in risk communication and decision making has not been well integrated into the atmospheric science community. Over the last five years, MMM has built a core interdisciplinary program with expertise in communication and use of weather-related information. Researchers in the group accomplish their goals by working closely with atmospheric and other physical scientists, with social science researchers in other parts of NCAR and the external community, and with stakeholders. This research based in MMM expands on related work on climate-weather-society interactions, in other NCAR groups and externally, by focusing specifically on communication and use of the weather and regional climate predictions that are an emphasis of MMM's physical science research. Having the research program embedded in MMM allows the physical science and communication work to inform each other, and it provides unique opportunities for designing interdisciplinary research that investigates how fundamental issues, such as uncertainty, span from weather processes through prediction to communication and use.

Research in this area focuses around three intersecting themes: communication, risk perception, and decision-making. MMM aims to advance knowledge of the communication, interpretation, and use of weather forecasts and warnings and of information about weather in the context of climate variability and change. This includes investigating how weather-related risk messages are generated and conveyed, how various groups conceptualize weather-related risk, and the underlying vulnerabilities and other contextual factors that influence weather-related decision making. MMM staff also collaborate with meteorology researchers, information providers, and decision-makers to improve the communication and usability of weather risk information, enhancing its societal benefits. Topics of study include weather hazards such as hurricanes, riverine and flash floods, and drought, both in the context of real-time decisions and longer-term planning, and everyday weather forecasts. A particular emphasis is placed on the roles of uncertainty. This work is interdisciplinary, applying social science concepts and methods to atmospheric and other physical science issues.

Plans

1) MMM will continue research, in collaboration with social scientists in other NCAR groups and externally, on how members of the public and other user groups obtain and interpret weather forecasts and warnings, and how they use this information in decisions about managing weather impacts. This work includes building understanding of people's perceptions of weather-related risk and of how these perceptions and other factors influence their decisions in the face of uncertainties about future weather and climate.

2) MMM will continue work with information providers, decision makers and cultures such as the Native Americans to investigate gaps in information generation, communication, and response and to improve the communication, usability, and value of weather risk messages.

3) MMM will work toward further development of projects that integrate work on risk perception, communication, and decision making with MMM's work on meteorological modeling, prediction, and data analysis. This will span from MMM's research in short-term forecasts and warnings to longer-term predictions of changes in weather-related risk.

4) MMM will continue efforts to support and help build the growing community of weather-society researchers and practitioners.

2. Mesoscale and Microscale Physical Studies

Atmospheric-prediction models attempt to forecast quantities of human interest such as precipitation, temperature and wind, at the level of precision of human interest O(1km)-O(1000km). The accuracy of these models however depends in a fundamental way on knowledge of processes occurring on much smaller spatial scales, such as turbulence, clouds and precipitation, radiation, etc. An analogous disparity in scales occurs in consideration of the forces that allow a balloon to be inflated: the paths of individual gas molecules hitting against a balloons interior are of little common interest, but the sum total of their effects, pressure, is the central fact about balloons. The challenge for mesoscale and microscale physical process studies is to understand enough about the small-scale processes (e.g., ice-particle initiation) to predict central weather and climate features (e.g., the timing, location, intensity and type of precipitation). The small-scale meteorological processes that most affect the accuracy of weather and climate predictions are: the physics of *clouds and precipitation*, the effects of *turbulence and surface exchange,* and how these processes act in combination. Moreover both of the latter areas (in italics) are central to gaining a predictive capability with respect to *chemical and biological meteorology*. MMM's research agenda on these items is detailed below.

But even with a state-of-the-art numerical forecast model having accurate parameterizations of clouds and turbulence, a forecast cannot be successful unless the modeling system is shown to have the capability of simulating the atmospheric phenomena of interest. The complexity of these phenomena motivates our focus on the *dynamics of mesoscale weather systems* such as hurricanes, severe convective systems such as squall lines and tornadoes, and other high-impact weather systems.

2.1 Clouds and Precipitation

Background

Scientists within MMM use a combination of in-situ and remote-sensing observations, numerical modeling, and laboratory experiments to study processes important for cloud formation and precipitation development. They collaborate with other researchers throughout NCAR and the broader community to improve understanding of these processes and their parameterization in weather and climate models. This is broadly dictated by the recognition that clouds are one of the greatest uncertainties in climate models and hence our ability to assess climate sensitivity and change. Moreover, the indirect impact of atmospheric aerosols on weather and climate remains highly uncertain. With the advent of new high-resolution modeling tools (including regional NWP and climate models, global cloud-resolving models, and “superparameterized” climate models), microphysics has taken on an even greater role since it is directly coupled to the model dynamics without use of traditional convection parameterizations. MMM is uniquely positioned to advance research in this area since it is involved in several relevant aspects, including field observations, laboratory studies, theory, microphysics parameterization development, and numerical modeling. This position helps to facilitate knowledge transfer and coordination between observations, model development and testing, and application.

Since the 2008 Strategic Plan, MMM staff members have continued participating in major field projects on various aspects of cloud physics, often in lead roles. Such field projects include DC3, ICE-T, GRIP, MACPEX, MC3E, and GCPEX, among others. In particular, MMM scientists have collected in-situ observations of cloud-particle properties, focusing on data that has been often unavailable for cloud modelers. These data included microphysical observations high up in the eyewalls of hurricanes (PREDICT, GRIP), in strong updraft regions of midlatitude convection (MC3E, DC3), and at temperatures from +20C to below -70C in tropical locations (ICE-T, NAMMA, SCOUT). New probes, capable of microscopically resolving the surface texture of small ice crystals in cold clouds (MACPEX, AIDA Cloud Chamber), have produced stunning new results that have major new implications for characterizing cloud radiative properties from satellites.

Research modeling in MMM has involved studying microphysics-turbulence interactions, including turbulent impacts on droplet collision-coalescence, as well as microphysics-dynamics interactions in different regimes including shallow- and deep-convective clouds and continental or maritime-based clouds. The microphysical/dynamical interactions resulting from aircraft-induced ice crystals in cloud layers have been investigated in WRF. Considerable effort has also been undertaken to develop microphysics parameterizations capable of simulating the impact of cloud-condensation and ice nuclei and in analytically representing the size distributions of the particles, and to use these parameterizations to explore indirect effects of atmospheric aerosols including dust. Such work has included studies ranging from the impact of aerosols in cloud-resolving simulations of radiative-convective equilibrium to the effects of aerosols on simulated convective storms using WRF.

Since 2008, microphysics parameterizations developed by MMM scientists have been implemented in the public release versions of WRF, CAM/CESM, and the "superparameterized" CAM (in collaboration with the NSF Center for Multiscale Modeling of Atmospheric Processes), among other models, and used by scientists throughout the research and application communities. This work has strongly leveraged other aspects of MMM research, including collection of observations, detailed research modeling, and real-time WRF weather forecasting efforts.

In addition to these efforts, MMM scientists have provided leadership in collaborative research and support in other ways. This has included the development of an NCAR-wide informal program focusing on multi-faceted aspects of cloud and precipitation physics. a program which is expected to take a leadership role in the development of "scale-aware physics" and aerosol-cloud interactions (see below). MMM also hosted the recent international First Pan-GASS (GEWEX Atmospheric System Studies) workshop, focused on representation of atmospheric processes including clouds and precipitation in models, which attracted approximately 230 attendees.

Plans

1) MMM will continue supporting and leading field programs focused on cloud and precipitation observations, including the development and testing of new observational capabilities.

2) Research modeling of clouds and precipitation will continue to be a focus in MMM. This will involve studying interactions of microphysics and dynamics across the range of relevant scales, from the microscale to mesoscale. It will also include interactions of clouds and precipitation with atmospheric chemistry and aerosols, including indirect effects of aerosols on weather and climate, and the effects of African dust on convection and the development of tropical cyclones and hurricanes. This will be done in collaboration with ACOM, CGD, RAL, and the wider research community.

3) MMM will coordinate cloud and precipitation research with data-assimilation efforts in MMM to explore emerging, related topics in these areas. This coordination will include integration with cloud analysis and the use of data-assimilation systems to improve microphysical parameterizations, including parameter estimation.

4) MMM will continue development and testing of microphysics parameterizations in weather and climate models, including WRF, MPAS, and CAM/CESM. A specific focus of this effort will be to address multi-scale aspects of moist physics, including development of physically based parameterizations that are scale insensitive, to address a growing need in models with flexible grid resolutions (e.g., MPAS). Toward this goal, MMM will coordinate with other laboratories within NCAR to establish a program that addresses common needs for scale-insensitive parameterizations in models across lab-specific applications (WRF, MPAS, and CAM/CESM in particular). The development of "scale-aware" physics is initially expected to be a grassroots effort coordinated by

parameterization developers within MMM, CGD, and RAL, with the potential for a more formal structure as the effort progress.

2.2 Boundary-Layer Turbulence and Surface Exchange

Background

Boundary layers, and at a more fundamental level, boundary-layer turbulence, are an essential component of weather and climate as they regulate the crucial fluxes of momentum, heat and scalars between the atmosphere and land surfaces, the atmosphere and ocean, and at stably stratified interfaces separating the more turbulent boundary layers from the overlying less turbulent troposphere. These flux exchanges occur over a wide spectrum of scales ranging from millimeters (e.g., spray over the ocean) to hundreds of kilometers (e.g., tropical storms) to global climate scales (e.g., clouds and land-surface heterogeneity). MMM employs observational and simulation tools for boundary-layer turbulence studies including aircraft, remote sensors and in situ field observations, and increasingly, large-eddy and direct numerical simulations (LES and DNS) of turbulence on large parallel supercomputers. MMM's boundary-layer turbulence research continues to emphasize an increased understanding of the coupling between three-dimensional high-Reynolds-number turbulence and a variety of physical processes with a goal of improved parameterization.

Since the last Strategic Plan (2008), MMM has continued to enhance its large-eddy simulation capability for the atmospheric and oceanic boundary layers by developing a highly parallelized code capable of running on more than 65,000 computational cores. This baseline code has been coupled to numerous other physical processes with a range of time and space scales, e.g., land surface schemes with varying amounts of biological and chemical complexity, surface gravity (water) waves, atmospheric dispersion models, and small-scale terrain. An example of surface/ocean boundary-layer coupling is depicted in Fig. 7. Complimentary to these modeling efforts, MMM has planned, participated in, and analyzed results from observational studies, e.g., CHATS, CASES99, LIFT, HRES, and ITOP (the latter two are campaigns organized by the Office of Naval Research). MMM also continues to analyze numerical datasets for developing improved turbulence parameterizations for cloud-resolving models.

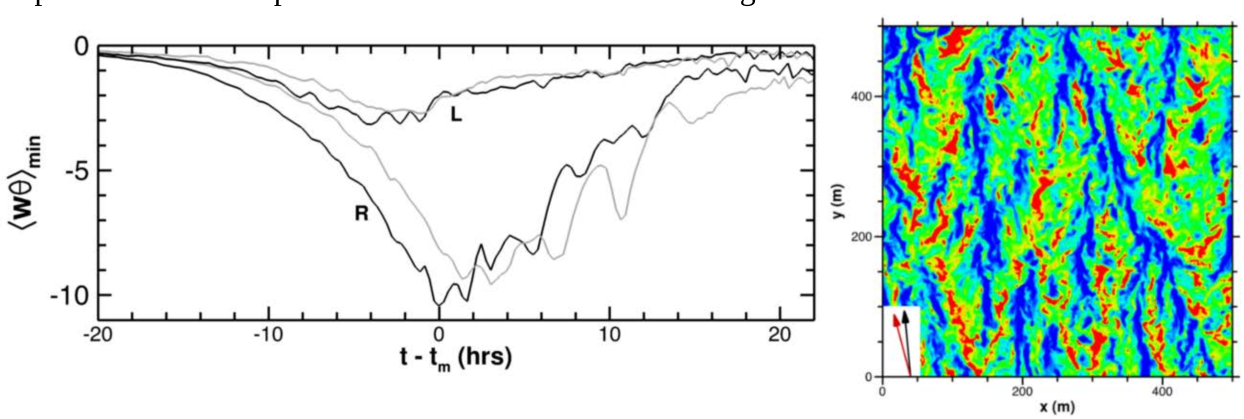


Figure 7 Response of the ocean boundary layer to high winds and waves generated by Hurricane Frances. The large-scale forcings applied to the LES model are products from the NCEP wave-prediction code WaveWatch III. The left panel depicts the time evolution of the normalized entrainment flux at the base of the ocean boundary layer on the left (L) and right (R) hand sides of the storm track with (black lines) and without (gray lines) surface wave effects.

Time is referenced to the time of maximum winds. Note the increase in entrainment on the right hand side of the storm induced by surface wave generated turbulence. The right panel shows contours of vertical velocity normalized by friction velocity at the time of maximum winds. The coherent turbulent (Langmuir) cells (the dark blue contours) are 100s of meters in length and are depth filling. The black and red arrows depict the direction of the wind and surface wave fields respectively.

Plans

1) MMM will continue to develop and apply large-eddy simulations to further improve our fundamental understanding of the surface connections between atmospheric turbulence and landscapes and the wavy ocean surface. This includes high-resolution (near petascale) turbulence simulations of marine boundary layers with surface-wave effects and spray under high winds, of canopy turbulence with diurnal forcing, of strongly stratified nocturnal boundary layers, over small-scale topography for wind energy, and with coupling to atmospheric dispersion studies.

2) MMM will partner with university colleagues, other NCAR laboratories, and outside agencies in observational studies of nocturnal boundary layers and field campaigns focused on the measurement of turbulent flows for wind-energy applications and air-sea interaction.

3) MMM will also continue to pursue scale-aware turbulence parameterizations for cloud, climate and weather models by analyzing LES and observational databases.

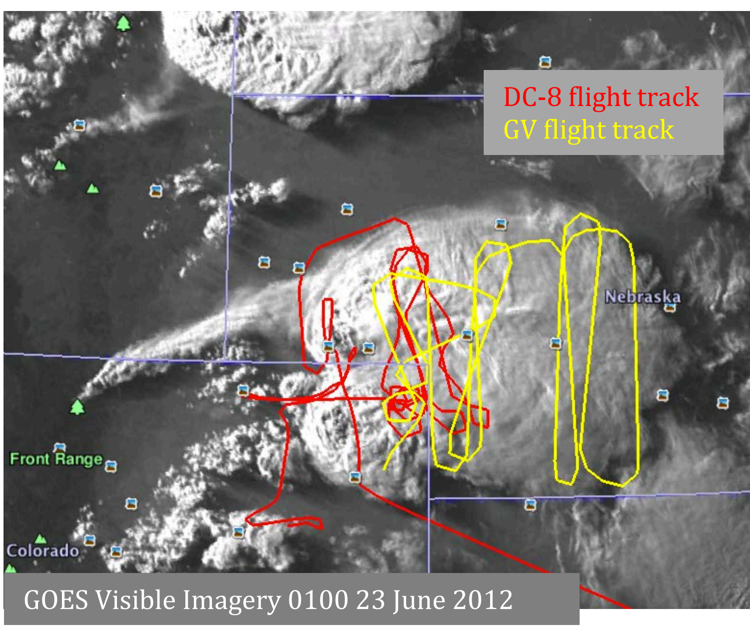
2.3 Chemical and Biological Meteorology

Background

Chemical and biological interactions are important parts of the Earth system, resulting from their close connection with the ecosystem, water cycles, boundary-layer meteorology, land-surface changes, precipitation, cloud systems, fire, air pollution, and urbanization. These interactions control energy partitioning at the Earth surface, which in turn influences the planetary boundary layer and drives the weather-climate system. With the increasing concern surrounding the potential impacts of global warming, understanding transport and effects of chemical constituents and particulates is becoming increasingly important; this includes the chemical reactions associated with aerosol transformation, cloud formation, and numerous issues confronting our growing urban societies. As such, research activities connecting chemical and biological meteorology are highly interdisciplinary, therefore involving significant interaction and collaboration across NCAR's other laboratories and with outside national laboratories, institutes, and universities.

MMM's research efforts toward refined description of chemical and biological coupling with the atmosphere relies on a combination of models, observations and theory. Our modeling efforts in this arena hinge on tools such as: WRF coupled with chemistry (WRF-Chem), WRF-Fire, NCAR's canopy-resolving large-eddy simulation (LES) code coupled to a chemistry module or driving a particle dispersion model, idealized one-dimensional models of the boundary layer incorporating canopies, chemistry and airborne measurements of biologic nuclei (ICE-L, ICE-T), as well as NCAR's primary land-surface models (Noah and CLM). WRF-Chem simulations of aerosol effects on summer-time precipitation are being conducted in the context of ongoing and upcoming BEACHON-related field programs currently taking place in the Rocky Mountain West and planned for the southeast U.S. and Amazon regions. Turbulence-resolving simulations using the NCAR LES have identified the importance of entrainment at the top of the boundary layer on the interpretation of surface- and aircraft-based observations, illuminated atmospheric stability influences controlling turbulent exchange of momentum, heat, moisture, and trace gases between the underlying surface, the canopy layers, and the overlying boundary layer by coupling the turbulence with a recently developed multi-level-canopy version of Noah, and clarified canopy influences on particle dispersion. Simple 1D models serve both as a learning tool toward understanding turbulence-canopy-chemistry interactions and as a vehicle to bring process-level understanding to bear within parameterizations for larger scale models (e.g., WRF, CESM).

Since 2008, MMM has lead or participated in a wide variety of canopy- and chemistry-focused field campaigns and subsequent data analysis. Each campaign has emphasized different components of the interconnected Earth system, for example the Canopy Horizontal Array Turbulence Study (CHATS) used a novel sampling strategy to investigate seasonal canopy variations on turbulent exchange of biogenic species. The ongoing Manitou Forest Observatory collected a three-year contiguous record examining the influence of episodic precipitation in water-limited ecosystems on canopy-induced sources and on subsequent atmospheric chemical processing producing secondary organic aerosol. The Deep Convective Clouds and Chemistry (DC3; Fig. 8) field campaign investigated linkages between the boundary layer and deep convective clouds on ozone production in the free-troposphere. Elevation-determined biome variations were used in MONTES in an attempt to understand climate-change impacts on future biogenic chemical emissions.



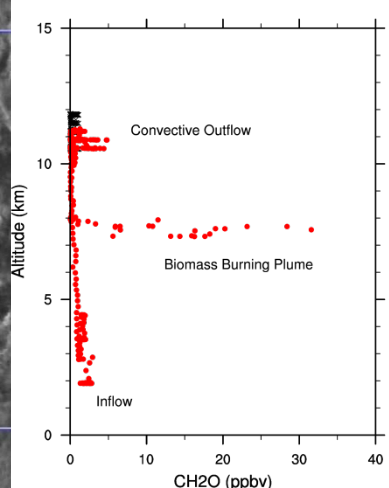


Figure 8 Left: GOES visible satellite photo showing the thunderstorm that the NCAR GV (yellow flight track) and NASA DC-8 (red flight track) sampled on 22 June 2012. To the left of the storm is the smoke plume from the High

Park fire that is being ingested by the storm. Right: Formaldehyde (CH_2O) measurements as a function of altitude from the GV (black points) and DC-8 (red points) showing the very high concentrations of CH_2O in the smoke plume and somewhat elevated values in the convective outflow.

Plans

1) Enhance or develop scale-aware parameterizations representing the representation of canopy-atmosphere coupling reactant transport, and chemical processing within NCAR's Community Models.

2) Improve the understanding of scalar transport especially under stable conditions through analysis of field observations and modeling studies.

3) Improve the ability of coupled weather-wildland fire models [i.e., the Coupled Atmosphere-Wildland Fire Environment (CAWFE) model, and WRF with WRF-Fire] to simulate wildland fire evolution, their affects on the land surface, and smoke impacts.

4) Characterize the effects of continental, mid-latitude deep convection on the transport and transformation of ozone and its precursors (nitrogen oxides and hydrogen oxide radicals and their precursors) as well as aerosols by analyzing measurements and modeling of storms sampled during DC3.

5) Address the role of organic chemistry in the aqueous phase on the formation of secondary organic aerosols through cloud resolving model simulations using the WRF model.

6) Produce multi-scale simulations to understand the weather/climate processes contributing to catastrophic wildfire events and the potential for them to occur under future (weather/climate) scenarios and connect to impacts on air quality via collaborations with ACOM.

2.4 Dynamics of Mesoscale Weather Systems

Background

Atmospheric prediction is most successful when correct results are obtained for correct reasons. Consider, for example, an event where 1 inch of rainfall occurs in 1 hour in the evening. A prediction of light rain all day that leads to 1 inch of total accumulated rainfall is not as successful as a prediction of heavy rainfall for a short period of time late in the day. Therefore MMM seeks not only to predict weather systems but also to represent those systems as accurately as possible. MMM has a long and distinguished history of documenting how mesoscale weather systems work and why – MMM studies the *dynamics* of weather systems.

A particular emphasis in MMM has been high-impact convective weather systems such as squall lines, hurricanes, and tornado-producing thunderstorms. In a recent series of studies, MMM scientists showed how numerical models could produce hurricanes with intensity greater than that ever observed, despite very realistic initial conditions. The reason is that the particular combination of thermodynamics and flow structure in hurricane eyewalls acts as a form of atmospheric front in which mesoscale gradients are enhanced. Turbulent phenomena like eyewall mesovortices can limit this tendency to enhance gradients, but MMM scientists showed that extraordinarily small horizontal grid spacing (< 100 m) is needed to accurately simulate this process. Because these research studies are not constrained by limited timeframes to which operational forecasts must abide, they are free to utilize higher resolution that can reveal additional insights. For example, recent high-resolution modeling studies of mesoscale precipitation systems (squall lines) have lead to several insights such as how turbulence that affects aircraft can be generated far away from a squall line, and how the complex flow in squall lines acts together with microphysics to create severe winds at the surface.

Several research tools have emerged from MMM's dynamic studies, perhaps most noticeable being numerical modeling systems. The Eulerian-Lagrangian (EULAG) model was designed specifically to perform numerical experiments in a virtual laboratory, and has been used to study a wide range of geophysical phenomena beyond what is capable in NWP-specific models (like WRF). EULAG is currently being used by researchers around the world to study a great variety of phenomena, and within MMM it is being used for studies of small-scale cloud processes. On the other end of the spectrum of complexity are very simple models that can be run quickly on laptops and standalone workstations. An axisymmetric hurricane model was developed during MMM's studies of hurricane intensity and this model has since been used at several universities. Lessons learned from using these idealized modeling tools has fed back into MMM's other modeling systems, like WRF, including recent changes in surface-layer and microphysics schemes to allow for more realistic hurricane structure. The need to accurately represent weather phenomena in models has driven many of the advances in numerical techniques that have emerged from MMM.

Plans

1) MMM will continue to explore and document the dynamics of mesoscale weather systems, focusing in particular on high-impact weather events such as severe convective windstorms, heavy rainfall, tornadoes, and hurricanes. Idealized representation of these phenomenon through numerical simulations and/or theoretical reasoning will be evaluated with observational data whenever possible. To this end, data collected from field projects (e.g., VORTEX2, DC3, MPEX) will continue to play an important role in MMM's dynamics studies.

2) Continuing advances in computing resources will be utilized to simulate phenomena more accurately through higher resolution and more advanced physical parameterizations. As one example, the *Yellowstone* supercomputing facility at the NCAR-Wyoming Supercomputing Center will be used to simulate tornado formation and maintenance within large eddy simulations of supercell thunderstorms. MMM will also explore direct numerical simulations of tornado vortices in tornado-chamber-like simulations, which will be used to evaluate and design subgrid turbulence schemes for severe storms.

3) MMM will continue to share the tools they develop from studies of the dynamics of mesoscale weather systems. When possible and appropriate, lessons learned from simpler numerical models will be transferred to WRF and MPAS.

CONCLUSION

The present document provides a background and outlines MMM's goals and methods for achieving higher-resolution weather forecasts and climate predictions and projections in the next five years. The success of the enterprise stands on the tripod of numerical modeling (including physics parameterizations), data assimilation and model verification. In addition, the relevance of our efforts to society turns on our ability to communicate them to the intended beneficiaries. Section 1 outlines our modeling and experimental forecasting efforts in mesoscale weather and climate problems with a heavy emphasis on our service to the community in providing the most accurate and flexible modeling systems available for general use. Section 2 outlines our plans in the realm of physical studies relevant to producing deeper understandings and consequently more accurate representations of microscale effects on mesoscale predictions.

List of Acronyms

ACAPS – AFWA Coupled Analysis and Prediction System
4D-Var – Four-Dimensional Variational
ACOM – Atmospheric Chemistry Observations & Modeling
AFWA – Air Force Weather Agency
AHW – Advanced research Hurricane WRF
AIDA – Aerosols Interaction and Dynamics in the Atmosphere
AirDat – A company that manufactures and manages the global network of tropospheric airborne meteorological-data-reporting sensors on commercial airlines
AIRS – Atmospheric InfraRed Sounder
AMPS – Antarctic Mesoscale Prediction System
ARW – Advanced Research WRF
AVN0 – GFS model
BEACHON – Biosphere-atmosphere Exchange of Aerosols within Cloud, Carbon and Hydrologic cycles, including Organics & Nitrogen
CALIPSO – Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation
CAM – Community Atmosphere Model
CASES99 – Cooperative Atmosphere Surface Exchange Study 99
CAWFE –Couple Atmosphere-Wildland Fire Environment
CCSM – Community Climate System Model
CESM – Community Earth System Model
CGD – Climate and Global Dynamics Laboratory
CHATS – Canopy Horizontal Array Turbulence Study
CISL – Computational & Information Systems Laboratory
CloudSat – Experimental satellite that uses radar to observe clouds and precipitation from space
CMMAP – Center for Multiscale Modeling of Atmospheric Processes
CONUS – CONtiguous United States
CWB – Chinese Weather Bureau (Taiwan)
DART – Data Assimilation Research Testbed
DC3 - Deep Convective Clouds and Chemistry
DDFI – Diabatic Digital Filter Initialization
DNS – Direct Numerical Simulation
EnKF – Ensemble Kalman Filter
EULAG – EULerian – LAGrangian
FRONT-PORCH – Front Range Observation Network Testbed – Precipitation Observations and Research on Convection and Hydrometeorology
GEWEX – Global Energy and Water cycle Experiment
GCPEX – GPM Cold-season Precipitation Experiment
GASS – Global Atmospheric System Study
GFS – Global Forecast System
GIS – Geographic Information Systems
GRIP – the Genesis and Rapid Intensification Processes experiment
GSI – Gridpoint Statistical Interpolation
HFIP - Hurricane Forecast Improvement Program

HRES High-RESolution Air-Sea Interaction
HWT – Hazardous Weather Testbed
ICE-D – Ice in Clouds Experiment – Dusty clouds
ICE-L – Ice in Clouds Experiment – Lenticular clouds
ICE-T – Ice in Clouds Experiment – Tropical clouds
IMAGe – Institute for Mathematics Applied to Geosciences
ITOP – Impact of Typhoons on the Ocean in the Pacific
LANL – Los Alamos National Laboratory
LES – Large-Eddy Simulation
LGEM – Logistic Growth Equation Model
LIFT – Lidar In Flat Terrain
MACPEX – Mid-latitude Airborne Cirrus Properties Experiment
MC3E – Midlatitude Continental Convective Cloud Experiment
MM4 – Fourth-generation Mesoscale Model
MM5 – Fifth-generation Mesoscale Model
MMM – Mesoscale and Microscale Meteorology Laboratory
MPAS – Model for Prediction Across Scales
MPEX – Mesoscale Predictability Experiment
MTP – Microwave Temperature Profile
NAMMA – NASA African Monsoon Multidisciplinary Analyses
NASA - National Aeronautics and Space Administration
NCAR – National Center for Atmospheric Research
NCEP – National Centers for Environmental Prediction
NRCM – Nested Regional Climate Model
NOAA – National Oceanic and Atmospheric Administration
NSF – National Science Foundation
NWP – Numerical Weather Prediction
PREDICT – PRE-Depression Investigation of Cloud-systems in the Tropics
RAL – Research Applications Laboratory
RCRS – Regional Climate Research Section
RUC – Rapid Update Cycle
SCOUT – Stratospheric-Climate Links with Emphasis on the Upper Troposphere and Lower Stratosphere
SHF5 – A simple statistical TC intensity model that uses climatology and persistence as predictors.
SUNY – State University of New York
TC – Tropical Cyclone
UCAR – University Corporation for Atmospheric Research
USAP – U.S. Antarctic Program
USAF – U.S. Air Force
UTC – Universal Time Coordinate
VORTEX-2 – Verification of the Origins of Rotation in Tornadoes Experiment-2
WRF – Weather Research and Forecasting
WRF-Chem – Weather Research and Forecasting coupled with chemistry
WRF-Fire – Weather Research and Forecasting wildland forest behavior module
WRFDA – Weather Research and Forecasting Data Assimilation system