Singletrack: A vision for the future of community atmospheric modeling

This document lays out a vision for a unified community atmosphere model capability spanning weather to climate to geospace. The document describes the shared vision, the frontier science goals in several areas (Weather, Climate, Space Weather, Air Quality), and provides an outline of the current state of community models, the requirements for a unified model, and some of the key tasks to get there.

Overall Vision

Science applications in climate, weather, and geospace require atmospheric models with a broad range of capabilities. The National Center for Atmospheric Research (NCAR) has worked with the research community to develop, maintain and support atmospheric models to meet the needs of the weather, climate and geospace community.

Over the last decade, as research objectives and atmospheric simulation needs have evolved, it has become clear that NCAR and the community would greatly benefit by moving to a single atmospheric modeling system for the community's weather, climate and geospace applications. *Singletrack* is the NCAR effort to develop a vision for a shared single atmospheric modeling system. There are many benefits flowing from a shared atmospheric modeling system motivating this vision:

- Frontier science goals require new simulation capabilities for both existing and new applications as described in the *Frontier Science* section below.
- Atmospheric models are becoming increasingly more complex, and sharing models, model components and infrastructure will make much more efficient use of development, maintenance and support resources, and better engage the community.
- Computational platforms are evolving rapidly, and sharing models and infrastructure will greatly improve our ability to respond to, and take advantage of, these evolving platforms.
- There is increasing overlap in critical applications for climate, weather, and geospace research. A shared simulation platform will help bring together these communities where overlap in their applications exist. Both the research communities themselves and the models and shared infrastructure will greatly benefit from the synergies and the diverse approaches of multiple communities to a single atmospheric modeling system.

The primary goal of Singletrack is to be able to conduct frontier science simulations in climate, weather and geospace research using the same modeling system. The system will share where possible the same infrastructure and atmospheric model components such as dynamical cores and physical parameterizations. The Singletrack atmospheric modeling system would be composed of a series of interoperable pieces or components: dynamical cores, physical parameterizations, suites of parameterizations or even chemical models. These components could be configured differently for different applications to satisfy different atmospheric application and workflow requirements. Such a system would draw heavily from existing community science (methods, dynamical cores, parameterizations), but would develop a common infrastructure over time to enable sharing of currently disparate components. We envision an evolution and evaluation phase to share and examine the suitability of different components for shared applications, thus the system will evolve over time toward a single shared “model” (common components with common infrastructure). The infrastructure will be designed from a full set of Singletrack requirements that enable the frontier applications. More implementation details of this ‘roadmap’ are below.

A unified modeling effort will serve existing applications and community models at NCAR. Existing science goals will be supported. Singletrack meets the atmospheric needs identified in the most current CESM and WRF strategic plans. For WRF and MPAS, Singletrack will support forecast and weather science, and enable better portability and testing of physical parameterizations across scales. Singletrack can serve as the atmosphere model for a next generation CESM, supporting existing climate applications with improved testing across scales, diagnostics and portability and traceability of shared physics as well. No change in CESM community governance is needed to incorporate a singletrack model into CESM. Both WRF/MPAS and CESM will gain from synergies and efficiencies.

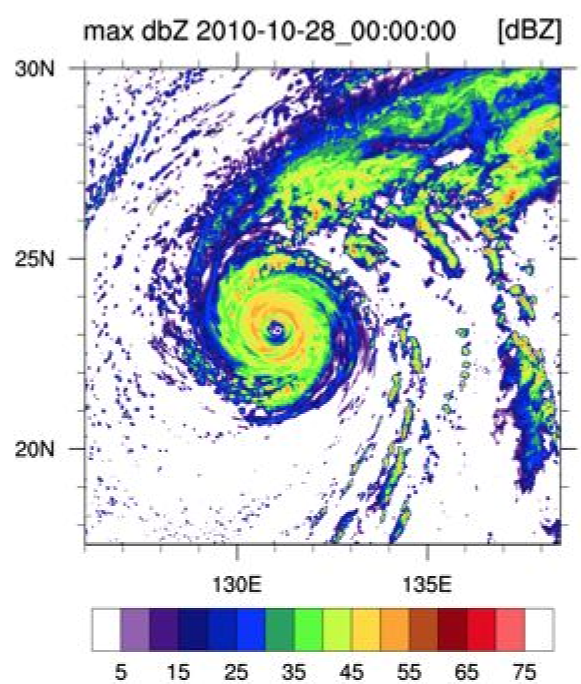
This document outlines the frontier science applications that are beyond the capabilities of our current modeling systems, but could be enabled for the community with a Singletrack weather to climate effort. A roadmap of where we are and how we might develop a single modeling system to enable these applications completes this document

Frontier Science

We envision several key frontier science applications in several areas: short term (weather) prediction of coupled phenomena, extreme events in climate, polar prediction, space weather, and air quality prediction.

Tropical cyclone predictability

There are several outstanding questions concerning tropical cyclones (TCs) and their predictability that require an advanced ESM. These include determining the predictability of TC formation at medium to extended range (5-30 days), identifying TC formation processes, understanding the mechanisms underlying the interaction between TCs and the larger-scale circulation, and exploring the earth-system dynamics that control TC climatology.

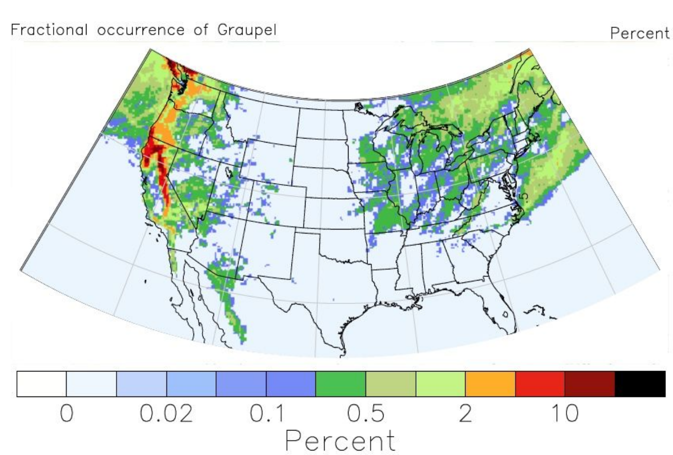


Dynamics underlying these problems involve the atmosphere, ocean, land, and their interactions, and they represent the larger-scale influence and organization of small-scale dynamics - atmospheric convection and its interaction with larger-scale atmospheric circulation, the ocean boundary layer and ocean mesoscale eddies, and land processes such as Saharan dust influencing tropical convection through radiative and microphysical interactions. A convection permitting atmospheric model ($\Delta x < 5$ km) coupled with an eddy-resolving ocean model ($\Delta x < 1/12$ degree), along with aerosol and dust capabilities, will produce detailed simulations of TCs and their earth-system interactions that will include realistic resolved TC intensity and structure for even the strongest TCs. These scientific results will also help address longer timescale questions related to the role of TCs, their character and their predictability in future climates.

Extreme events in climate

A critical challenge in climate and hydrological research is predicting the distribution of extreme events (thunderstorms, mesoscale convective systems, tropical cyclones) as well as generally high precipitation (floods) or the absence of precipitation (droughts) on sub-seasonal to climate timescales. Hydrological extremes, the presence or absence of extreme water, are critical for prediction on many scales, particularly on the climate scale. Understanding risks of flood and drought, and how they may change over time and from region to region are critical societal needs. Precipitation is particularly challenging to assess and predict, because variability and processes span from cloud microphysics (micrometers) to organized convection (1 to 100 kilometers) to synoptic systems (100s of kilometers).

We are now at a unique time where new methods and ideas from across the sub-disciplines of atmospheric and climate science can be brought to bear on the problem of representing precipitation. High-resolution weather simulations feature complex representations of processes for precipitation formation, relying on more explicit resolution of the cloud dynamics. For example, the figure below shows the frequency of occurrence of graupel, an indicator of extreme and damaging mixed phase precipitation, in a prototype configuration of a climate model (CESM 2) with modified cloud microphysics run globally with a mesh refined to a 14km resolution over the United States. This is an attempt to duplicate the features and complexity found in most mesoscale weather models, but at a climate scale (this model was run for a several year simulation).

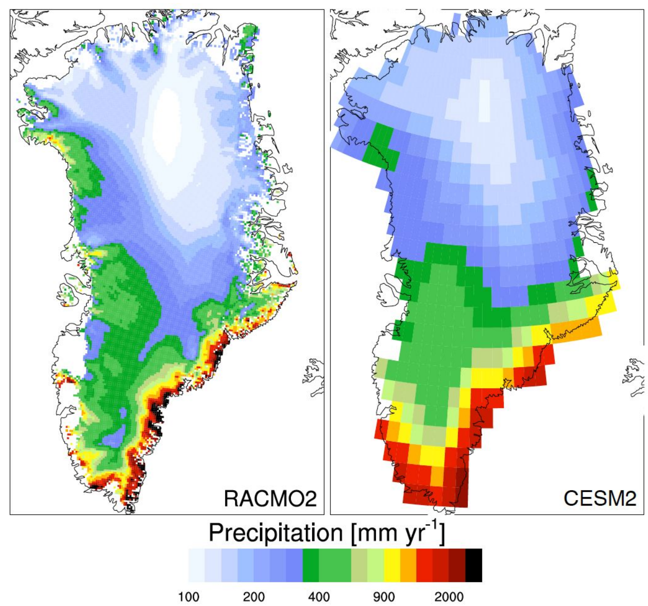


Weather models (WRF) are being used in similar fashion to capture at convective permitting scales (< 5 km) high impact weather over long time scales. While able to capture much of the important weather phenomena, they are not currently able to handle dynamic vegetation growth, ocean coupling in a reliable and efficient manner, and sea ice impacts on the large scale flows.

Climate models bring interactive land and ocean surfaces, conservative transport, and closed energy budgets that are important for representing longer timescales. Thus there is benefit in combining ongoing efforts.

An Earth System Model (ESM) based on advanced atmospheric component will enable an understanding of the frequency and intensity of weather extremes for future climate states.

Coupled Prediction of the Arctic

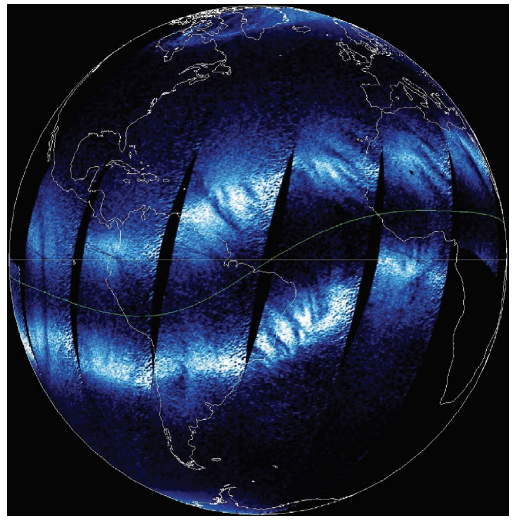


One particular area where weather and climate come together is understanding processes and predictability of polar regions, especially the Arctic. The Arctic is a critical region to understand and predict. It also spans a range of components and disciplines, including not just meteorology and climate broadly, but land surface, biogeochemistry, the cryosphere (including snow, ice sheets and sea ice) and the ocean. Thus predictability on scales from sub-seasonal to seasonal (S2S) prediction of the coupled Arctic system and requires fidelity to processes in a coupled system. High resolution (5-10km) simulations to represent the detailed structure of topography, sea and land ice, and oceans need to be combined with coupled capability to simulate oceans and sea ice in a global framework to enable predictability and a better understanding of the coupled processes in the Arctic. This same prediction framework in a global system can be extended to a decadal framework at 10-25km resolution. As an example, the figure (From Jan Lenaerts, Univ Colorado) shows precipitation from CESM2 at 1˚ (100km) resolution compared to a regional model (RACMO2) at 0.1˚ (10km) resolution. Significant precipitation biases remain in regions critical for the surface mass balance of the Greenland ice sheet, limiting our ability to predict future sea level rise.

Space Weather Predictability

Space weather events that impact technological systems are especially manifested in the ionosphere and thermosphere. These include disturbances with scales from global to mesoscale such as absorption events from flares and energetic particles, ground-induced currents that are transmitted by the ionosphere, and small-scale instabilities that cause scintillations. The effects on radio communications are well-known, and disruptions of navigation systems are increasingly important, especially for precision applications such as in aviation.

Thermospheric manifestations of space weather are critical for tracking the orbiting objects increasingly populating near-Earth space.



Ionosphere and thermosphere disturbances are caused by both solar/geomagnetic and lower atmospheric forcing. Simulating and predicting the upper atmosphere and its impact on surface climate and human systems requires a comprehensive modeling approach to integrate traditional atmospheric models with progress in specialized ionospheric dynamics and physics models on geomagnetic grids. Sophisticated data assimilation techniques are needed to integrate diverse measurements into theoretical descriptions. A major goal of integrated geospace modeling is to perform short-term geospace forecasting using solar measurements and models. High-resolution modeling capabilities, with horizontal resolution of ~10km, are also necessary to capture small-scale and impactful space weather events, such as the onset and development of ionospheric equatorial plasma bubbles, as shown in the ultraviolet image taken by the GUVI instrument on board the NASA TIMED satellite (as the dark streaks across the bright ionospheric background).

Air quality science and prediction

Air pollution is a serious threat to human health and food security: poor air quality causes one in eight deaths globally and air pollutants reduce crop yields that could otherwise feed millions of people. Air pollution hazards include high amounts of ozone and fine and ultrafine aerosols from anthropogenic and wildfire emissions. Extreme air quality events can be triggered by heat waves or stagnation events, as occurred in Paris during the summer of 2003. Hence, there is a pressing need to develop the next generation of air quality management and prediction systems, to enable extreme event risk assessment and to inform mitigation strategies.

Short-term climate pollutants (reactive species and aerosols) can also affect weather and climate by altering radiation and clouds, while clouds play a role in redistributing and removing trace gases and aerosols. These multiple links between air quality, weather and climate necessitate a flexible modeling system across many scales.

Critical applications include the representation of air quality in urban regions and interactions between atmospheric chemistry and radiation at small scales, up to the climate scale. Urban air quality applications will require regional scale comprehensive chemical modeling at fine horizontal (<1km) and vertical (multiple layers in the urban canopy) resolution. For regional impacts of urban air quality, scales of 5-10 km in a global configuration are necessary to allow the two-way coupling between phenomena that occur on the urban, regional and global scales. Application examples include the effects of wildfires in remote regions on urban air-quality, or improvements in sub-seasonal to seasonal air quality prediction from better representation of the teleconnections in global-scale phenomena (e.g. the El Niño Southern Oscillation) within a single modeling framework. Air quality forecasts will benefit from an advanced chemical data assimilation capability.

The new Model Independent Chemistry Module (MICM), implemented in the proposed unified atmospheric model, allows for chemistry to be represented consistently in simulations from the urban scale to global scale and across NCAR atmosphere models. MICM, currently under development, provides a single entry point for the specification of chemical schemes and parameterizations suitable for prediction of atmospheric composition. It will supersede the current chemistry modules in WRF-CHEM, CAM-CHEM, and WACCM, bringing those communities and their expertise under a unified framework.

Frontier Science Summary

The applications described above are detailed in the table below. In many cases they overlap, requiring horizontal resolutions down to ~3km in a limited region of the planet, and coupling of an atmospheric model to other components (land, ocean, sea-ice). Singletrack presumes parallel development of similar unified chemistry and land models within a coupled system. Requirements also include a regional capability (not just refinement, but a model with boundaries), and the ability to represent atmospheric processes up to the ionosphere (for geospace).

Singletrack Application Examples and Configurations

Frontier	*Example Application*	*Configuration*
Weather	Tropical Cyclones	3km refined mesh, coupled ocean, forecasts
Climate	Hydrologic Extremes	3km refined mesh, forecast and climate simulations
Polar	Arctic Prediction	3km refined mesh, coupled ocean, land, sea ice, land ice. Forecast and climate simulations
Geospace	Space Weather Prediction	25km global atmosphere to the ionosphere, forecast.
Chemistry	Urban/Regional Air Quality Prediction	Urban: <1km regional forecast. Regional: 3km refined global mesh, climate and forecast

Roadmap: A Unified Atmospheric Model in a Unified ESM

The vision for a unified atmospheric model, in its essence, calls for an advanced atmospheric modeling system embedded in an earth system model, one that is capable of frontier science applications in climate, weather and geospace applications, that includes chemistry and data assimilation capabilities, and that can be applied over the globe and over regional domains in the coupled system. Some of these capabilities exist in current modeling systems. This roadmap briefly describes the current state of modeling, identifies key requirements necessary to meet the needs of the applications outlined above, and identifies key tasks and resource needs.

Current NCAR community atmosphere modeling capability includes very successful and widely used models such as the atmospheric components of the Community Earth System Model (CESM): the Community Atmosphere Model (CAM) and the Whole Atmosphere Community Climate Model (WACCM and WACCM-X). WACCM-X includes geospace modeling capability. Community weather models include the Weather Research and Forecast model (WRF) and the Model for Prediction Across Scales (MPAS).

Key requirements

Frontier science applications such as those noted above imply several important requirements on an atmospheric model. The key requirements are outlined here with further detail provided in the Singletrack discussion documents, and generally encompass physical parameterizations, dynamical cores (fluid-flow solvers), and infrastructure. Physics and dynamics requirements derive from the need to simulate the atmosphere from global to cloud scales. Physical parameterizations should conserve mass and energy, be consistent with each other, and provide consistent solutions across these scales and across model configurations. Consistent parameterizations are called *scale-aware* or *scale-insensitive*, and their development is a difficult research problem. Dynamical cores must conserve mass, have good total energy conservation characteristics, and, for high resolution applications, be able to explicitly simulate clouds. Geospace applications require deep atmosphere extensions to the dynamical core and the ability to run some of the physics on different (e.g. geomagnetic) grids. Chemical applications require efficient conservative transport algorithms, and consistent treatment of aerosols and trace gases with physical processes. Global uniform meshes, global meshes with refinement, and regional meshes need to be supported within the dynamical core. The infrastructure must enable flexibility with development and evaluation of different dynamical cores and physical parameterizations. It must support the ability to run both global and regional fully-coupled earth system configurations, but also provide easy access to simulations with a ‘hierarchy’ of models such as single column models, idealized atmospheric configurations, and atmosphere-only configurations.

From Here to There: Key tasks and resources needed.

A set of detailed plans is being developed for implementation of this vision. The target science questions and vision lead to applications. The applications imply specific model configurations that need to be developed and tested. This includes entirely new functionality or new methods, as well as adapting and testing existing models, code and configurations. We are working on a detailed list of tasks and specific priorities to enable the applications noted above. At present these plans are still in draft form.

The Singletrack framework is envisioned as a community model framework and a parallel effort is underway to engage the community in Singletrack goals and applications. An important part of this effort is to design and implement a community governance model based on our shared experiences developing and maintaining existing successful community modeling systems. Governance is a critical part of model development and the Singletrack framework is an opportunity to evolve our current community interactions to a higher level.

Singletrack is an opportunity to take the tremendous science capability we have in disparate areas of atmospheric modeling from weather to climate to chemistry to geospace and prediction and to re-imagine them working together in new ways to advance knowledge and better serve society. The capability to do this is in our grasp with tremendous human capital at NCAR that can be brought to bear with the community.

Further documentation on the Singletrack project includes a current status (what we have done so far, and what we are planning) as well as detailed reports on applications and science goals, requirements and detailed next steps from different working groups on physics, dynamical cores, infrastructure and data assimilation.