Atmospheric Science for Renewable Energy
Science Plan
FY2019-FY2023

9 May 2018

Background

Renewable energy from solar and wind sources is an important part of the Nation's overall energy portfolio, and continues to grow every year. At the end of 2016, wind and solar energy sources provided approximately 80 GW and 42 GWs of power, respectively, with approximately an additional 9 GW and 16 GW of wind and solar capacity added in 2017.

The efficiency of these renewable energy sources is highly dependent on the weather conditions; for example, overhead clouds can greatly diminish the amount of solar radiation at the surface resulting in a decrease in the amount of energy that can be derived from the sun. If there is an anticipated decrease in the production from either of these renewable energy sources, the power utility companies can revert to different sources of energy (e.g., natural gas or coal turbines) to make up the shortfall. However, if the decrease is unanticipated, then the power utility company typically has to pursue a much more expensive way to make up the shortfall such as purchasing power from a different supplier. Thus, there is a strong desire to have improved weather forecasts that are tailored specifically for the renewable energy community to help with the planning and optimal use of renewable energy in the total energy supply.

The Atmospheric Science for Renewable Energy (ASRE) program at the NOAA Earth System Research Laboratory (ESRL) has been supporting research for improving forecasts for renewable energy purposes since 2010. The ASRE Program's Mission is "developing forecasts, observations of wind and solar resources, and tools to improve the efficiency and sustainability of the energy system through better understanding and modeling." The focus of the ASRE program for FY2019-2023 is to provide improved forecasts at time scales relevant for renewable energy, especially for the 12 to 36 hr period (i.e. "day ahead") for hub-height winds (i.e. from the surface to 200 m above the ground level) and solar radiation in all weather regimes. The goal is for the ASRE-sponsored research to improve operational weather prediction models, and in particular, the high-resolution rapid refresh model (HRRR)[1]. The HRRR is initialized every hour, and provides 18-36 hr forecasts, making it the near-ideal model for providing guidance to the renewable energy community.

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[1] It is anticipated that by 2022 the current HRRR, which is WRF-ARW based, will be replaced by the storm-scale RRFS (rapid-refresh forecast system), which will use the FV3 dynamic core. For sake of simplicity, HRRR will be used throughout this document for both of these rapid-refresh modeling systems. It is anticipated that HRRR forecasts lengths will be extended to 48 hrs, making it a true "day ahead" model, when the next version of the model is released to NWS operations.

In order to improve the predictive capability of the HRRR for renewable energy forecasts, a better understanding of the various physical processes that affect downwelling solar radiation and low-level winds is needed. These processes include interactions of the planetary boundary layer (PBL) with the earth's surface, turbulent mixing by the surface and by clouds, the formation and evolution of clouds within the PBL and into the free-troposphere, the evolution of the thermodynamic and kinematic profiles during the morning and evening transitions, and much more. Detailed observations of thermodynamic, kinematic, cloud, radiation, and surface properties are critical for characterizing the evolution of the PBL and understanding the processes at work that affect the PBL and above. Various modeling frameworks, including large-eddy simulation (LES) and single column models (SCM), will be used together with these observations to gain insight into the various processes at work in the PBL and how to represent them in the HRRR. Furthermore, this improved understanding must lead to more accurate model parameterizations of these processes and ultimately to improved wind and solar energy forecasts, as demonstrated via statistical analysis of the HRRR forecasts against observations.

The four divisions in NOAA ESRL are uniquely positioned to address these challenges. The Physical Sciences Division (PSD), Chemical Sciences Division (CSD), and Global Monitoring Division (GMD) all have extensive experience in observations, analyses, and radiative transfer modeling needed by the ASRE program. Scientists within PSD and CSD also have experience with LES and SCM frameworks. The Global Systems Division (GSD) has been developing the HRRR model, including both the data assimilation techniques used to initialize the model and the numerical schemes that represent various processes, such as the turbulent mixing and boundary layer clouds within the model. The four divisions have worked successfully together on projects such as the Wind Forecast Improvement Project, and thus have established relationships that will be extremely useful in advancing ASRE's research goals.

ASRE's current focus can be summarized in this statement:

> To improve solar and wind renewable energy forecasts by improving the representation of boundary layer and other processes in numerical weather prediction models.

To accomplish this, two objectives must be met. To address these objectives, some high-level activities are required:

- Identify the causes of deficiencies in the prediction of low-level winds and solar radiation components in the HRRR model using observations and process models
    - Collect and analyze BL thermodynamic and kinematic profiles, cloud property, aerosol property, land surface, and radiative flux observations to characterize and understand the errors in HRRR predictions of winds and clouds

- Improve quantitative predictions and their uncertainties in the solar and wind energy forecasts

  - Improve model physics and data assimilation systems to advance understanding of sub-grid scale processes important for wind and solar energy forecasts
  - Develop techniques to characterize and estimate uncertainties in these renewable energy forecasts

There are a large number of high-level scientific questions that naturally arise when considering these two objectives. The ASRE program will work to address these questions, all of which will lead to improved representation of PBL processes. However, ASRE is not a general PBL-based science program, and thus its research (and the questions listed below) should all ultimately work towards improving predictions of surface solar radiation (including the separation into direct beam and diffuse fields) and low-level (less than 200 m) winds, as these are what are important for renewable energy forecasts.

Several of these high-level questions are tightly coupled. They are associated with understanding the diurnal variability, surface-atmosphere interactions, entrainment zone processes, cloud property characterization, cloud evolution and mixing, and radiative transfer processes. There are also two high-level questions regarding model initialization techniques and uncertainty characterization. Since ASRE's mission is to improve the operational forecasts of renewable energy, these questions are phrased in "how well do NOAA forecast models address these questions"; however, physical understanding via observational analysis and utilization of LES and SCM models will be critical to evaluating and improving the HRRR. Additional details on these questions are provided below.

High-level science questions:

1. **Diurnal variability**:
   The thermodynamic and kinematic structure, including the characteristics of the turbulent mixing, of the PBL evolve significantly over the diurnal cycle. During the daytime, a convectively driven well-mixed PBL usually develops due to solar heating of the surface, while at night a surface-based inversion often develops resulting in a stable lower troposphere and occasionally the development of a low-level jet. Does the HRRR represent this diurnal evolution in temperature (i.e., the stability), radiative flux, humidity, and moisture correctly? Does the model represent the morning and evening transitions (i.e., the transitions between the stable nocturnal PBL and the convective well-mixed PBL) correctly? Does the model represent the evolution of the turbulent kinetic energy profile in the PBL correctly? Does the model capture the development and evolution of the nocturnal low-level jet correctly?

2. **Surface-atmosphere interactions**:
   The interactions between the PBL and the land- or water-surface include a number of processes that must be represented in NWP models. Most of these processes are active at resolutions much finer than the model resolution, and thus must be parameterized. These interactions include the effect of orographic drag on the low-level winds, the exchange of sensible and latent heat flux and radiative energy between the surface and the atmosphere,

coastal interactions, and the subsequent impact on the mixing in the atmosphere just above the surface. These interactions can also impact the formation and evolution of boundary layer clouds. Does the HRRR adequately represent these surface-atmosphere interactions? Are boundary layer clouds sensitive to the inhomogeneity of the land-surface? If so, how should this inhomogeneity be represented in the HRRR?

3. **Entrainment zone processes**:
   The entrainment zone, which is the interface between the PBL and the free troposphere above, is often characterized by vertical gradients in temperature, water vapor, and aerosols, and frequently significant wind shear can exist at the same level. The entrainment zone is where mixing between the PBL and free troposphere occurs, and the magnitude of this mixing depends strongly on the gradients in temperature, humidity, and wind. Clouds often form in this layer also, which contributes to the mixing in different ways. However, the lifetime of the clouds depends strongly on the characteristics of the entrainment zone; for example, dry air entrained from above will quickly erode a cloud layer. Are the higher order moment profiles of temperature, humidity, and wind as well as the profiles of sensible and latent heat around the entrainment zone properly represented in the HRRR? How do variations in these higher order moments impact the development/lifetime of boundary layer clouds? How do the entrainment rates in both clear sky and cloudy cases depend on environmental conditions? Does the model capture the evolution of these higher order moments and flux profile in the entrainment zone properly throughout the diurnal cycle?

4. **Cloud properties**:
   Clouds have a wide range of macro- and microphysical properties. These cloud properties strongly affect the radiative fluxes that interact with the cloud, modifying both the local diabatic heating rate profile around the cloud as well as the shortwave and longwave radiative fluxes at the surface. Furthermore, cloud-based processes such as precipitation can result in the development of convective cold pools, which can greatly impact the wind and temperature structure and evolution near the surface. Thus, NWP models must be able to simulate clouds in a realistic manner. Is the HRRR able to generate the correct distribution of cloud macrophysical (e.g., cloud fraction, cloud base height, cloud vertical thickness) and microphysical (e.g., liquid water path, effective radius) for different meteorological regimes and cloud types (e.g., stratus, fair weather cumulus)?

5. **Cloud evolution and mixing**:
   Clouds have a distinct life cycle, from formation through dissipation, which depends strongly on the ambient environment. Changes in the humidity near clouds, shear at cloud boundaries, aerosol concentrations, etc. can greatly impact the properties of the cloud, thereby altering its life cycle. Furthermore, due to diabatic effects (both latent and radiative), the evolution of the cloud over its life cycle can impact the turbulent mixing profile around the cloud itself, which ultimately can impact the wind field and the cloud itself. Does the HRRR properly represent how clouds evolve through their lifecycle?

6. **Radiative transfer**:
   The production of energy from solar energy is very dependent on the intensity of the solar radiation that reaches the Earth's surface; thus, accurately forecasting both the intensity of the direct beam and the diffuse field are important. Variations in the macro- and microphysical properties of clouds and aerosols will impact the downwelling solar flux. For example, the downwelling solar flux is very sensitive to changes in the liquid water path of the clouds (LWP) when the LWP is small (i.e., less than 100 g m^{-2}). Additionally, the downwelling radiative fluxes are very sensitive to the assumed vertical overlap of clouds; a "random" overlap will result in a smaller shortwave flux at the surface than a "maximum" overlap. Does the HRRR properly distribute the downwelling solar radiation into direct and diffuse components in cloudy (e.g., boundary layer cumulus over a wide range of LWP values) and non-cloudy (i.e., aerosol) atmospheres? Is the HRRR properly representing the effects of cloud overlap?

As indicated above, the previous six questions are highly coupled. For example, moisture fluxes from the land surface could lead to increases in boundary layer cloudiness which would then decrease the downwelling shortwave radiative flux; however, entrainment at the top of the convective boundary layer could modulate this. Similarly, uncertainties in land-atmosphere interactions could affect the collapse of the convective boundary layer during the evening transition, thereby leading to errors in the development of the nocturnal stable boundary layer and the formation of a low-level jet. Thus, it may be difficult to isolate research in one of these areas from the others, thereby suggesting that a unified approach may yield more progress.

However, there are two important questions that are, perhaps, more isolated from the others.

7. **Model initialization**:
   Numerical weather prediction is often considered an initial value problem. Certainly, if the model is not initialized well to represent the current conditions, then a poor forecast will result. Improvements in data assimilation techniques, both to use additional observation types and to improve how the current observations are being used, need to occur to enable a better initialization of the model. Furthermore, data assimilation can be performed at a range of scales, and recently there have been some advances in developing multi-scale data assimilation techniques to enable smaller mesoscale structures to be initialized into the model analysis. Do improvements in data assimilation techniques, or assimilating new observations, improve the representation of PBL and cloud properties, and thus improve the forecasting of wind and solar energy at the surface?

8. **Uncertainty characterization**:
   Ultimately, no forecast will be perfect. However, even imperfect forecasts can still add value, provided the bias and uncertainty in the forecast are understood. The forecast uncertainty is dependent on the meteorological regime (i.e., fair weather event, overcast conditions, frontal passage, etc.), as the model may be able to represent one weather type better than another. The uncertainty of the forecast will also have a spatial and temporal component, and will likely be dependent on the forecast period (i.e., longer forecasts are

more uncertain then shorter forecasts). Can we develop techniques that characterize and quantify the propagation of uncertainty in the forecast as a function of meteorological condition, spatial and temporal variability, forecast time, etc.? Can we develop advanced post-processing techniques that improve the accuracy and reduce the uncertainty of these renewable energy forecasts?

These are questions are broad and encompass a wide range of research. Ultimately, the research performed under the auspices of ASRE is aimed at improving forecasts of winds below 200 m and solar radiation at the surface in the 12-36 hour forecast window.