J12.3 SHORT-RANGE SOLAR RADIATION FORECASTS IN SUPPORT OF SMART GRID TECHNOLGY

George D. Modica[1], R. d'Entremont, E. Mlawer, and G. Gustafson

[1]Atmospheric and Environmental Research, Inc., Lexington, Massachusetts

1. INTRODUCTION

Solar and wind energy generation assets are fast emerging as sources that will eventually supply a greater share of domestic electricity needs. The US power grid will require new infrastructure to connect these power generation facilities with consumers, as well as smarter controls to better match fluctuating supply and demand cycles. For example, solar energy generation facilities will be impacted by changes in the local cloud distribution. If these intra-day changes could be detected and forecast, the information could be used to order increases (decreases) in power production (consumption) from elsewhere.

In this paper we describe a prospective solar radiation forecast system that integrates cloud analysis, prediction, and radiative transfer technologies to provide the smart grid with this valuable information. The proposed system combines imager data from ground- and space-based remote sensing systems, a cloud forecast model to provide a detailed forecast of various cloud properties for time periods of minutes up to an hour or more, and a radiative transfer model for computation of downwelling solar irradiance in the appropriate waveband at the solar collector. In later sections we describe the components of the forecast system in further detail and illustrates some of its capabilities.

1.1. Forecast Challenge and Approach

Modern weather prediction methods span a wide range of applications and techniques. Some of the most common methodologies are compared in terms of forecast skill in Figure 1. Each presents specific advantages and disadvantages. Perhaps the most common forecast method is the application of regional and global numerical weather prediction (NWP) models to provide 6-240+ hour forecasts of meso- and synoptic-scale atmospheric motions. However, shorter-range weather forecasts are also important for a variety of applications related to, for example, aviation, public safety, weather sensitive commerce, and sporting events. In some cases, the conventional NWP model approach does not yield the best results for these applications, especially if the objective is very-short range forecasts (i.e., 30 minutes to 1 hour).

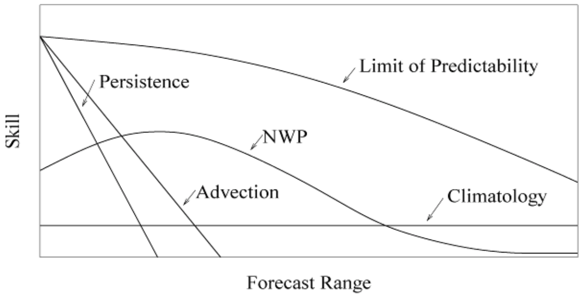

Figure 1. Diagram of skill as function of forecast range for a variety of nowCast methodologies. At different forecast ranges, different forecast techniques have varying skill. The theoretical limit to predictability is caused by the chaotic nature of the atmosphere.

In principle, the solar radiation forecast problem could be treated with an NWP model. After all, NWP models can ingest a wide a variety of data types and can be run with quite high spatial resolutions (e.g., 1-km) with good forecast skill. NWP models, however, require significant computational resources and usually require a period at the beginning of the forecast for geostrophic adjustment (a process where the mass and momentum fields mutually adjust to each other). Consequently, their skill does not generally match even simple advection models for the very short forecast periods of interest here.

The key challenges for forecasting solar radiation are accurate depiction of the local cloud distribution over the next hour and accurate quantitative evaluation of the downwelling solar radiation at the surface. Since clouds are the predominant factor in determining the amount of downwelling solar radiation at the surface, we have chosen an advection-based cloud forecast methodology appropriate for very short-range forecast periods. Advection is the horizontal transfer of air or cloud mass properties by the velocity field of the atmosphere. Note from Figure 1 that advection methods offer skill performance superior to NWP for short forecast ranges.

The most simple advection techniques compute a single movement vector for a single domain. The movement vector is then used to provide short-term forecasts simply by translating features of interest—such as clouds—at the speed and direction of the computed vector. In more sophisticated advection

---

Corresponding author address: George D. Modica, AER, Inc., 131 Hartwell Ave., Lexington, MA, 02421-3126; email: gmodica@aer.com

techniques, this vector can vary horizontally and vertically within the domain. Extrapolation uses the past movement of features of interest for short-term predictions of their future positions. Ground- and space-based imagers provide high-resolution cloud structures and wind fields to help maximize forecast precision and accuracy in the nowcast area of interest,.

The general concept of operations for the solar forecast algorithm is presented in Section 2; additional information about the individual components is discussed in Section 3. Some concluding remarks are provided in Section 4.

2. CONCEPT OF OPERATIONS

The general concept of operations for a solar radiation forecast system is illustrated in Figure 2. First, space-based cloud imagery data is collected, processed, and archived. The space-based cloud imagery may be supported with *in situ* ground-based cloud imager data. Ancillary NWP and radiative transfer model (RTM) data are required to support later process. In the next step, an analysis of the imager data yields a general 3-dimensional field of the cloud distribution as well as specific information about the clouds, such as type (i.e., liquid or solid), base, and top. The initial cloud distribution is then projected forward in time with a cloud forecast module. The cloud distribution at the forecast time is next used as an input to a RTM. The RTM computes the solar flux incident at the level of the solar panel or collector. The concept of operations shown in Figure 2 includes a quality assurance process that includes feedback from final observations of solar radiation.

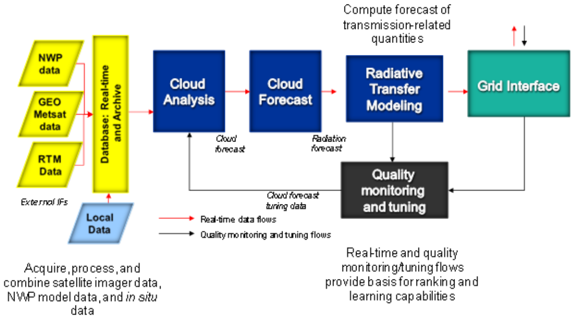

Figure 2. Schematic view of a weather impact forecast system showing input data, wind and cloud forecast modules, integration, and QA

3. DESIGN CONSIDERATIONS

The concept of operations serves as a general blueprint for an operational system. Each of the components that comprise the complete system shown in Figure 2 has been used with success in other applications. We anticipate that most of the effort required to build an integrated system will be related to issues pertaining to module interfaces and quality assurance. A more detailed description of the system modules is presented next.

3.1. Cloud Analysis and Characterization

Before clouds can first be forecast, their initial distribution must be determined. This is accomplished with a cloud detection algorithm. The cloud-detection algorithm is actually a suite of tests that use spectral signatures to discriminate cloud from clear-scene surfaces. The cloud analysis processing steps are shown in Figure 3. Data for the cloud tests is provided primarily by the GOES family of satellites, although ground-based imager data can also be integrated to provide better local cloud detection. Various cloud detection techniques are employed, including simple temperature thresholds, inter-channel comparisons and comparisons between the channel data and spectral information characterizing the clear-scene surface. The selection of tests is applied to each pixel in the analysis scene and is a function of the level of solar illumination and the available sensor channels. Some tests require ancillary data that is provided by an NWP model. Information on the cloud phase (i.e., liquid vs. frozen) is also extracted from the image data in addition to the cloud detection functions. The ensuing cloud property retrieval results in pixel-level products, such as cloud top and base, cloud mask, an optical depth.

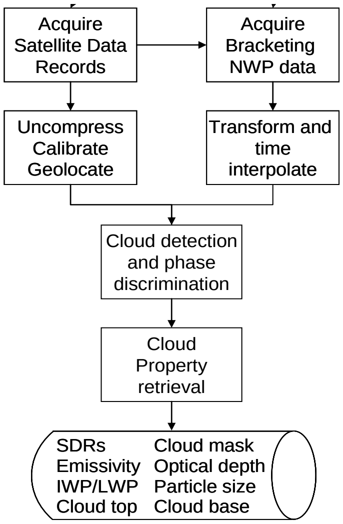

Figure 3. Cloud analysis processing steps

3.2. Cloud Forecast

The cloud forecast module employs a feature-tracked cross-correlation technique for generating short-term cloud forecast products. The general premise of cross-correlation techniques is that for short-term (0-1-hour) predictions the past movement of cloud features of interest will yield their future positions. The cross-correlation method utilizes cloud features determined during a cluster analysis step. Features are followed digitally between a pair of input images in order to generate a forecast movement vector field. GOES satellite and ground-based imager data can both be used for cloud-tracked winds. For every feature center identified in the first image "A," a search is performed in the second image "B" for a corresponding match. Once all the identified features in image "A" have been tracked and quality checked, a trajectory wind field is generated from a sparsely populated wind-vector grid. This is accomplished in a three-step process illustrated in Figure 4. The first step is that of computing and grid-referencing the optimal motion vectors for each of the features that were tracked. The resultant field sparsely populates the grid, as is illustrated by the gray vectors in Frame 1 of Figure 4. In Step 2, a nested subgrid is defined within the original grid, and for each point on this subgrid a wind vector is assigned using a distance-weighted average of every feature-tracked wind. The blue vectors denote this field in Frame 2 of Figure 4. Once the subgrid is populated, a 2-D optimum interpolation is performed to assign a motion vector to every pixel in the projection. Low- and high-level flow fields can be calculated based on the prior motion of low- and high-level clouds, respectively. The low-level field is used to advect low cloud features and the high-level field for high cloud features (Figure 5). With a quality-checked forecast flow field now in place, each cloud feature in image "B" is advected using the feature-tracked trajectories. Although features are advected in the 0-1 hour timeframe with no strengthening or weakening of fields, cross-correlation accuracies are routinely higher than their NWP counterparts during this short forecast period.

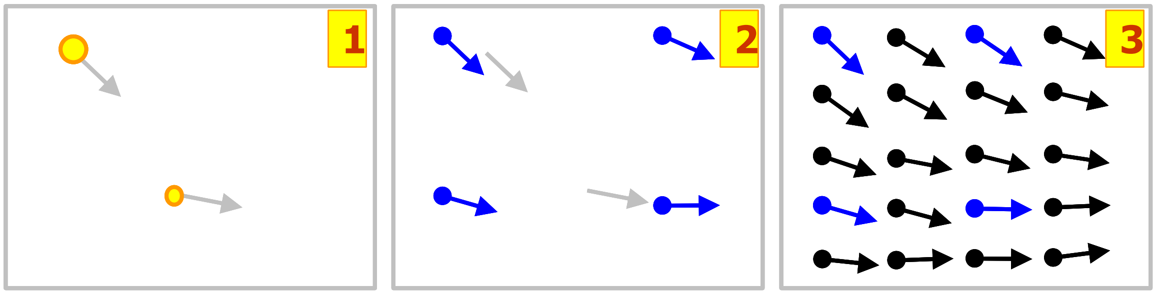

Figure 4. Building the feature-tracked trajectory forecast field. See text for discussion.

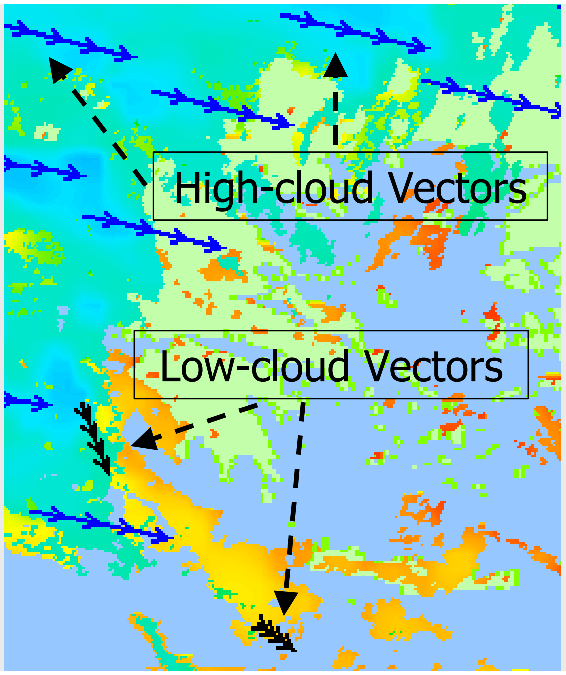

Figure 5. Building separate feature-tracked trajectory forecast fields for high (blue vectors) and low clouds (black vectors). Note the vertical wind shear. Arrows indicate 15-minute time steps.

Finally, cloud microphysical properties in terms of cloud top, base, and cloud optical depth (see Figure 3) are extracted from the forecast cloud field for later input to the radiative transfer model (Section 3.3).

We acquired a dataset of space- and ground-based imager data during earlier demonstrations of the cloud forecast module's capabilities with the intent of performing some of the procedures that would be necessary in the implementation of an integrated solar radiation forecast system. Figure 6 shows a sample image from a ground-based cloud imager, called the Total Sky Imager (Long et al. 2001). The instrument was situated at the Atmospheric Radiation Measurement (ARM) program's Southern Great Plains (SGP) facility. The TSI is an automatic, full-color sky imager system that provides real-time display of daytime sky conditions. The TSI does not provide calibrated radiance data, but rather photographic images. New technological advances have led to ground-based imagers that can provide calibrated radiances in a variety of visible and infrared wavelength bands.

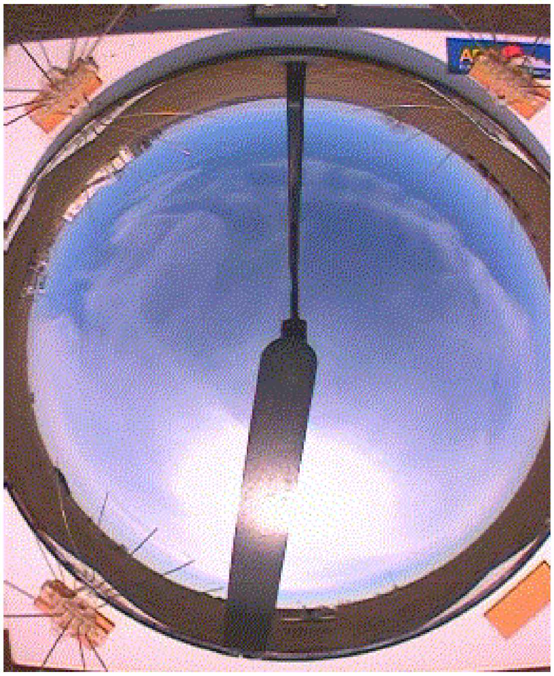

Figure 6. Raw image from the TSI located at the ARM SGP site in Lamont, KS at 1900 UTC 22 Feb 2007

The azimuthal, or "fisheye" projection of the TSI image is cumbersome to deal with in practice, so we opted to transform the data onto a rectangular projection. Figure 7 shows the raw image data after transformation onto a rectangular projection. A multispectral image generated from GOES-12 satellite data is shown in Figure 8. That image shows a space-based perspective of the cirrus cloud distribution observed by the ground-based imager instrument.

Figure 7. Same data as shown in Figure 6, but after transformation to a rectangular projection.

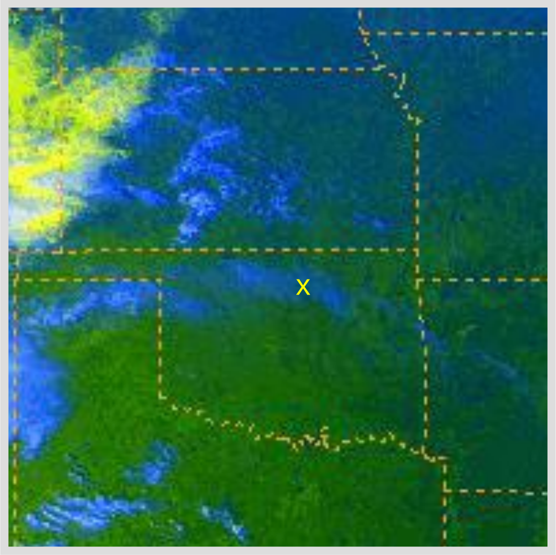

Figure 8. GOES-12 multispectral image of data from 1900 22 Feb 2007 centered over the ARM SGP site, marked by an 'x.' The image was generated by using the visible (0.65 µm channel 1) to drive the red and green guns of the display, and the infrared (10.7 µm channel 4) to drive the blue.

The data in the rectangular projection of Figure 7 were used to test the cloud advection methodology outlined earlier in this section. Vertical temperature sounding data is required as part of the process to estimate the cloud height; alternatively, NWP model can provide this information to prescribe the top and base of the clouds, and is also required to map the TSI to the satellite projection. Newer ground imager technology can provide calibrated visible and infrared radiance data, leading to a more straightforward and reliable estimation of the cloud height.

3.3. Radiative Transfer Modeling

With the forecast cloud information determined from 3.2 above and environmental information from an NWP model, an RTM can be used to provide the downwelling flux at the level of the solar collector in the frequency band of interest. The Rapid Radiative Transfer Model (RRTM; Mlawer et al. 1997, Mlawer et al. 1998) has been demonstrated to provide accurate downwelling solar radiation fluxes at the surface when combined with cloud inputs. RRTM is a rapid radiative transfer model that utilizes the correlated-k approach to calculate fluxes and heating rates efficiently and accurately. Figure 9 shows a comparison of *in situ* solar radiation flux data collected for several case studies at the ARM SGP site along with calculations from RRTM, its global model companion RRTMG, and CHARTS, which is a radiative transfer that includes the effect of scattering processes.

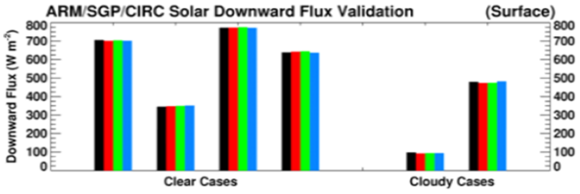

Figure 9. Comparison of downwelling solar radiation (Wm^{-2}) computed from RRTM (green), RRTMG (blue), CHARTS (red), and observations collected at the ARM SGP site for four clear cases (left) and two cloudy cases (right).

The graph in Figure 9 shows that the RTM models computed values of downwelling solar radiation flux at the surface that were very close to observed. Both clear and cloudy sky cases were selected. The cloudy cases demonstrate the RTM's ability to modulate the clear sky radiative transfer processes in the presence of clouds

4. SUMMARY AND CONCLUSIONS

We have described a solar radiation forecast system designed to provide short range forecasts of 30 minutes to 1 hour duration. The proposed system combines data from ground- and space-based imaging instruments, a cloud forecast model to provide a detailed forecast of the cloud distribution and cloud properties, and a radiative transfer model for computation of downwelling solar irradiance in the appropriate waveband at the solar collector. The main components have been tested individually and in limited combination. These pieces can be integrated in a straightforward design to produce an end-to-end system for real time solar radiation forecasts for the growing solar energy industry.

Acknowledgements: Data used in this study was provided by the DOE ARM Southern Great Plains facility.

REFERENCES

Long, CN, DW Slater, and T Tooman. 2001. Total Sky Imager Model 880 Status and Testing Results, ARM Technical Report ARM TR-006, U.S. Department of Energy, Washington, D.C.

Mlawer, E.J., S.J. Taubman, P.D. Brown, M.J. Iacono and S.A. Clough, 1997: RRTM, a validated correlated-k model for the longwave, *J. Geophys. Res.*, **102**, 16,663-16,682.

Mlawer, E.J., and S.A. Clough, 1998: Shortwave and longwave enhancements in the rapid radiative transfer model, in Proceedings of the 7th Atmospheric Radiation Measurement (ARM) Science Team Meeting, U.S. Department of Energy, CONF-970365.