Agricultural Management Decision Aids Driven by Real-Time Satellite Data

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ABSTRACT

In a NASA-sponsored program entitled "Use of Earth and Space Science Data Over the Internet," scientists at the University of Wisconsin—Madison have developed a suite of products for agriculture that are based in satellite and conventional observations, as well as state-of-the-art forecast models of the atmosphere and soil–canopy environments. These products include an irrigation scheduling product based in satellite estimates of daily solar energy, a frost protection product that relies on prediction models and satellite estimates of clouds, and a product for the prediction of foliar disease that is based in satellite net radiation, rainfall measured by NEXRAD, and a detailed model of the soil–canopy environment. During the growing season, the first two products are available in near-real time on the Internet. The last product involving foliar disease depends on a decision support system named WISDOM developed by the University of Wisconsin—Extension, which resides locally on growers' home computers. Growers interface WISDOM with a server to obtain the rainfall, meteorological data, surface radiation inputs, and canopy model output required by WISDOM for the blight models.

1. Introduction

The use of computer-based Decision Support Systems (DSSs) is common for business and other applications where providing timely information and decision assistance to users can make a significant difference in the efficiency, cost-effectiveness, and environmental impact of their enterprises. Even at the scale of the family farm, agriculture is increasingly complex and everyday decisions regarding irrigation, the application of agricultural chemicals, and what measures to take to protect a crop against frost damage or disease can make the difference between profit and loss in a growing season. In the longer term, these same decisions can make a significant difference on the environmental impact of agriculture and the prospects for future growing seasons, as well as on the quality of life in the farming community.

As one of the projects in the National Aeronautics and Space Administration (NASA) program entitled "Public Use of Earth and Space Science Data Over the Internet," interdisciplinary scientists at the University of Wisconsin—Madison Cooperative Institute for Meteorological Satellite Studies (CIMSS) and Department of Soil Science are bringing such DSSs for agriculture into the space age through the coupling of satellite data and data products, conventional data and state-of-the-art computer models of the land surface and atmosphere. Earlier attempts to apply satellite data to agriculture were plagued by data and information movement difficulties, which made the information systems problematic and unreliable. This situation has changed, however, and the timely retrieval of the multiple near-real-time satellite and

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supporting datasets required for routine use by agricultural applications is now feasible. This will become increasingly so with the future availability of such data on the Internet. Similarly, dissemination of the resulting data and analyses to end users is now possible via the Internet, satellite-based commercial data transmission services, and telecommunication services.

In the project to be described, named TiSDat (for Timely Satellite Data for Agricultural Management), University of Wisconsin scientists selected agricultural sectors in which data availability was thought to be hampering the full adoption of currently available knowledge to management decision making. These applications were also selected based on the present availability of some form of decision framework that could be improved through the application of satellite data and modern computer modeling techniques. The crops initially targeted for decision support systems are of comparatively high economic value and the associated growers are motivated and well organized. Last, but equally important, in each area selected, the use of an improved information base has the potential to have a positive impact on environmental quality.

The list of prototype decision support services includes (a) an irrigation scheduling product based in satellite estimates of incident solar energy and an associated product for estimating electrical power demand; (b) a frost protection product using satellite estimates of cloud cover (to estimate the nighttime downwelling longwave radiation), and surface and synoptic data, all coupled to forecast models for the atmosphere and soil–canopy environments; and (c) a plant disease warning decision support system that uses a satellite-based estimate of the surface solar and longwave radiation coupled to a soil–canopy model. Of these products, the irrigation scheduling, frost protection, and plant disease systems are currently operational and will be described in detail, while the electrical power demand product is in development. Though the prototype products are being developed initially for applications in Wisconsin, there are many other agricultural regions that can benefit from similar information. We are working to encourage adoption by the private sector once value has been demonstrated. Further relevance and commercialization potential have been added to the work with the discontinuation (as of 1995) of agricultural forecasting by the National Weather Service (NWS).

2. Applications

a. Irrigation scheduling

Irrigation is an essential practice for crops grown on sandy soils (where the water retained by the soil is insufficient to supply plant demands between rains) and also in agricultural regions where rainfall is limited. Both in the United States and worldwide, irrigated regions are about twice as productive as nonirrigated agricultural lands; however, there is little potential for expansion of the current irrigated acreage and irrigation water supply (Postel 1993). Thus, optimal management of existing resources is extremely important. Excessive irrigation leads to leaching of fertilizers and other agricultural chemicals from the soil into the ground water, as well as an increased electrical power usage (to pump the irrigation water). This electrical demand unfortunately coincides with the peak summer demand of electricity for air conditioning.

In one standard approach to decide when to irrigate and how much irrigation water to apply, growers maintain a daily balance of soil water using estimates of the amount of water the crop extracted from the soil during a day, the total capacity of the soil to hold plant-available water, and the previous day's level of this water. For many agricultural crops, when the amount of soil water is not a limiting factor, the quantity of water that the plants evaporate depends most strongly on how much energy is available during the day and secondarily on other factors, such as the air temperature, humidity, wind speed, and the plant species. Thus, knowledge of daily available solar energy for evaporating water from a crop (evapotranspiration) is fundamental to irrigation management.

Satellite data can provide the high quality estimates of incident solar energy at the surface (insolation) required for evapotranspiration estimates with much greater spatial detail and cost effectiveness than can be achieved using a network of ground-based pyranometers. The techniques for evaluating insolation using satellite imagery in the visible portion of the electromagnetic spectrum date back to the late 1970s and early 1980s, when several such systems were developed (see, e.g., Tarpley 1979; Gautier et al. 1980; Diak and Gautier 1983; Pinker and Laszlo 1992). Reviews of such methods are given in Pinker et al. (1995) and Schmetz (1989).

The model used here to estimate solar energy is similar to that described by Diak and Gautier (1983), which was developed for the early U.S. series of Geostationary Operational Environmental Satellites (*GOES 3–7*). It has been modified for the new generation of GOES satellites (*GOES-8* and *GOES-9*), which have somewhat different characteristics (Diak et al. 1996; Menzel and Purdum 1994).

Usually, 8–12 individual GOES images are used during the course of a day (depending on the length of daylight), at hourly intervals, to make "snapshots," that is, instantaneous estimates of the solar energy conditions at the satellite image times. The instantaneous solar energy estimates from individual images are then numerically integrated over time to provide daily estimates of solar energy at a site. These daily estimates agree to an rms accuracy of 10% with measurements made with ground-based pyranometers (Diak et al. 1996).

Figure 1 shows an example of a contour map of the daily solar energy totals estimated from images taken by *GOES-8* for the eastern half of the United States. The contours are overlaid on a *GOES-8* image from the afternoon of the same day (13 September 1997). The solar energy amounts are most strongly related to the presence or absence of clouds during the day. Clouds may have a high variability in space and time, so that even ground-based measurements of solar energy may misrepresent insolation at a location just a short distance away from the instrument site. The GOES satellite is able to detect variations in solar energy over distances as small as several miles and thus can provide superior information for spatially detailed estimates of irrigation requirements.

Many cultivated crops utilize water close to the so-called potential evapotranspiration rate when soil water is not limiting and simple methods exist to estimate this potential evapotranspiration. The method of estimating the potential evapotranspiration (ET_p) for Wisconsin is based on a formulation developed by Priestley and Taylor (1972) that is in very common use and has proven reliable for estimating ET_p in moist temperate regions. The Priestley–Taylor equation for ET_p is

$$ET_p = 1.26(R_n - G)S/(S + \gamma). \qquad (1)$$

In this equation, ET_p is potential evapotranspiration (W m^{-2}), R_n is the net radiation at the land surface (net solar flux + net thermal infrared flux, W m^{-2}), G is the soil heat flux (W m^{-2}), S is the slope of the saturation vapor pressure curve with respect to temperature at the temperature of the air (hPa K^{-1}), and finally γ is the psychrometric constant (hPa K^{-1}). A positive sign of the various fluxes indicates a flux toward the surface.

The term ($R_n - G$) is the available energy at the surface of the earth, which through surface energy budget considerations (neglecting the small relative amount of energy that plants use in photosynthesis) must either be partitioned into heating the lower atmosphere or used in the transpiration of water from plants or evaporation of water at the soil surface. In most daytime conditions, $R_n - G$ is the dominating term in the potential evapotranspiration. The $S/(S + \gamma)$ term of Eq. (1) modulates ET_p, taking into account how the

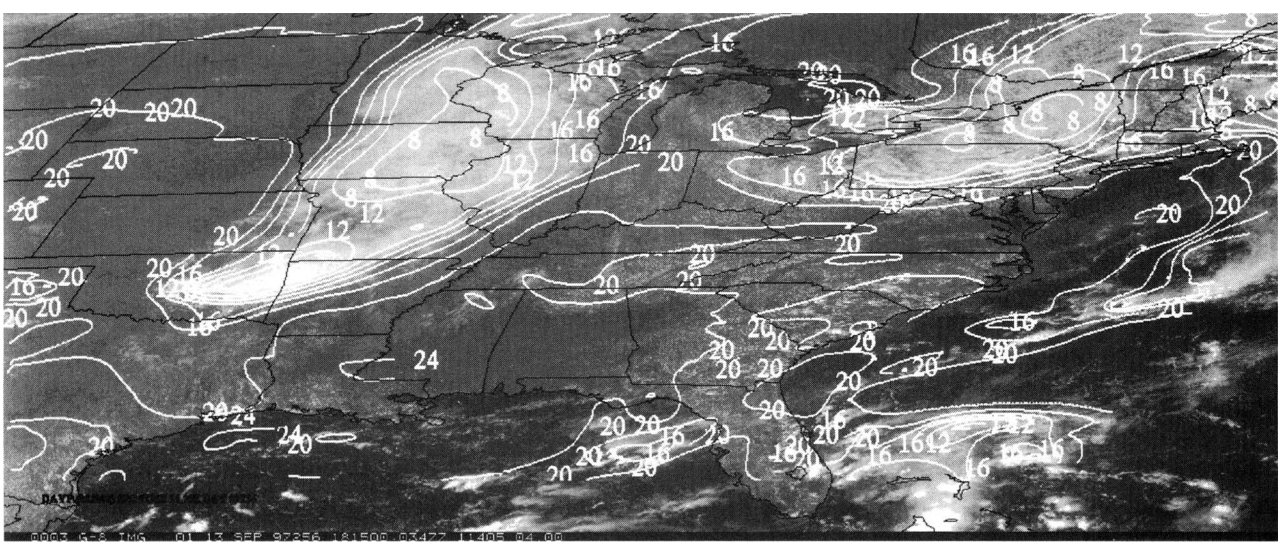

FIG. 1. Contours of daily solar energy (MJ m^{-2}) evaluated from *GOES-8* visible imagery for 13 September 1997 overlaid on a *GOES-8* image at 1800 UTC of the same day.

slope of the saturation vapor pressure curve with atmospheric temperature influences evapotranspiration, while the 1.26 is an empirical constant. This constant amalgamates the effects of atmospheric turbulent transfer coefficients and the atmospheric vapor pressure deficit that appear in more detailed methods for estimating ET_p (Penman 1948).

The net radiation (R_n, W m^{-2}) term in Eq. (1) is expressed in the standard manner as

$$R_n = S_0(1 - A) - L_u + L_d. \quad (2)$$

In this equation, S_0 is the incident solar flux (W m^{-2}), A is the surface albedo (dimensionless), L_u is upwelling thermal infrared flux (W m^{-2}), and L_d equals downwelling thermal infrared flux (W m^{-2}). The largest contribution to the net radiation and available energy (R_n–G) during daytime hours is usually the net solar energy at the surface. The incident solar flux is estimated from satellite data, as described above. A surface albedo of 0.25 (a value representative of many vegetated and nonvegetated surfaces) is used to estimate the net solar radiation.

The net thermal infrared flux term (L_n) of the total net radiation consists of two directional terms, the first being the upward thermal radiation emitted by the surface (L_u) and the second term being the downwelling thermal radiation to the surface emitted by the atmosphere and clouds (L_d). Under clear conditions, the net effect is usually a loss of energy from the surface, with instantaneous values ranging from approximately 50 to 150 W m^{-2}. When clouds are present, this net loss from the surface is normally reduced from the clear-air value.

Operationally, the upwelling thermal radiation from the land surface is estimated using the surface air temperature from NWS reports as the emitting temperature in the Stefan–Boltzmann relationship, that is,

$$L_u = \varepsilon \sigma T^4. \quad (3)$$

In this equation, ε equals the surface emissivity (presumed = 0.98 for vegetated surfaces, dimensionless), σ equals the Stefan–Boltzmann constant (5.67 × 10^{-8} W m^{-2} K^{-4}), and T equals the surface emitting temperature (K). The daytime net longwave radiation budget is estimated using the following procedures. A clear-sky emissivity (ε_c, dimensionless) is calculated using the method of Idso (1981), which estimates emissivity as a function of the temperature and vapor pressure of the lower atmosphere. The equation for net longwave radiation at the surface under clear conditions is then

$$L_{nc} = L_u(1 - \varepsilon_c). \quad (4)$$

When clouds are present (detected in the solar insolation routines), a ratio (C, dimensionless) is calculated by dividing the actual incident solar radiation by a theoretical value calculated for clear-air conditions. This ratio C is used to estimate the influence of clouds on the clear net surface longwave radiation and the resulting cloudy net longwave radiation is then calculated using the expression

$$L_n = L_{nc}C. \quad (5)$$

This has the desired effect of reducing the net longwave flux from its clear-sky value [Eq. (4)] when clouds are present. While the estimation of the L_n term in the radiation budget may have large relative errors compared to the range of its potential values, this net thermal radiation for daytime periods is usually small compared with the solar component of the total net radiation. As a result, errors in the total net radiation budget caused by errors in estimating L_n are relatively small. The ground flux term (G) in Eq. (1) is also often a smaller term in the energy budget of the land surface, especially for vegetation-covered soil. We estimate the daily conduction total as 0.10 times the daily net radiation, an average for vegetated surfaces.

Figure 2 shows an example of the final evapotranspiration product provided to growers, a geographical map of daily potential evapotranspiration totals [daily potential evapotranspiration energy totals from Eq. (1) have been converted to their water equivalent]. It is an estimate of how much soil water was used by crops on that day and thus what will need to be replaced via irrigation to keep a constant value of soil moisture. The map is for the same day as the insolation map shown in Fig. 1 (13 September 1997) and the close resemblance between the insolation totals and potential evapotranspiration is evident. Since the methods estimate evapotranspiration for a complete coverage of the ground by the crop leaves, users reduce the daily evapotranspiration from the full-cover value that we supply based on their local evaluation of the fraction cover of vegetation.

Geographical maps of estimated insolation and evapotranspiration, as well as some of the other agricultural products to be discussed below, are produced every day during the growing season and can be accessed on the Web site of the University of Wisconsin Department of Soil Science (http://www.soils.wisc.edu/wimnext) and the Cooperative Institute for Meteorological Satellite Studies (http://cimss.ssec.wisc.edu).

b. Frost protection of high-value crops

Ready access to real-time satellite and surface data and forecast model predictions of minimum temperature can lessen frost damage, improve harvests, and reduce the use of water applied to prevent such damage. In Wisconsin, 13 000 acres of cultivated cranberry are the major frost protection challenge. With a per-acre crop value of nearly $6,000, these cranberry regions were a logical first choice for a prototype frost protection product. For cranberries, the standard frost preventative procedure is to apply water to the cranberry beds by either sprinkling or flooding, depending on the time of year and wind conditions. Thus, any improved information on impending frost conditions can aid in minimizing water usage and the resulting environmental and energy impacts.

Successful prediction of air temperature near any precise temperature value of interest, such as the freezing point of water, depends on skillfully describing the temporal evolution of many subtle environmental factors that influence the temperature, such as the humidity and wind speed of the lower atmosphere and the cloud conditions, as well as having relatively good information on the structure of a particular soil and canopy. For nonadvective situations, the net loss of thermal radiation from the surface is the forcing that drives the cooling of the lower atmosphere. Thus, one of the most important pieces of information to predict whether there will be an overnight frost is whether a region is clear or cloudy. When clouds are present, more thermal energy is returned to the surface due to downward emission by the clouds than when the atmosphere is clear. As a result, the surface as well as the air near the surface stays warmer and the chance of frost is reduced. During the night, the high-spatial-resolution cloud information obtained from the solar insolation routines (discussed in section 2a) is not available. Even at night, however, satellite data can provide excellent information on the geographical distribution of clouds, albeit at a reduced horizontal resolution. These cloud data, plus standard upper-air and surface synoptic data from several sources, are used as input to physical and statistical prediction models of the atmosphere and surface environment for the frost prediction decision support system.

1) Prediction sequence overview

The minimum temperature forecast system relies on a combination of satellite cloud information and synoptic upper-air and hourly surface measurements of temperature, humidity, and windspeed. Several computer forecast models, based in the physics of the atmosphere and land surface, as well as a statistical adjustment procedure are used to interpret the data sources and predict if freezing temperatures will occur overnight.

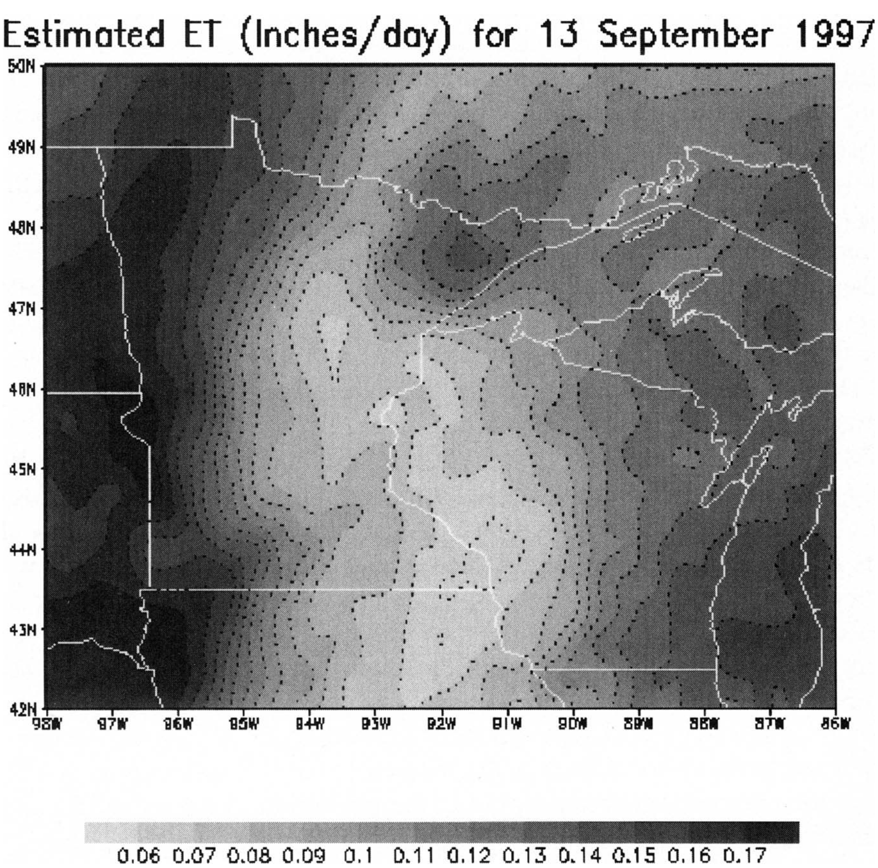

Fig. 2. Daily potential evapotranspiration (in. of water day^{-1}) for 13 September 1997.

An overview of the frost prediction sequence for a particular night is as follows. Synoptic data (upper-air temperature, windspeed, and moisture information) from radiosonde reports, surface data from the hourly reporting network, and satellite-derived cloud data (to be detailed) are assimilated into the CIMSS Regional Assimilation System (CRAS; coincidentally Latin for "tomorrow") run in near real time, with a base forecast time of 1200 UTC (0600 central standard time, CST) and a forecast duration of 48 h. The horizontal resolution of the forecast component of this system is approximately 80 km and the prediction region includes most of the continental United States. Details on the CRAS and its prior applications can be found in Diak et al. (1992), Wu et al. (1995), and Raymond and Aune (1998). The techniques used for the input of the satellite-based cloud data into the forecast model have been detailed in Wu et al. (1995) and Aune (1996).

Upon completion of the 1200 UTC mesoscale forecast, a time series of prognostic information on the air temperature, humidity, and wind speed of the lower atmosphere and also downwelling thermal radiation is passed to a one-dimensional soil/vegetation model, called the Atmosphere-Land Exchange (ALEX) System (a prognostic version of a model used to diagnose land surface fluxes from thermal infrared remote sensing data and formerly called the "two source" model; Norman et al. 1995). The CRAS predictions of the lower-atmospheric variables at the CRAS's lowest level (about 24 m) are used as upper boundary conditions in the forecast of ALEX. Prior to the passing of these predicted low-level variables from the CRAS to ALEX, a bias error correction to the CRAS output is made, based on a running 30-day compilation of the CRAS prediction errors of shelter-level variables. The prediction of downwelling thermal radiation (L_d) from the CRAS serves as an upper boundary condition in thermal radiation [in a balance equation similar to Eq. (2)] in the ALEX forecast. Two CRAS predictions of L_d are provided to the ALEX, one calculated for clear-sky conditions and a second that includes the effects of the clouds predicted by the CRAS, if they are present. If the CRAS predicts no clouds at a given time and location, the two L_d evaluations are identical.

Importantly, the ALEX incorporates a greater level of detail on the characteristics of the cranberry canopy and the cranberry growing region in the prediction than can be achieved in the CRAS with 80-km horizontal resolution. These characteristics are quite different than those of most of the other natural and cultivated vegetation in Wisconsin (Bland et al. 1995) in that in many ways they represent a wetland-type ecosystem. The ALEX also includes an explicit prediction of the temperature of the canopy and the air within the canopy, important information for growers. Two separate ALEX forecasts are made, one using the "clear-sky" L_d output of the CRAS and a second using the actual L_d CRAS prediction (including modeled clouds). The clear-sky prediction of nighttime air temperature will always be as cold or colder than the forecast using the actual L_d provided by the CRAS and therefore provides a worst case frost scenario to the cranberry growers.

The 1200 UTC–based CRAS–ALEX prediction described provides the first estimate of temperatures for the day and is generally available at about noon local time. In the evening, several updates to this initial prediction are made, using timely satellite-derived cloud information and also surface-based measurements of air temperature, wind speed, and humidity from the National Weather Service Automated Surface Observation System (ASOS) and Federal Aviation Administration Automated Weather Observation System (AWOS). Real-time 10-km satellite-derived cloud data from the *GOES-8* atmospheric sounding instrument are provided to the TiSDat effort through the cooperation of the National Oceanic and Atmospheric Administration (NOAA) Advanced Satellite Products Project at the University of Wisconsin Space Science and Engineering Center; details on how they are produced can be found in Hayden and Wade (1996). Daily real-time cloud products are viewable both on the CIMSS and NOAA Web sites (http://cimss.ssec.wisc.edu/ and http://www.noaa.gov/, respectively).

2) Forecast updating procedures

Figure 3 is a flow chart showing data inputs and timing of the frost prediction forecasts and updates utilizing satellite cloud information and hourly measurements of low-level atmospheric variables. The first prediction, made using data at 1200 UTC (including a satellite assessment of clouds) and the CRAS–ALEX combination, has been described in the preceding section.

As the evening progresses, real-time satellite cloud information as well as surface hourly air temperature data are used to update the original 1200 UTC CRAS–ALEX prediction. The cloud data are used to estimate downwelling longwave radiation (L_d) at the surface and modify the original L_d information (the upper boundary condition in radiation for the ALEX prediction) provided by the CRAS to the ALEX. Surface hourly air temperature (ASOS) data are used to update the original 1200 UTC CRAS air temperature prediction (the upper boundary condition in temperature for the ALEX prediction). The satellite cloud (L_d) data and surface hourly air temperature measurements are merged in a continuous manner using a statistical interpolation procedure based in the differences between the measurement values at the observation times and the corresponding CRAS forecast of these variables (e.g., the CRAS forecast errors). After each data update of the CRAS boundary conditions, the ALEX is run again to produce updated estimates of low-level air temperature and canopy conditions.

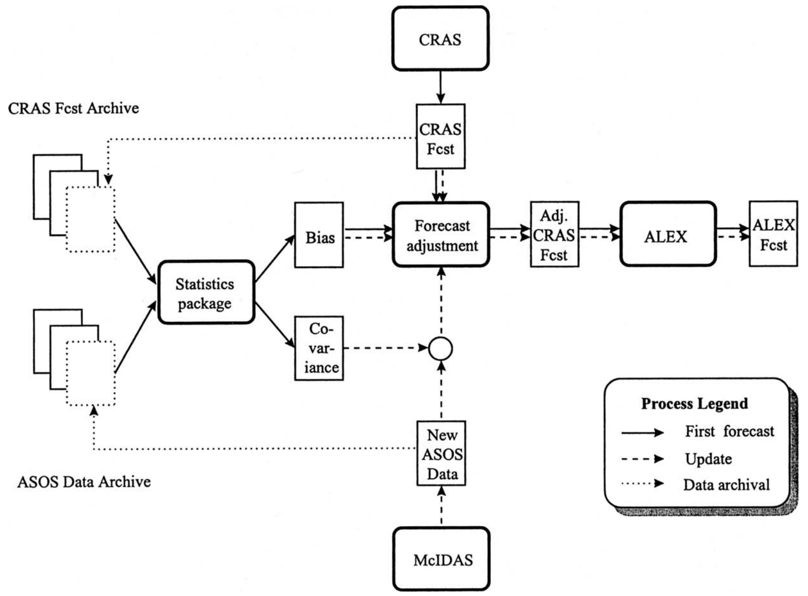

FIG. 3. Flow chart describing forecast and forecast update procedures for the cranberry frost protection system. The first forecast of the day is generated by the ALEX model using the CRAS forecast as the upper boundary condition. Throughout the rest of the day, the CRAS forecast is compared with new surface and satellite observations as they become available and adjusted as necessary using the statistical interpolation procedure described in the text. The ALEX model is then rerun and new bog forecasts are issued to our Web site. Any local system biases in the CRAS forecast are corrected before ingestion by ALEX.

Statistical interpolation (SI) procedures are widely used in meteorological analysis to estimate how the information from a measurement made at a given location should be distributed in the horizontal and vertical dimensions and, in the most complex data assimilation systems, in the temporal dimension as well. In our relatively simple system, we first capitalize on the fact that forecast errors (defined as the difference between the forecast value and measurement value of a variable such as temperature) are correlated in time. Intuitively, for example, if an air temperature observation at 0700 local time indicated that a prior forecast of air temperature was too warm, we might foresee that this forecast would also be too warm at 2000 and 2100 and adjust our expectations accordingly. Second, our experience in forecasting for Wisconsin cranberry regions, along with in situ measurements of thermal radiation at several cranberry growing locations, has indicated that the larger errors in the prediction of nighttime air temperature are generally a result of significant errors in the forecasting of clouds and the downwelling thermal radiation at the surface. Again intuitively, if satellite measurements indicated that a location was clear, while a model forecast predicted cloudy conditions, one would expect that the prediction would underestimate the amount of longwave cooling at night and be too warm. The SI method is a quantification of these "expectations," but it is based in the error statistics of CRAS forecasts of both air temperature and nighttime downwelling longwave radiation.

A running 30-day history database is maintained to catalog the errors in the CRAS forecasts of air temperature and downwelling longwave radiation (evaluated by a comparison of the forecasts with surface hourly measurements for temperature and the satellite product for downwelling longwave radiation). From this error information, the statistical relationships (covariances) between forecast errors of temperature at the nighttime hours and their relationship to errors in downwelling longwave radiation can be evaluated. Putting the intuitive example given above into a more quantitative framework, if surface hourly data indicate that there is an error in the forecast temperature at 1900 LT, from the error covariances, historically we know how strongly the temperature errors at later times in the evening have been correlated to this 1900 LT error. Via a concurrent assessment of the forecast downwelling longwave radiation using satellite cloud information, we also know statistically what temperature errors at later times will result from errors in the downwelling radiation forecast at the data update time. Adjustments are made to the overnight

CRAS prediction of temperature and downwelling longwave radiation that are proportional to the differences between measurements and predictions at 1900 LT and the correlations between errors at that time and errors at later times in those variables.

Currently, four SI updates to the 1200 UTC CRAS forecast of temperature are performed at 1800, 2000, 2200, and 0000 CST (0000, 0200, 0400, and 0600 UTC). Each of the updates utilizes satellite and surface data from that time. The data is used to modify the original 1200 UTC CRAS forecast of air temperature, L_d, wind speed, and vapor pressure. As in the original CRAS/ALEX sequence, these updated variables are passed to the ALEX to provide upper boundary conditions for its subsequent forecast.

Figure 4 shows a series of forecast results for air temperature at 2 m for the day of 14 May 1997 at a cranberry bog site (Cranmoor, Wisconsin) where verification measurements are taken. The original morning CRAS forecast predicted cloudy skies over Cranmoor on the evening of this day, when in fact it was clear on that night. The original cranberry forecast therefore predicted an overnight minimum bog temperature that was approximately 1.5°C too high and several degrees above freezing. The 1800 LT GOES satellite image showed that this region was much clearer than originally forecast. The input CRAS forecast was statistically adjusted to represent the new 1800 LT information on cloud conditions, shelter-level air temperature and humidity, and anemometer-level wind speed. The original forecast was significantly improved. Subsequent updates continue to improve the forecast, as shown in Fig. 4. Preliminary statistics on forecasts run in 1997 show that the updates reduce the forecast errors in minimum temperatures from approximately 1.5°C in the original morning forecast to about 1°C by the time of the last update (0000 LT).

c. Plant disease management

A final aspect of crop management to which we bring the tools of remote sensing, modeling, and the Internet is management of foliar (leaf) diseases in potato. The threat posed by these diseases depends significantly on temperature and humidity within the crop canopy and the presence of free water on leaves (Stevenson 1993). Free water on the leaves can be supplied by rain, irrigation, or dew, while the residence time of the water is influenced by the ambient net radiation (supplying energy for evaporation during the daytime or influencing whether the nighttime

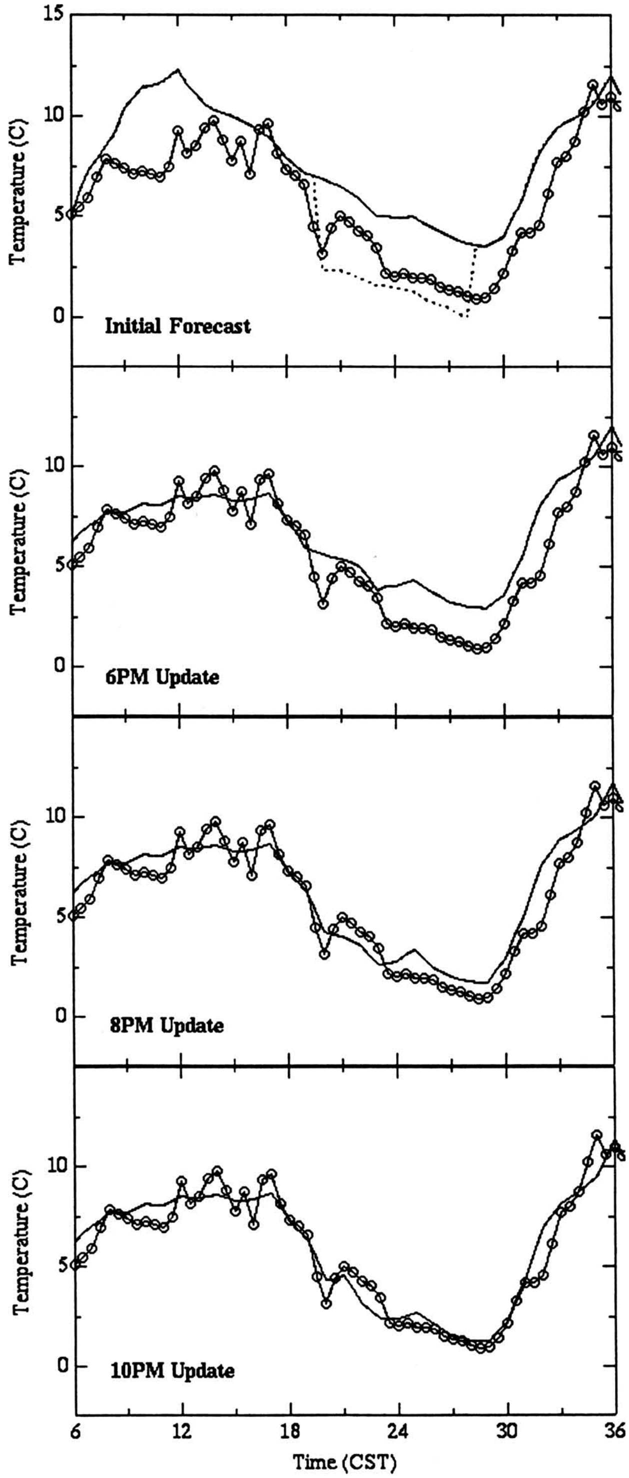

FIG. 4. Effect of updates on minimum temperature forecast accuracy. Circles indicate measurements of air temperature taken within the bog canopy; solid lines indicate the in-bog temperature forecast update at the time specified. The dotted line in the first frame indicates our overnight clear-sky forecast, which agrees well with the measurements.

canopy air temperature falls to the dewpoint temperature at night), as well as the atmospheric humidity and temperature conditions.

Present control strategies include fungicide application to the leaves numerous times during the season. Weather observations are used in a number of different models to recommend the frequency of sprays required for adequate protection of the crop. Among the most widely used models for the disease early blight is one developed by Pscheidt and Stevenson (1986) and included in the potato crop management decision support system WISDOM, from the University of Wisconsin—Extension. Use of the early blight model within WISDOM reduces the number of fungicide applications used compared to conventional practices.

Inputs required by this early blight model (and that for the disease late blight, as well) include the duration of periods of relative humidity near the leaves greater than 90% and temperature during those periods. Growers or their consultants now determine these data using electronic or mechanical measurement and recording systems placed in the canopy. Electronic recorders can be accessed via telephone and the data transferred directly to WISDOM, but measurements made by mechanical recorders must be manually retrieved and entered into WISDOM.

The TiSDat product for this application uses satellite, surface, and radar data inputs, coupled to a version of the ALEX adapted to potato, to provide WISDOM with the data required by the blight models (the duration of high-humidity conditions in the canopy and the time history of the canopy air temperature) for each field modeled by a grower or consultant. In operation, the user first connects to his or her Internet service provider and WISDOM (resident on the user's local computer) connects to the TiSDat server to retrieve the needed data for the particular site. The relevant datasets include the satellite-based hourly estimates of solar radiation and net longwave radiation (both previously discussed), as well as rainfall data from the WSR-88D National Weather Service Network and surface hourly data interpolated from ASOS measurements. The data are input into a version of the ALEX incorporating the vegetation characteristics appropriate for potato. The output of the ALEX is a time history of the potato canopy humidity and temperature from the observed atmospheric and net radiation conditions. An example time course of measured and modeled in-canopy relative humidity is shown in Fig. 5. Importantly, periods of relative humidity greater than 90% are well identified.

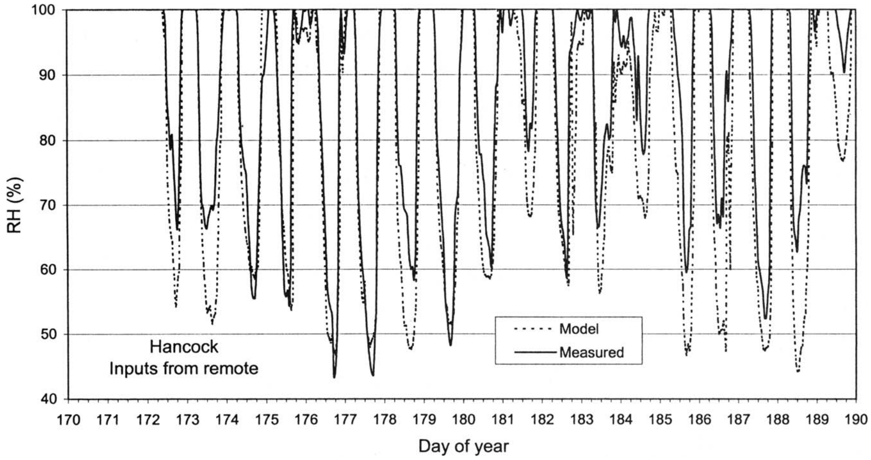

FIG. 5. Measured and modeled relative humidity in a potato crop canopy growing on a sandy soil at Hancock, Wisconsin.

3. Summary and conclusions

Scientists at the University of Wisconsin—Madison in cooperation with NASA are providing a suite of real-time agricultural decision support systems to growers in Wisconsin and other regions of the country that are based in satellite and conventional data coupled to state-of-the-art forecast models of the atmosphere and soil canopy system. In both their production and distribution, these products rely to large extent on new capabilities provided by the Internet and World Wide Web for data acquisition and product distribution.

The evapotranspiration/irrigation scheduling product utilizes a satellite evaluation of the daytime net radiation, most strongly related to daily solar radiation. The GOES satellites, with their high spatial and temporal resolution, are well suited to estimating this incident solar radiation with high accuracy and spatial detail. An offshoot of this irrigation scheduling product, related to electrical power demand (electricity to pump irrigation water), is in development.

The frost protection decision support system utilizes a satellite cloud product (derived using the infrared atmospheric sounding channels of the *GOES-8* satellite) to correct forecast errors in the downwelling thermal infrared radiation at the land surface. Model forecast errors in low-level air temperatures during the nighttime hours are strongly related to model errors in the prediction of clouds (and often lead these temperature errors in time), so that correcting cloud errors via the satellite information has proven extremely useful for improving temperature predictions. These satellite cloud data and ASOS and AWOS surface air temperature measurements have been combined in a relatively seamless manner using an update procedure based in principles of statistical interpolation. A detailed soil–canopy model is used in this product to provide growers with important primary information, such as the predicted temperatures of the vegetation and air within the canopy.

The plant disease decision support system WISDOM can access via the Internet the required inputs from a TiSDat model running on our server. This ease of access for needed weather and microclimate inputs should foster adoption of this Decision Support System, thereby reducing fungicide applications.

Slow adoption of new decision support tools within agriculture is a general area of concern (Cox 1996). As indicated earlier, the initial three TiSDat products were selected in part based on the existence of a DSS already in use by some of the growers. The use of evapotranspiration estimates from automated stations and accessed by telephone voice synthesizer was established in Wisconsin prior to TiSDat, but e-mail and Wide World Web access to the TiSDat ET_p product has increased during each of the past two seasons of operation. Although a prototype TiSDat cranberry frost warning product has been available on the Web for the past two growing seasons, this product has just now become fully operational (at the start of the 1998 growing season). Thus, grower reaction prior to this year has been limited. It is known, however, that Web usage is growing rapidly among this community and we have seen a steady and significant rise in the number of daily Web hits (since the inception of the TiSDat program) from Internet providers known to service Wisconsin cranberry growing regions. We anticipate an appreciable fraction (although less than half) of the growers will access the forecasts over the Web and we will partially quantify the adoption of our methods by monitoring Web server statistics. Finally, use of the modeled canopy humidity information is limited by adoption of the WISDOM software package. While large and progressive growers use the product, there are unknown barriers to adoption by the majority of growers. Development continues on WISDOM, which may lead to a more widely adopted version. Meanwhile, we are studying the validity of regional fungicide application recommendation made using the TiSDat technology and the Web.

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References

Aune, R. M., 1996: Initializing cloud predictions using the *GOES-8* sounder. Preprints, *Eighth Conf. on Satellite Meteorology and Oceanography,* Atlanta, GA, Amer. Meteor. Soc., 408–412.

Bland, W. L., J. T. Loew, and J. M. Norman, 1995: Evaporation from cranberry. *Agric. For. Meteor.,* **81,** 1–12.

Cox, P. G., 1996: Some issues in the design of agricultural decision support systems. *Agric. Systems,* **52,** 355–381.

Diak, G. R., and C. Gautier, 1983: Improvements to a simple physical model for estimating insolation from GOES data. *J. Climate Appl. Meteor.,* **22,** 505–508.

——, D. Kim, M. S. Whipple, and X. Wu, 1992: Preparing for the AMSU. *Bull. Amer. Meteor. Soc.,* **73,** 1971–1984.

——, W. L. Bland, and J. R. Mecikalski, 1996: A note on first estimates of surface insolation from *GOES-8* visible satellite data. *Agric. For. Meteor.,* **82,** 219–226.

Gautier, C., G. R. Diak, and S. Masse, 1980: A simple physical model to estimate incident solar radiation at the surface from GOES satellite data. *J. Appl. Meteor.,* **19,** 1007–1012.

Hayden, C. M., and G. S. Wade, 1996: Derived product imagery from *GOES-8*. *J. Appl. Meteor.,* **35,** 153–162.

Idso, S. B., 1981: A set of equations for full spectrum and 8–14 μm and 10.5–12.5 μm thermal radiation from cloudless skies. *Water Resour. Res.,* **17,** 295–304.

Menzel, W. P., and J. F. W. Purdum, 1994: Introducing *GOES-1*: The first of a new generation of geostationary operational environmental satellites. *Bull. Amer. Meteor. Soc.,* **75,** 757–781.

Norman, J. M., W. P. Kustas, and K. S. Humes, 1995: A two-source approach for estimating soil and vegetation energy fluxes from observations of directional radiometric surface temperature. *Agric. For. Meteor.,* **77,** 153–166.

Penman, H. L., 1948: Natural evaporation from open water, bare soil and grass. *Proc. Roy. Soc. London,* **193,** 120–145.

Pinker, R. T., and I. Laszlo, 1992: Modeling surface solar irradiance for satellite applications on global scale. *J. Appl. Meteor.,* **31,** 194–211.

——, R. Frouin, and Z. Li, 1995: A review of satellite methods to derive surface shortwave irradiance. *Remote Sens. Environ.,* **51,** 105–124.

Postel, S., 1993: Water and agriculture. *Water in Crisis. A Guide to the World's Fresh Water Resources,* P. H. Gleick, Ed., Oxford University Press, 56–66.

Priestley, C. H. B., and R. J. Taylor, 1972: On the assessment of surface heat flux and evaporation using large-scale parameters. *Mon. Wea. Rev.*, **100,** 81–92.

Pscheidt, J. W., and W. R. Stevenson, 1986: Comparison of forecasting methods for control of potato early blight in Wisconsin. *Plant Disease,* **70,** 915–920.

Raymond, W. H., and R. M. Aune, 1998: Improved precipitation forecasts using parameterized grid-scale precipitation drag. *Mon. Wea. Rev.,* **126,** 693–710.

Schmetz, J., 1989: Towards a surface radiation climatology: Retrieval of downward irradiances from satellites. *Atmos. Res.,* **23,** 287–321.

Schreiner, A. J., D. A. Unger, W. P. Menzel, G. P. Ellrod, K. I. Strabala, and J. L. Pellet, 1993: A comparison of ground and satellite observations of cloud cover. *Bull. Amer. Meteor. Soc.,* **74,** 1851–1861.

Stevenson, W. R., 1993: Management of early blight and late blight. *Potato Health Management.* R. C. Rowe, Ed., APS Press, 141–147.

Tarpley, J. D., 1979: Estimating incident solar radiation at the surface from geostationary satellite data. *J. Appl. Meteor.,* **18,** 1172–1181.

Wu, X., G. R. Diak, C. M. Hayden, and J. A. Young. 1995: Short-range precipitation forecasts using assimilation of simulated satellite water vapor profiles and cloud liquid water. *Mon. Wea. Rev.,* **123,** 347–365.