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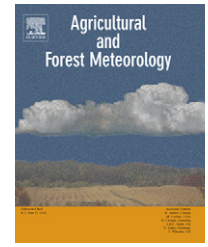

Dew frequency, duration, amount, and distribution in corn and soybean during SMEX05

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ABSTRACT

Dew affects the brightness temperature of vegetation and backscatter from vegetation at microwave wavelengths. Must this effect be taken into account in order to avoid corrupting remotely sensed observations of important ecosystem variables such as soil moisture? As a first step towards answering this question, we report the frequency and duration of dew events, the total amount of dew in the canopy, and the distribution of dew within the canopy for two different types of crop canopy, corn and soybean, during SMEX05, a 21-day field experiment conducted during June and July, 2005, in Iowa, USA. We observed dew to be present more than 50% of the time in both corn and soybean at common satellite overpass times of 1:30 and 6:00 CST. Dew was most likely to be present between 12:00 and 6:30 CST, and as late as 9:00 CST. Two different methods to scale the liquid water measured on single leaves to the entire vegetation canopy produced similar results, and we observed dew amounts that were comparable, and in some cases higher, than those that have been shown to affect the microwave brightness temperature and backscatter. The distribution of dew within the canopy among the top and bottom of a leaf and (for corn) the leaf collar may influence its effect on remotely sensed measurements. We found that this distribution is different for light, moderate, and heavy dew events. A modeling approach will be necessary to estimate dew at larger spatial scales associated with satellite remote sensing. The Atmosphere–Land Exchange (ALEX) model, a land surface process model that accounts for both dewfall and distillation, produced estimates of dew amount and duration that were in agreement with manual observations and observations made with leaf wetness sensors.

1. Introduction

Dew is the natural deposition of water onto a surface due to condensation of water vapor (Monteith, 1957). Although dew is a vital source of moisture to ecosystems in arid climates (Zangville, 1996; Jacobs et al., 1998), moisture on plant surfaces promotes the development of disease in many crops (Chtioui et al., 1999). For example, the amount of time that moisture is present on plant surfaces affects the expansion of lesions of many fungal pathogens (Huber and Gillespie, 1992), the scheduling of fungicide application on tomatoes (Pitblado, 1988; Gillespie et al., 1993), and impacts the management of gray mold (Shtienberg and Elad, 1997) and brown spot on pears (Llorente et al., 2000). Knowledge of spatial and temporal

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variations of dew may allow farmers to make crop management decisions that could be both economically and environmentally beneficial.

Besides the direct effects of dew on the hydrology and biology of ecosystems, dew may also contaminate remotely sensed measurements of important ecosystem variables such as soil moisture, land surface temperature, and vegetation biomass. At microwave frequencies, the land surface brightness temperature is sensitive to both the temperature of the vegetation canopy and the water content of the soil surface beneath the canopy (Hornbuckle and England, 2004) as well as other canopy and soil surface properties. However, the emission and scattering of microwave radiation in the canopy is determined primarily by the amount of liquid water stored in the vegetation (Ferrazzoli et al., 1992; Wigneron et al., 2004). Water contained within vegetation tissue is the main factor, but dew also affects both terrestrial brightness temperature (Jones and Vonder Harr, 1997; Lin and Minnis, 2000; Hornbuckle et al., 2006) and backscatter (Gillespie et al., 1990; Wood et al., 2002). In certain cases, it may be necessary to quantify and remove the dew signal to effectively use either passive or active microwave remote sensing observations of the land surface.

One of the objectives of a recent field experiment was to determine the extent to which dew effects terrestrial microwave emission and whether this contribution is significant enough to corrupt passive microwave observations. Soil Moisture Experiment 2005 (SMEX05) was a watershed-scale validation and calibration study for passive microwave remote sensing that involved multiple research groups from U.S. universities and the U.S. government. The main focus of the experiment was to model and validate passive microwave observations of the land surface made with the WindSat passive microwave radiometer system on-board the Coriolis satellite (Gaiser et al., 2004). Since WindSat passes over much of Earth's surface in the early morning hours when dew is often present, the effect of leaf wetness on microwave signals must be understood in order to interpret these measurements correctly. Besides WindSat, many other current and planned microwave remote sensing satellites also have overpass times that occur at night or in the early morning hours when dew may be present (e.g. Kerr et al., 2001; Parkinson, 2003; Entekhabi et al., 2004).

Three activities related to determining the effect of dew on passive microwave observations were performed. First, time-series measurements of leaf wetness and local micrometeorology were made to observe and model the onset, deposition, and dryoff of dew. Second, the time-series measurements were repeated at several sites throughout the watershed in order to observe and model the spatial distribution of dew. Third, passive microwave observations over the experiment area were made with airborne and satellite sensors. Measurements of near-surface soil moisture, fluxes of water and energy between the land surface and atmosphere, vegetation biomass and plant structure, and diurnal temperature changes within the soil and canopy were also made during the experiment.

In this paper, we present work associated with the first activity. We report observations of the frequency and duration of dew events, the total amount of dew in the canopy, and the distribution of dew within the canopy for two different types of vegetation: corn (*Zea maize* L.) and soybean (*Glycine max* L. *Merr*). We made these measurements in order to answer the following questions.

- How often is dew present? If dew does affect remotely sensed measurements of soil moisture and other important ecosystem variables, is this a phenomenon that occurs often enough to warrant consideration? Or does dew occur infrequently? We report the frequency of dew events during SMEX05.
- At what time of day is dew likely to be present? Remote sensing instruments on geosynchronous satellites pass over areas on Earth's surface at approximately the same local time. Is it likely that dew will be present at that time? We report the duration of dew events during SMEX05.
- How much dew is present? The effect of dew on remotely sensed observations will likely depend on the total amount of dew. Heavy dews will be more likely to corrupt remote sensing measurements than light dews. We compare two methods used to scale the dew observed on single leaves to the entire canopy.
- Where is dew deposited within the canopy? The location of free water within the canopy deposited by dew may determine how dew affects remotely sensed measurements (Hornbuckle et al., 2006, 2007). We report the amount of dew that collected on the tops of leaves, on the bottoms of leaves, and (for corn) in the leaf collars where leaves connect to stems.

Finally, we compare observed dew duration and the total amount of observed dew with the predictions of a physically based land surface process model, the Atmosphere–Land Exchange (ALEX) model (Anderson et al., 2000), forced with local micrometeorology. Since this model explicitly takes into account the movement of water vapor among the soil, vegetation, and lower atmosphere, we hypothesized that the ALEX model would accurately estimate the time at which dew begins to form, the time at which the dew has completely evaporated, and the amount of dew. This modeling analysis is important for two reasons. First, accurate model estimates of dew amount and duration will verify that our manual observations are consistent with observed meteorological conditions and strengthen our conclusions. Second, if dew is found to affect remotely sensed measurements, manual measurements will be impractical at the scales of remotely sensed measurements and a modeling approach will have to be used. We considered an accurate estimation of onset and dryoff to be within $\pm$30 min of automated observations from leaf wetness sensors and an accurate estimation of dew amount to be within 0.1 kg m^{-2}of manual measurements. To test our hypothesis, we closely examined 6 days from the SMEX05 experiment period that represented typical light, moderate, and heavy dew days in both corn and soybean fields.

2. Measurements

SMEX05 began on 14 June (day of year 165) and ended 5 July (day of year 186), 2005. The experiment took place south and west of Ames, IA, USA, in an area of approximately 200 km^2 that includes the Walnut Creek watershed. This area has a Koeppen climate classification of severe mid-latitude, and receives on average 835 mm of annual precipitation. Nearly 95% of the land is devoted to agriculture, with the vast majority of that land planted to corn and soybean crops (Doriaswamy et al., 2004). Participants in SMEX05 monitored near-surface soil moisture and vegetation characteristics in >30 fields within the experiment area. In addition to other measurements, a total of 42 leaf wetness duration sensors were installed in several fields. In this paper, we focus on the measurements of dew in four fields known during SMEX05 as WC10 (corn), WC22 (corn), WC11 (soybean), and WC15 (soybean). The location of these fields is shown in Fig. 1.

2.1. Leaf wetness duration

We deployed leaf wetness duration sensors (Model 237, Campbell Scientific) in order to measure the time period between when the dew begins to form and when the dew has completely evaporated. Each sensor is a circuit board imprinted with interlacing gold-plated fingers at the surface. Condensation on the sensor changes the electrical conductance between the fingers (Davis and Hughes, 1970). For accurate measurements of leaf wetness duration, the surface characteristics of these sensors must closely match those of real leaves, both in terms of emissivity and the interaction with liquid water films and droplets (Sentelhas et al., 2004). These sensors were painted on contract by Robert Olson of Savannah, GA, with paint specifically developed for this application. Three coats of paint were applied to each sensor: a flat black latex and two coats of a custom off-white latex. These particular sensors have been used in many field experiments (Gillespie and Kidd, 1978; Getz, 1978; Lau et al., 2000; Sentelhas et al., 2004).

We placed four leaf wetness duration sensors in each of the five fields examined in this paper, arranging them in pairs on two metal stakes so that one sensor in each pair was at one-third of the height of the vegetation canopy and the other at two-thirds of the height of the canopy. All sensors were oriented to face due north (Lau et al., 2000) and placed within the row at least 50 m from the edge of the field. We performed regular height adjustments to ensure that the each sensor remained at the correct height as the canopy grew and that leaves did not touch or block the field of view of the sensors. A datalogger measured the conductance of each sensor every 5 min, and recorded the percent time the surface of the sensor was wet within 15-min period.

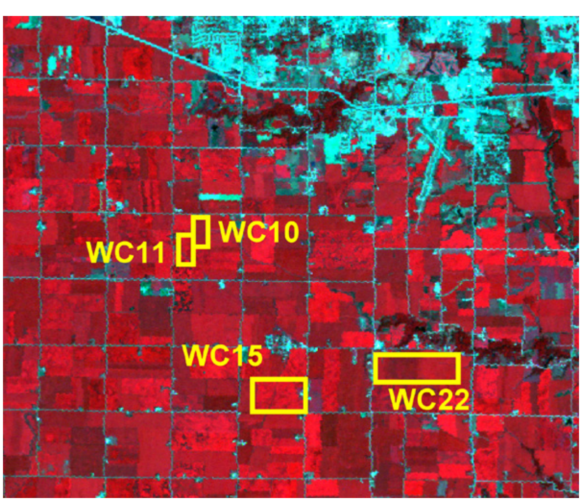

Fig. 1 – Location of four fields intensively sampled for dew during SMEX05 near Ames, IA.

2.2. Dew amount

The full procedure we used to measure the amount of dew and other details including the accuracy of some of the individual measurements can be found in Kabela (2006). We present the pertinent information here. We prepared several plastic sandwich bags (Ziploc Snack Bags, S.C. Johnson & Son, Inc., Racine, WI) that contained a single paper towel (Scott Towels, Kimberly–Clark Corp., Neenah, WI). We numbered each bag and recorded its mass. Within each of the five fields, we chose three locations at which to measure dew. Jacobs et al. (1990, 1994) and Jacobs and Nieveen (1995) found that for corn the minimum amount of dew accumulation occurred at approximately one-third of canopy height, and that the maximum dew accumulation occurred at approximately two-thirds of canopy height. Furthermore, the largest variation in dew accumulation occurred near the top of the canopy (Jacobs et al., 1990; Jacobs and Nieveen, 1995). In order to estimate dew amount in the canopy, we measured dew on one leaf at one-third of canopy height and on two leaves at two-thirds of canopy height at each location. We assumed that one-third of the leaves in the canopy were similar to the lowest leaf sampled and that two-thirds of the leaves in the canopy were similar to the top two leaves sampled.

After putting on rubber examination gloves to reduce the chance of contaminating paper towels with oil or water, we opened two control bags, placed the paper towels in the bags in contact with the canopy environment for approximately 10 s, and sealed the towels in their respective bags. We used three paper towels to collect the dew from each corn leaf and two paper towels to collect the dew from each soybean leaf. We defined a corn leaf to be that part of the plant that extends from the stem to the tip of the leaf. For soybean, we considered a trifoliate to be a single leaf. For corn, we also included the liquid water that collects at the collar where a leaf and the stem connect, in which case we used the first paper towel to absorb this water. For leaves near the ground, we found that simply placing the paper towel in the collar was sufficient. It was more difficult to retrieve water in the collar for leaves high above the ground. To collect this liquid water, we twisted the towel into the shape of a pencil and inserted it into the collar.

We used the other paper towels to absorb liquid water from the top and bottom of the leaf, one for each side. If large drops of liquid water were present on the leaf, we first used the proper towel to absorb the drops. We then sandwiched the leaf with the towels and gently wiped the dew off, starting from the bottom of the leaf near the stem to the tip of the leaf. After we dried each portion of the leaf, we replaced all of the towels in their respective bags, then excised the leaf and placed it in a separate paper bag. During the dew measurement procedure, the team member who was not using the towels gently held back the surrounding vegetation in order to prevent liquid water from other leaves from dripping onto the leaf under investigation or onto the paper towels.

In order to coincide with the WindSat overpass (shortly after 6:30 CST) and the flights of an airborne WindSat simulator deployed during SMEX05, we conducted our canopy sampling procedure in the early morning (5:30–8 CST). We sampled on mornings when weather conditions for dew formation were favorable. Favorable conditions occurred more than half the days of the experiment. In addition to the measurement of dew, at each location we also used an LAI-2000 Plant Canopy Analyzer (LI-COR, Lincoln, NE) to estimate the leaf-area index (LAI) of the full canopy, the top two-thirds of the canopy, and the top one-third of the canopy. We also recorded the height of the canopy, the number of leaves per plant, the number of plants per area, the GPS coordinates, and the time of day. We measured the mass of the plastic bags and determined the area of each leaf with an optical scanner within approximately 2 h after we finished sampling.

2.3. *Micrometeorology*

Within each field, adjacent to each set of four leaf wetness duration sensors, we measured air temperature, relative humidity, wind speed and direction, net radiation, precipitation, soil moisture, and fluxes of sensible heat, latent heat, and carbon dioxide. We measured air temperature and relative humidity with a temperature and relative humidity probe (HMP45C, Vaisala Inc., Helsinki, Finland); wind speed with a CSAT3-D Sonic Anemometer (R. M. Young, Traverse City, MI); net radiation with a four-component CNR1 (Kipp & Zonen, The Netherlands); precipitation with a TE525 tipping bucket rain gauge (Texas Electronics, Dallas, TX); soil moisture just below the soil surface with Hydra Probes (Vitel Inc., Chantilly, VA); and fluctuations of water vapor and carbon dioxide with a LI7500 Open Path CO_2/H_2O Analyzer (LI-COR). We placed towers that supported most of these instruments at least 50 m from field edges in order to obtain homogeneous fetches.

3. Observations

The frequency, timing, and amount of dew may all be important factors in determining the effect of dew on remotely sensed measurements of soil moisture, and potentially other remotely sensed measurements such as vegetation temperature and vegetation biomass. Even the distribution of dew within the canopy among leaf surfaces and other reservoirs may be important. For example, Hornbuckle et al. (2006, 2007) found that free water in the canopy deposited by dew has a different effect on the 1.4 GHz brightness temperature of corn than free water deposited by intercepted precipitation. Dew decreased the brightness temperature of corn at 1.4 GHz whereas intercepted precipitation increased the brightness temperature. Hornbuckle et al. (2007) hypothesized that this difference in the effect of dew and intercepted precipitation on the brightness temperature occurs because each process wets the canopy in different ways, for two different types of vegetation, corn and soybean.

3.1. *Dew frequency and duration*

The frequency of occurrence of liquid water on leaves as measured by leaf wetness sensors during SMEX05 is shown in

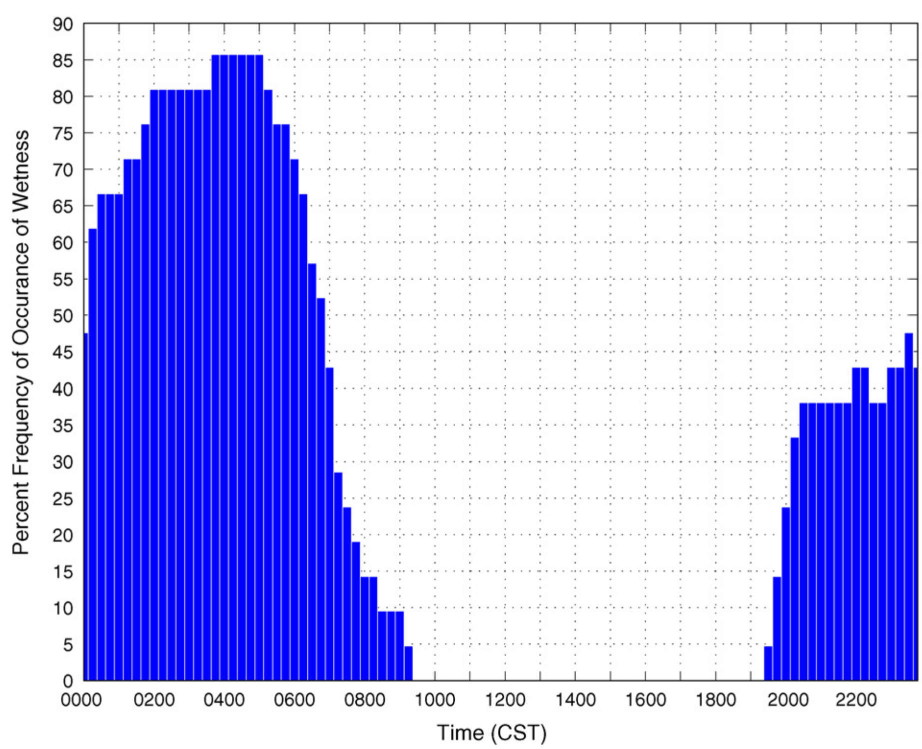

Fig. 2 – Percent of days during SMEX05 (14 Jun–5 July) that at least one wetness sensor was wet with dew in one field of corn (WC10) as a function of time of day.

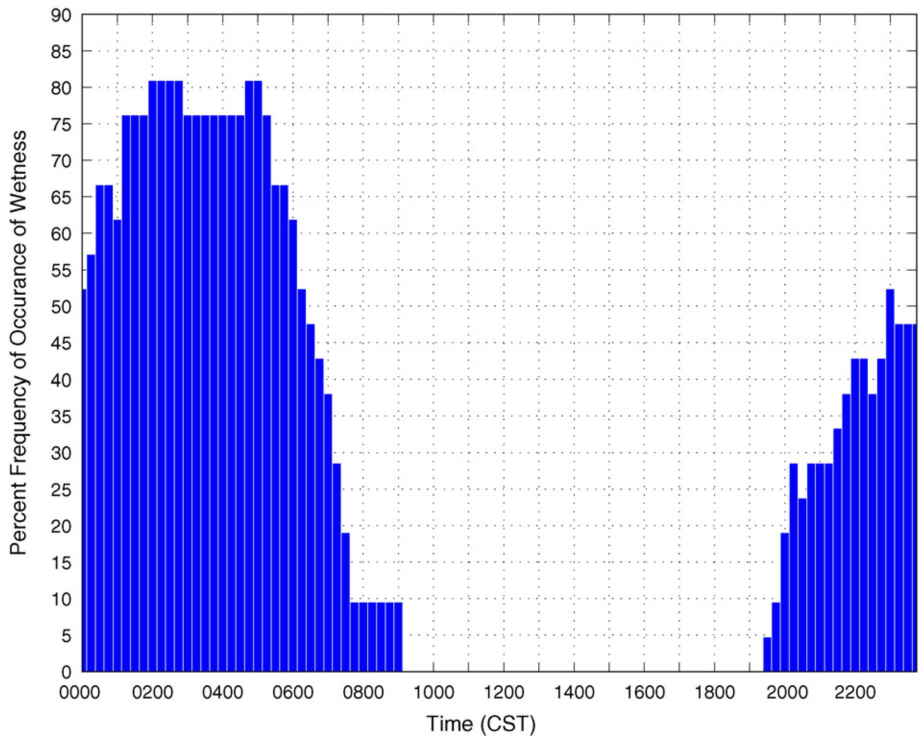

Fig. 3 – Percent of days during SMEX05 (14 June–5 July) that at least one wetness sensor was wet with dew in one field of soybean (WC11) as a function of time of day.

Figs. 2 and 3 for the dew sensors in fields WC10 (corn) and WC11 (soybean), respectively. For each 15-min interval, these histograms display the percent of days during SMEX05 that at least one of four leaf wetness sensors in each field was wet during all or part the interval. We filtered the data to eliminate days during which wetness was caused by intercepted precipitation. Histograms for the other fields intensively monitored for dew are similar.

For the corn canopy in field WC10, dew was present on 18 of the 21 days (86%) of SMEX05 and most frequently from approximately 12:30 until 6:30 CST. Dew was present for a significant number of days during SMEX05 up to approximately 7:00 CST (7 out of 21 days, or 43%). Dew was present as late as 9:15 CST and as early as 19:30 CST, leaving approximately 10 h during the diurnal cycle that were totally dew-free. At the WindSat overpass time of approximately 6:30 CST, dew was present on 12 of the 21 days (57%). At other common overpass times of 1:30 and 6:00 CST, dew was present on 16 (76%) and 15 (71%) of the 21 days, respectively.

For the soybean canopy in field WC11, dew was present on 17 of the 21 days (81%) of SMEX05 and most frequently from approximately 12:00 until 6:30 CST. Dew was present for a significant number of days during SMEX05 up to approximately 7:00 CST (8 out of 21 days, or 38%). Dew was present as late as 9:15 CST and as early as 19:30 CST, again leaving approximately 10 h during the diurnal cycle that were totally dew-free. At the WindSat overpass time of approximately 6:30 CST, dew was present on 8 of the 21 days (38%). At other common overpass times of 1:30 and 6:00 CST, dew was present on 16 (76%) and 13 (62%) of the 21 days, respectively.

3.2. *Dew amount*

Using our manual measurements, we calculated the amount of dew in terms of the depth of an equivalent uniform layer of liquid water per area with units of mm. In our actual calculations, we found dew amount in units of kg m^{-2} (mass of water per ground area, also called the total leaf wetness), but this is numerically equivalent to dew measured in units of mm such that 1.0 kg m^{-2} of dew is equivalent to 1.0 mm of dew.

We used two different methods to scale dew from leaf to canopy. In the first method, we calculated the amount of dew using direct measurements of the vegetation canopy. We denote this dew amount with the notation W_{dd}. We found the mean mass of water per leaf from the samples taken in each field, multiplied this by the mean number of leaves per plant, and then multiplied this by the mean plant density.

$$W_{dd} = \frac{\text{water mass}}{\text{leaf}} \times \frac{\text{leaves}}{\text{plant}} \times \frac{\text{plants}}{\text{ground area}} \tag{1}$$

To obtain the mean number of leaves per plant and the mean plant density, we counted the plants and the leaves per plant along a 1-m transect near the sampling location and measured the row spacing.

In the second method, we calculated the amount of dew using indirect measurements of leaf-area index (LAI) that we made with an LAI2000 Plant Canopy Analyzer. We denote this dew amount with the notation W_{dL}. We found the mean mass of water per leaf area from the samples taken in each field by measuring both the mass of water on each leaf and the two-sided surface area of each leaf. We calculated the surface area of each leaf by creating a digital image of the leaf with a

Table 1 – Dew amount on corn for three different days with distinctly different amounts of dew using both direct measurements (W_{dd}) and indirect measurements (W_{dL}) of the structure of the vegetation canopy

Level of dew	Date	Time (CST)	Location	LAI	W_{dd} (mm)	W_{dL} (mm)
Light	6/23/2005	05:55	WC10	2.57	0.02	0.01
		06:10		1.98	0.03	0.02
		06:20		2.66	0.01	0.01
Moderate	6/19/2005	05:50	WC10	2.01	0.09	0.08
		06:10		1.40	0.1	0.08
		06:20		2.54	0.1	0.08
		07:20		1.90	0.03	0.03
Heavy	7/2/2005	06:35	WC22	3.01	0.6	0.5
		06:55		3.10	0.4	0.3
		07:15		3.18	0.4	0.3

scanner and using software to find the leaf area. We then multiplied this by twice the measured LAI since LAI is defined as the single-sided leaf area per ground area.

$$W_{dL} = \frac{\text{water mass}}{\text{leaf area}} \times (2 \times \text{LAI}) \qquad (2)$$

In each method, we made the assumption that one-third of the leaves in the canopy were similar to the lowest leaf sampled and that two-thirds of the leaves in the canopy were similar to the top two leaves sampled. Dew amounts on both corn and soybean calculated using each method are shown in Tables 1 and 2, respectively, for 3 days with distinctly different amounts of dew.

We observed a range of dew from 0.01 to 0.6 mm in corn and from 0.003 to 0.8 mm in soybean on days that we chose to represent light, moderate, and heavy dew events. The absolute difference between the amount of dew calculated with each method was always 0.1 mm or less except for a single observation (heavy dew in soybean at 06:45 CDT). Direct measurements of dew (W_{dd}) were never less than the indirect measurements of dew (W_{dL}) in corn. For soybean, the indirect measurements tended to be higher than the direct measurements, but W_{dL} was less than W_{dd} twice. These two tendencies must be related to the structure of these two different types of crop. Because there is not a standard method to measure the amount of dew, we cannot determine which method is more accurate.

We did not determine an overall error estimate for the dew amount quantities defined in (1) and (2). Although the error of water mass per leaf and leaf surface area, for example, are reported in Kabela (2006), the error associated with the natural spatial variability of dew is not known. Since this natural variability is likely significant compared to measurement errors, we do not believe it is possible to derive a meaningful error estimate of dew amount.

We have chosen to use the indirect method as the ''true'' amount of dew in this paper for two reasons. First, there is no standard for dew measurement. Second, the indirect method includes the most accurate measurement of the amount of liquid water per leaf surface area. Third, the indirect method is more convenient in terms of the measurements that must be made in the field. Instead of counting the number of leaves on several plants (in order to find the mean number of leaves per plant) and the number of plants per ground area, all that is required in the indirect method is one measurement of LAI which can be made easily. We report all subsequent measurements of dew amount in this paper as calculated using the indirect method.

3.3. *Dew distribution*

The distribution of dew among the top and bottom sides of leaves and (for corn) the leaf collar for 3 days with distinctly different amounts of dew are shown in Tables 3 and 4. We

Table 2 – Dew amount on soybean for three different days with distinctly different amounts of dew using both direct measurements (W_{dd}) and indirect measurements (W_{dL}) of the structure of the vegetation canopy

Level of dew	Date	Time (CST)	Location	LAI	W_{dd} (mm)	W_{dL} (mm)
Light	6/19/2005	06:40	WC11	0.42	0.007	0.01
		06:55		0.47	0.004	0.005
		07:05		0.66	0.003	0.007
Moderate	6/22/2005	06:35	WC15	0.72	0.2	0.1
		06:45		0.52	0.06	0.06
		06:55		1.05	0.06	0.05
Heavy	7/2/2005	05:45	WC15	1.78	0.6	0.4
		06:05		1.68	0.7	0.7
		06:15		2.09	0.7	0.8
		07:45		2.10	0.2	0.2
		07:55		1.75	0.05	0.06
		08:05		1.65	0.1	0.1

Table 3 – Distribution of dew on corn between the top of a leaf, the bottom of a leaf, and the leaf collar for three different days with distinctly different amounts of dew

Level of dew	Date	Time (CST)	Location	Top (%)	Bottom (%)	Collar (%)
Light	6/23/2005	05:55	WC10	73.4	10.3	16.3
		06:10		48.3	38.1	13.6
		06:20		51.0	17.5	31.5
Moderate	6/19/2005	05:50	WC10	24.8	40.2	35.0
		06:10		35.4	44.6	20.0
		06:20		21.1	46.9	32.0
		07:20		40.0	43.9	16.1
Heavy	7/2/2005	06:35	WC22	15.1	42.9	42.0
		06:55		9.0	52.9	38.1
		07:15		12.0	47.8	40.3

calculated these distributions using the measurements described in Section 2.2. For corn, most of the dew was found on top of the leaf during the light dew event. For the moderate dew event, the dew was more evenly distributed among the top and bottom of a leaf and the leaf collar. For the heavy dew event, we found only a small percentage of the total dew amount on top of the leaf with the rest distributed between the bottom of the leaf and the collar. For the moderate and heavy dew events, we found more dew on the bottom of a corn leaf than on the top in every instance. The percentage of dew in the leaf collar was lowest during the light dew event and greatest during the heavy dew event. For soybean, more dew was generally found on the top of a leaf than on the bottom for the light and moderate levels of dew. Since the percentage of dew on the top of a leaf tended to decrease with time while the percentage of dew on the bottom of a leaf tended to increase with time for the light and moderate dew events, it appears that the top of a soybean leaf dries more quickly than the bottom. For the heavy dew event in soybean, we found a higher percentage of the dew on the bottom of the leaf.

4. Analysis

Moisture on leaves can result from either intercepted precipitation or dew. Dew is the result of three processes: dewfall, distillation, and guttation (Monteith, 1957; Garratt and Segal, 1988). Dewfall occurs when water vapor originating from above the canopy condenses on vegetation. Distillation is the condensation of water that has evaporated from the soil. Guttation is a process by which water secreted by the plant itself collects on the canopy. Since guttation accounts for the smallest amount of dew and has been found to be insignificant in corn (Atzema et al., 1990), we do not consider guttation in our analysis. We used our observations of dew in corn and soybean to test the ALEX model, a physically based land surface process model that simulates both dewfall and distillation. This model also provides a framework through which we can verify that our manual observations of dew amount and the leaf wetness sensor observations of dew duration are consistent with observed meteorological conditions (Fig. 4). Most importantly, if dew is found to affect remotely sensed measurements, manual measurements will be impractical at the scales of remotely sensed measurements and a modeling approach will have to be used.

4.1. *The ALEX model*

We estimated the amount and timing of dew with the Atmosphere–Land Exchange (ALEX) model (Anderson et al., 2000), one of many land surface models that describes the transport of heat, water vapor, carbon, and momentum within the soil–plant–atmosphere system. The ALEX model is unique

Table 4 – Distribution of dew on soybean between the top of a leaf and the bottom of a leaf for three different days with distinctly different amounts of dew

Level of dew	Date	Time (CST)	Location	Top (%)	Bottom (%)
Light	6/19/2005	06:40	WC11	52.6	47.4
		06:55		59.7	40.3
		07:05		38.9	61.1
Moderate	6/22/2005	06:35	WC15	57.1	42.9
		06:45		55.2	44.8
		06:55		50.3	49.7
Heavy	7/2/2005	05:45	WC15	37.6	62.4
		06:05		48.8	51.2
		06:15		47.5	52.5
		07:45		35.3	64.7
		07:55		33.3	66.7
		08:05		42.0	58.0

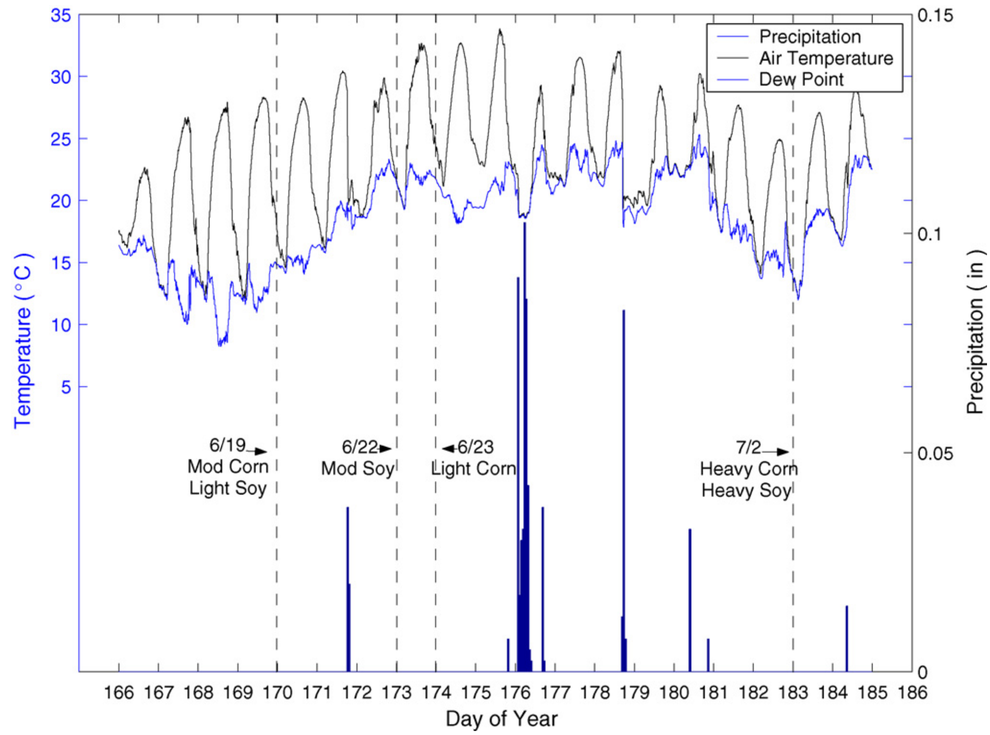

Fig. 4 – Air temperature, dew point temperature, and precipitation observed in WC10 between 15 June (day of year 166) and 4 July (day of year 185), 2005.

because it was developed for practical application in agriculture and weather forecasting (Anderson et al., 2001). It is a simplified version of the comprehensive land surface model Cupid (Norman, 1979; Norman and Campbell, 1983), requiring considerably fewer input parameters and less computing time. Like the Cupid model, the use of empirical relationships has been purposely kept to a minimum so that the ALEX model can be applied to a variety of crops and is not restricted to a certain set of environmental conditions.

The ALEX model estimates dew within the canopy by coupling air temperature and water vapor pressure measured above the canopy to the temperature and water vapor pressure conditions in the canopy airspace, at the leaf surface, and at the soil surface using physical principles of energy balance and turbulent exchange. Vapor pressure in the canopy airspace is influenced by not only atmospheric vapor pressure, evaporation from leaf surfaces, and canopy transpiration, but also by the evaporation of water from the soil. ALEX uses the Richard's Equation to compute the time-dependent soil moisture profile, taking into account root uptake, drainage, and soil evaporation. In numerical experiments with Cupid, Wilson et al. (1999) found that a wet soil could extend the period of leaf wetness by 2 hours as compared to a dry soil. Because ALEX also considers the role of soil moisture in producing dew, it is distinct from other models that have been used to predict leaf wetness that neglect distillation (Pedro and Gillespie, 1982; Gleason et al., 1994; Chtioui et al., 1999).

Free water accumulates on leaf surfaces through the interception of rainfall or irrigation, or by condensation when the vegetation temperature falls below the dew point inside the canopy. In the ALEX model, the size of the canopy reservoir for free water, W_{max}, is assumed to be a linear function of leaf-area index:

$$W_{max} = 2 \times W_{leaf} \times LAI \tag{3}$$

where W_{leaf} is the maximum potential reservoir of water per unit single-sided leaf area and it is assumed that both sides of a leaf are wetted equally. The W_{leaf} reservoir is limited in the model to ≤ 0.15 mm per unit leaf area, according to the measurements made in potato by Wilson et al. (1999). Any accumulated water exceeding this threshold is assumed to drip to the soil surface. Because dew tends to form in beads and not as a uniform film, the fraction of leaf area covered with water grows linearly with free water to a maximum allowed value (Anderson et al., 2000).

Besides specifying vegetation characteristics (the type of crop, crop height, and LAI) and the soil properties, we did not "tune" or artificially adjust the parameters in the ALEX model in order to make the model estimates match the observations. We used measured soil texture and bulk density from fields WC10 and WC11. The soil in each field was a Webster clay loam with a texture of 45% sand, 23% silt, and 32% clay and an average bulk density of 1.3 Mg m^{-3}. The corresponding soil parameters were calculated as follows: pore air entry potential of -2.6 J kg^{-1}; soil moisture release curve exponent of 5.2; and a saturated hydraulic conductivity of 6.4×10^{-5} kg s m^{-3}. We specified a maximum soil depth of 1.5 m. The soil properties of the other fields were similar. We initialized the ALEX model with measured soil moisture values and ran the model from day of year 167 until 183.

4.2. Observed and modeled dew amount and duration

ALEX model predictions of dew duration and amount for light, moderate, and heavy dew events in both corn and soybean are shown in Figs. 5–10. We defined these three categories of dew events by dividing each of the dew days during SMEX05 equally into three different intensity categories. We considered dew amounts of less than 0.07 mm to be "light," dew amounts between 0.8 and 0.2 mm to be "moderate," and amounts greater than 0.2 mm to be "heavy." We report in this paper the results and analysis for 1 day in each of the dew intensity categories for each canopy in order to evaluate the performance of the model in a variety of physical conditions. These results were representative of our general findings. Also shown in these figures are our manual measurements of dew amount (W_{dL}). Each line of the bottom sub-figure represents the output of each of the four leaf wetness sensors located in the field as well as ALEX model predictions of the existence of dew in the canopy. A darkened box means that the specific sensor was wet for any period of time during the 15-min recording period. A darkened box for the ALEX model means that the model predicted dew in the canopy during that time interval.

We considered four different types of errors in our manual measurements of dew and assumed that the first three of these errors are not significant. First, we observed that dust from the surface of the leaf accumulated on the towels after wiping the leaf. The amount of dust was only enough to slightly discolor the towel. Second, it was possible that water vapor diffused through the plastic bag. Third, the temperature of the plastic bag may have changed from when it was sealed with the moist towel until we measured the mass of the bag and towel in the laboratory with a balance. Assuming a constant volume, a change in temperature would result in a change in pressure and a change in the relative amounts of liquid water and water vapor in the plastic bag, which would change the mass measured by the balance. Finally, as noted earlier, we exposed two different towels to the canopy environment at each site in order to measure the change in mass of the towel due simply to the process of removing and replacing the towel from the plastic bag in the canopy environment. In all cases, the mass of the control towels decreased after they had been exposed to the canopy environment (possibly because the canopy environment was less humid than the environment in which the bags were first sealed). The error bars in each figure represent this error.

For the dew event on 19 June (light dew in soybean, moderate in corn), a short period during which the relative humidity was high (as indicated by the closeness of the air and dew point temperatures) is shown in Fig. 4. Enough soil moisture was present before this measurement period to produce a moderate dew intensity in corn. However, a light dew period was observed in soybean due to the open canopy (low LAI). On 22 June (moderate dew in soybean), rainfall the night before in conjunction with a long period in which the relative humidity was high contributed to the moderate amount of dew. On 23 June (light dew in corn), despite the previous rainfall the air and dew point temperatures do not come close to each other, indicating low relative humidity and preventing a heavier dew. On 2 July (heavy dew in corn and soybean), rainfall during the previous week coupled with the growing corn and soybean (LAI values significantly increased over this period) and a high relative humidity over most of the night resulted in a heavy dew.

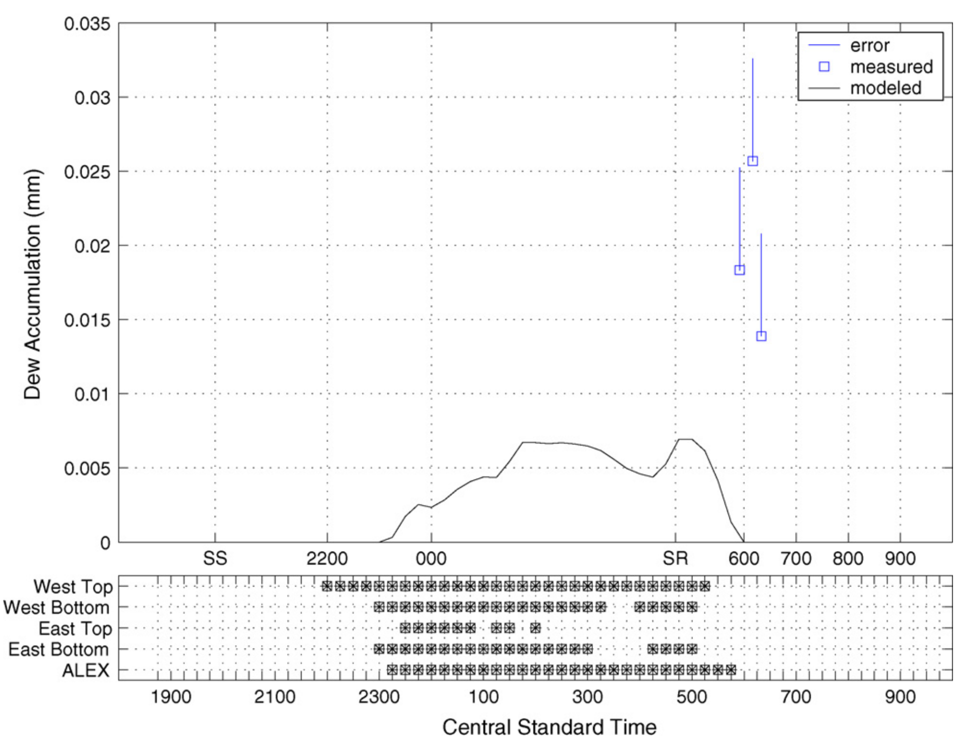

Fig. 5 – Observed and modeled dew amount and duration in a corn canopy during a light dew event on 21–22 June (day of year 172–173). Tick marks "SS" and "SR" indicate the time of sunset and sunrise, respectively.

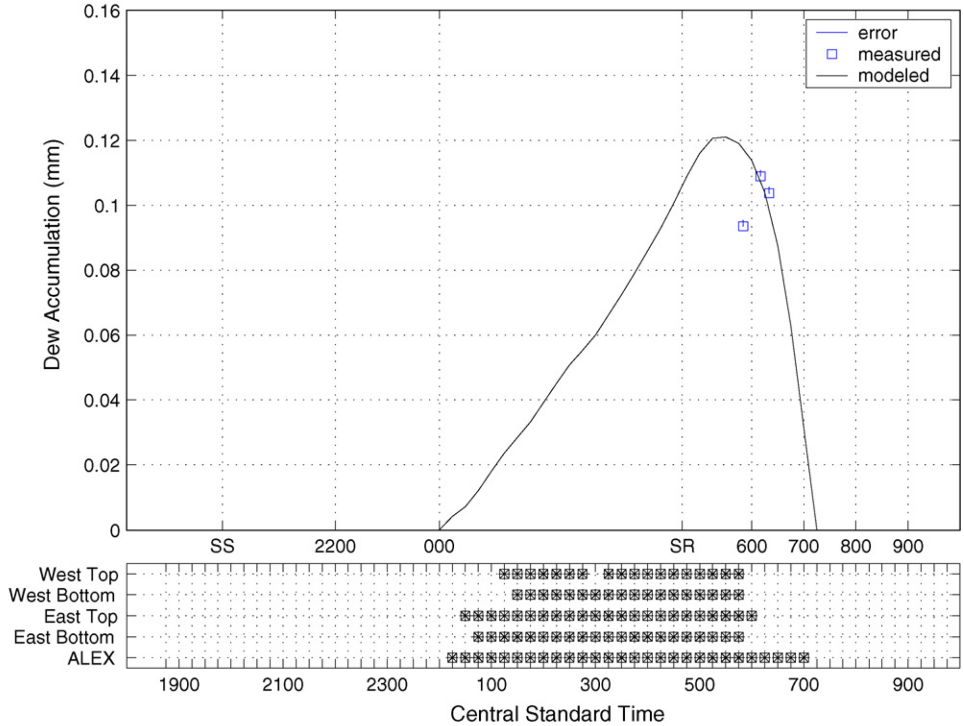

Fig. 6 – Observed and modeled dew amount and duration in a corn canopy during a moderate dew event on 18–19 June (day of year 169–170). Tick marks "SS" and "SR" indicate the time of sunset and sunrise, respectively.

The ALEX model was able to accurately estimate the time of dew onset and dryoff for both heavy dew cases. We consider model estimates to be ''accurate'' if they are within 30 min of the time at which any of the four leaf wetness sensors indicated water condensation. The ALEX model was also able to accurately estimate either the onset of dew or the dryoff of dew or both the onset and dryoff of dew in every case examined: dryoff for the light dew event in corn; onset for the

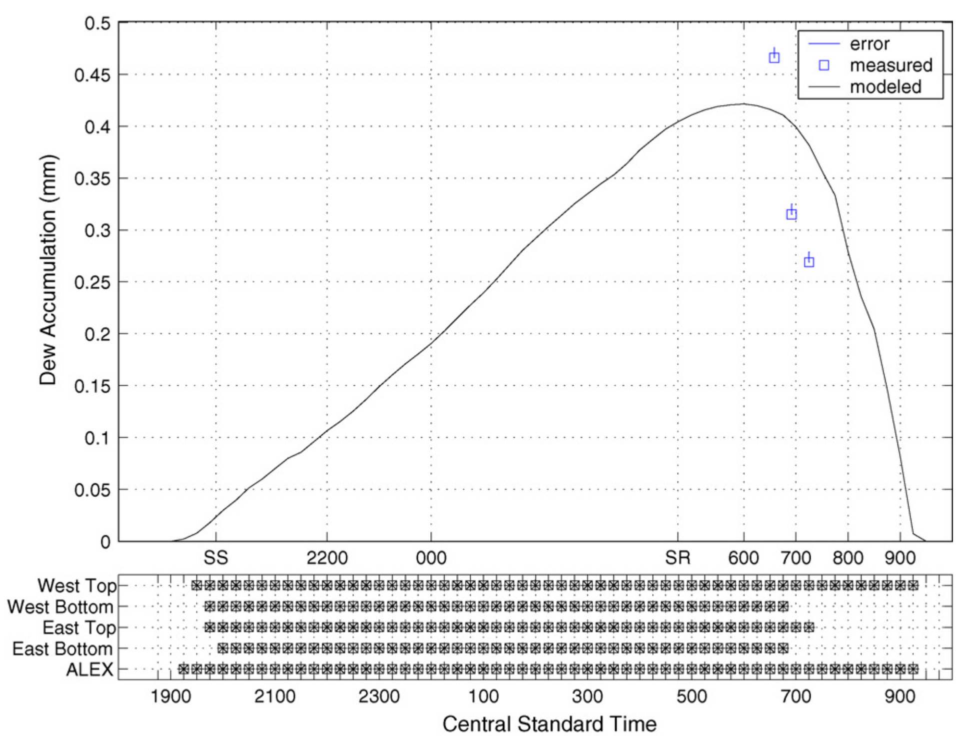

Fig. 7 – Observed and modeled dew amount and duration in a corn canopy during a heavy dew event on 1–2 July (day of year 182–183). Tick marks "SS" and "SR" indicate the time of sunset and sunrise, respectively.

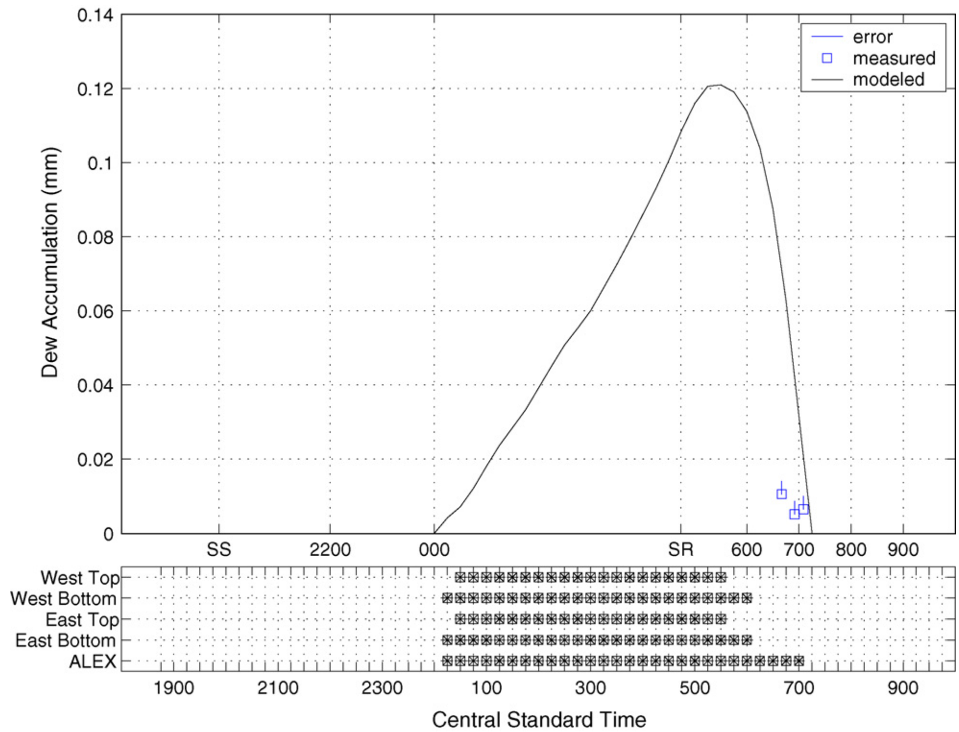

Fig. 8 – Observed and modeled dew amount and duration in a soybean canopy during a light dew event on 18–19 June (day of year 169–170). Tick marks "SS" and "SR" indicate the time of sunset and sunrise, respectively.

moderate dew event in corn; onset for the light dew in soybean; and both onset and dryoff for the moderate dew event in soybean. In every case, except one (the light dew event in corn), the time of dew onset predicted by the ALEX model was either earlier than or the same as the time indicated by the leaf wetness sensors. Furthermore, in every single case the time of dew dryoff predicted by the ALEX model was either later than or the same as the time indicated by the

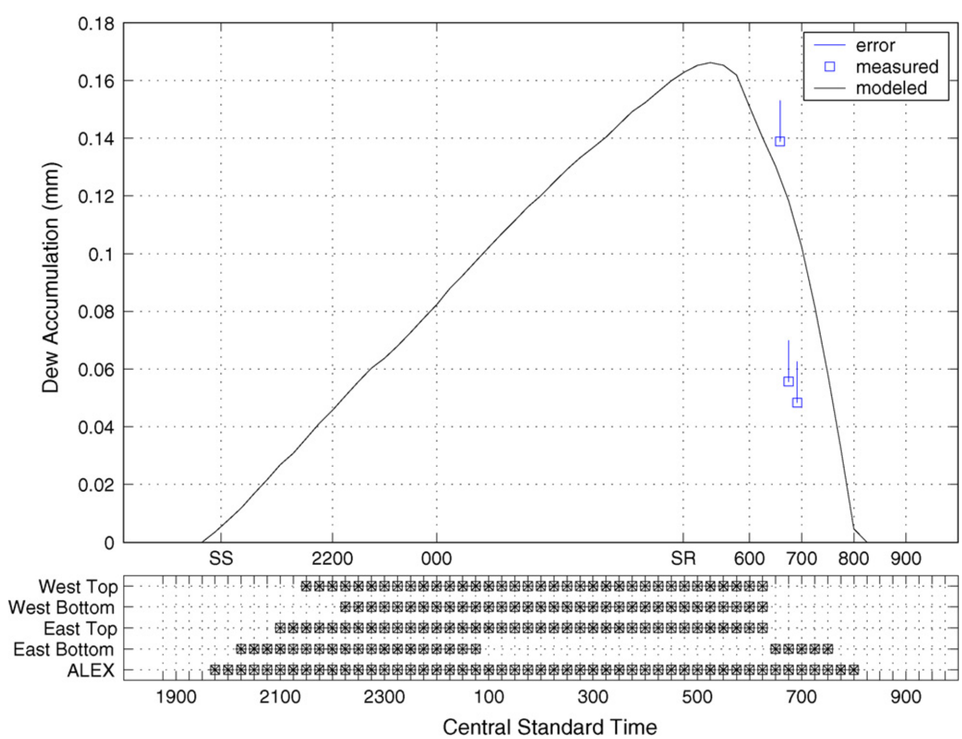

Fig. 9 – Observed and modeled dew amount and duration in a soybean canopy during a moderate dew event on 21–22 June (day of year 172–173). Tick marks "SS" and "SR" indicate the time of sunset and sunrise, respectively.

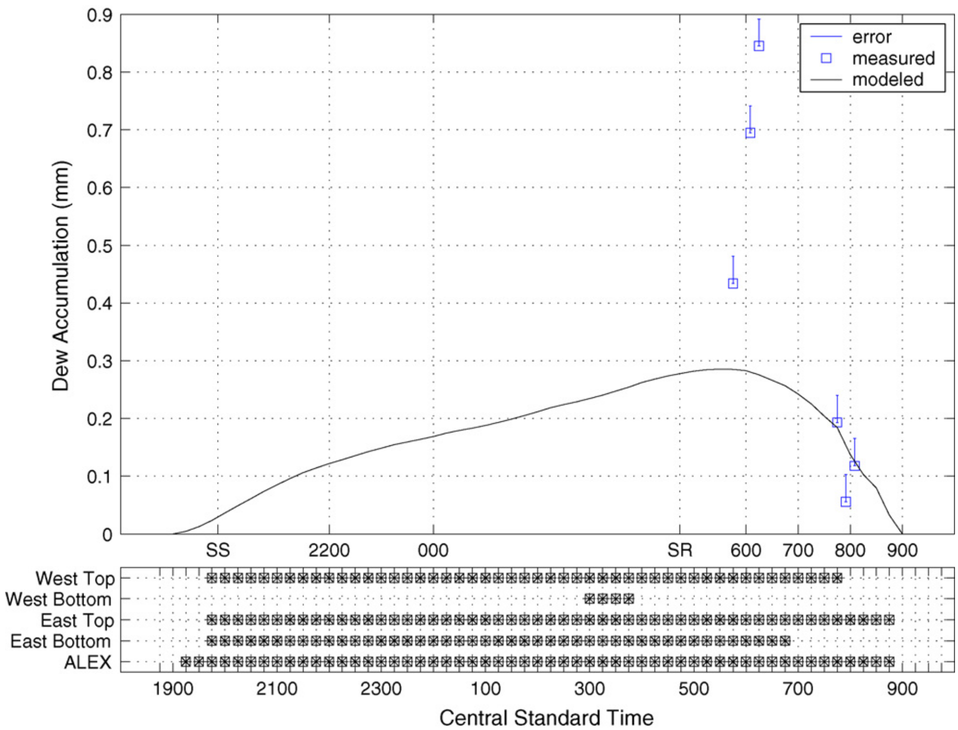

Fig. 10 – Observed and modeled dew amount and duration in a soybean canopy during a heavy dew event on 1–2 July (day of year 182–183). Tick marks "SS" and "SR" indicate the time of sunset and sunrise, respectively.

leaf wetness sensors. Although we have used the leaf wetness sensors as the standard in our investigation, the wetness sensors are not perfect representations of actual leaves and we cannot make a definitive evaluation of the estimations of dew duration made with the ALEX model.

In terms of the amount of dew, the predictions of the ALEX model were accurate (accuracy defined to be within 0.1 mm of manual observations) in every case except for three observations during the heavy dew event in soybean. We believe that the error observed during the heavy dew event in soybean is related to the manual observations. The ALEX model accurately estimated dew in corn in this work and has been successfully used to model dew in potato (Wilson et al., 1999). We believe that both the scaling procedure and the spatial variability of dew contributed to the error observed during the heavy dew event in soybean. We based our scaling procedure on observed vertical profiles of dew in a corn canopy. The profile of dew in a soybean canopy has not been reported and may be different. If the scaling procedure is changed to assume that half of the leaves in the canopy were similar to the lowest leaf sampled and half similar to the top two leaves sampled, the values of W_{dL} on 2 July at 5:45, 6:05, and 6:15 CST change from 0.4, 0.7, and 0.8 mm to 0.3, 0.6, and 0.8 mm. This change brings the measurement at 5:45 CST into agreement with the model. We hypothesize that the spatial variability of dew itself is responsible for the disagreement between the two measurements at 6:05 and 6:15 CST and the ALEX model. Further work on the validation of the model, especially in the early morning hours when dew begins to form, the vertical profile of dew in a soybean canopy, and the spatial variability of dew should be pursued.

5. Conclusions

Besides its impact on the hydrology and biology of ecosystems, dew may affect remotely sensed measurements of important ecosystems variables such as soil moisture. As part of SMEX05, a 21-day field experiment during June and July, 2005, in Central Iowa, we observed the frequency and duration of dew events, the total amount of dew in the canopy, and the distribution of dew within the canopy for two different types of vegetation, corn and soybean. We were able to answer the following questions.

How often is dew present? Dew was present on more than 80% of the days of SMEX05 in corn and soybean. Dew was found to be present at every hour of the day during the experiment except for approximately 10 h between 9:30 and 19:30 CST.

At what time of day is dew likely to be present? Dew was most likely to be present between 12:30 and 6:30 CST in both corn and soybean. At 1:30, 6:00, and 6:30 CST (which correspond to the overpass times of three current or planned satellite remote sensing instruments), dew was present 76%, 71%, and 57% of the days, respectively, in corn and 76%, 62%, and 38% of the days, respectively, in soybean. Dew was present until 7:00 CST on about 40% of days.

How much dew is present? We observed dew amounts from 0.01 and 0.6 mm in corn and from 0.003 to 0.8 mm in soybean on 3 days representing light, moderate, and heavy dew events. We used two different methods of scaling the liquid water observed on individual leaves to the entire canopy. We recommend for future field experiments a method that employs measurements of leaf-area index because this method uses the most accurate measurements of the amount of water per leaf surface area and because the measurements associated with this method are easy to acquire in the field. It is likely that the 0.8 mm maximum value of dew in soybean is too high due to assumptions in our scaling procedure and the spatial variability of dew. A maximum value of 0.3–0.4 mm is predicted by the ALEX model for this period. More research on the vertical profile of dew in a soybean canopy and on the spatial variability of dew is needed.

Where is dew deposited in the canopy? The location of free water in the canopy may influence its effect on the remote sensing signal (Hornbuckle et al., 2007). In corn, the majority of dew was found on top of the leaf for the light dew event. For the moderate and heavy dew events, we found more dew on the bottom of a corn leaf than on the top in every instance. The percentage of dew in the leaf collar was lowest during the light dew event and greatest during the heavy dew event. In soybean, generally observed more dew on the top of a leaf than on the bottom for a light and moderate dew event, and more dew on the bottom than on the top in a heavy dew event.

The ALEX model, a land surface process model that accounts for both dewfall and distillation, was able to accurately estimate (in comparison to leaf wetness sensors and manual observations) dew amount and duration in most of the cases that we examined. This modeling analysis supports our observations and points to a procedure that could be used to observe dew at larger spatial scales associated with satellite remote sensing. Although we have used the leaf wetness sensors and manual observations as standards in this investigation, both methods are not without error and it is difficult to evaluate the performance of the ALEX model as well as the exact nature of dew.

The geographical extent and time period of SMEX05 was determined by both science objectives and the available financial and human resources. Although the observations and analysis of dew in this paper only cover an approximately 1-month period during a single year, we have no reason to believe that weather conditions during this period were anomalous. Larger spatial scales of dew must be considered in order to determine the effect of dew on remotely sensed measurements from satellites. The ALEX model provides a possible bridge to these larger scales as it can be run regionally using meteorological inputs from standard synoptic data (Anderson et al., 2001) using boundary conditions and land-surface parameters obtained, for example, from NASA's Land Information System (LIS; Kumar et al., 2006). Alternatively, dew predictions could be derived from a remote sensing inversion of ALEX (ALEXI; Anderson et al., 2007).

Dew will be present more often than not when remote sensing satellites with early morning overpass times take measurements over the U.S. Midwest, assuming that the climate and land cover is similar to the SMEX05 region. Furthermore, the amounts of dew we observed during the experiment are comparable, and in some cases higher, than the dew amounts that have been shown to affect the brightness temperature of vegetation and backscatter from vegetation at microwave wavelengths (Gillespie et al., 1990; Hornbuckle et al., 2006). Additional research on the amount of dew that significantly affects remotely sensed measurements and how often this level of dew occurs is warranted.

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