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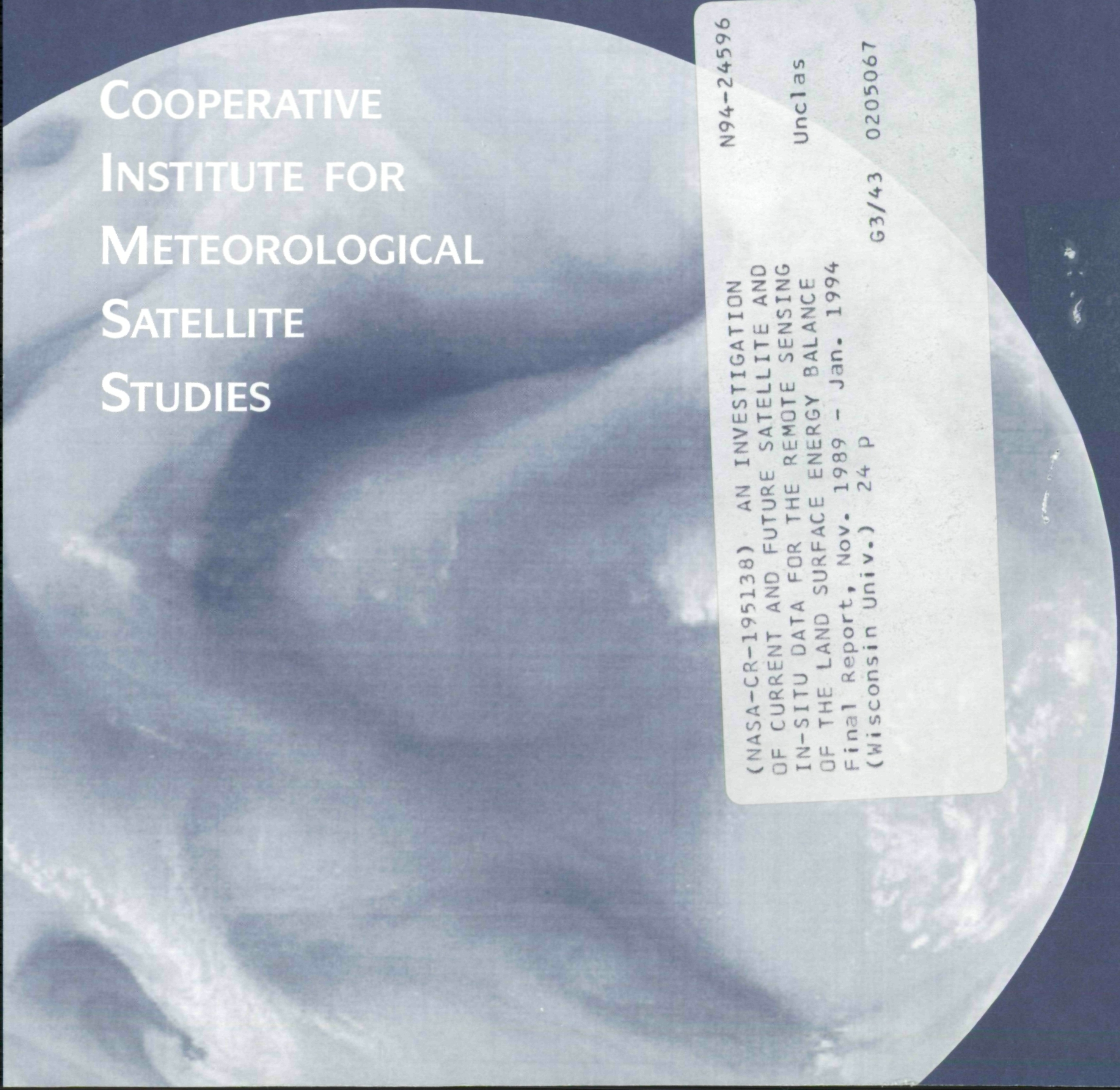

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An Investigation of Current and Future Satellite and In-Situ Data for the Remote Sensing of the Land Surface Energy Balance

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ABSTRACT

This final report from the University of Wisconsin-Madison Cooperative Institute for Meteorological Satellite Studies (CIMSS) summarizes a research program designed to improve our knowledge of the water and energy balance of the land surface through the application of remote sensing and in-situ data sources. The remote sensing data source investigations to be detailed involve surface radiometric ("skin") temperatures and also high-spectral-resolution infrared radiance data from atmospheric sounding instruments projected to be available at the end of the decade, which have shown promising results for evaluating the land-surface water and energy budget. The in-situ data types to be discussed are measurements of the temporal changes of the height of the planetary boundary layer and measurements of air temperature within the planetary boundary layer. Physical models of the land surface, planetary boundary layer and free atmosphere have been used as important tools to interpret the in-situ and remote sensing signals of the surface energy balance. A prototype "optimal" system for combining multiple data sources into a three-dimensional estimate of the surface energy balance was developed and first results from this system will be detailed. Potential new sources of data for this system and suggested continuation research will also be discussed.

I. Introduction

An outstanding problem in hydrology and meteorology across the entire range of space and time scales is estimating how the available net radiation at the land surface is distributed into the various component fluxes of the land surface energy balance, most importantly evapotranspiration and sensible heat flux. The importance of this partitioning of energy and water at the surface on the water balance and climate has been demonstrated through numerical studies by investigators who have used General Circulation Models (GCMs) to explore the effects of varying soil moisture and the resulting variations in the balance of sensible and latent heating on the global circulation and precipitation. Other modeling studies have noted the importance of regional variations in soil moisture and evapotranspiration on the character of mesoscale circulations, severe weather development, precipitation and other aspects of regional and smaller scale atmospheric phenomena. Information on latent and sensible heating at the land surface would also be valuable for agriculture, hydrology and many associated fields.

To date, it is only possible on relatively small spatial scales to measure the sensible heating and evapotranspiration from the land surface or the inter-annual variations which may result from changes in rainfall, soil moisture and vegetative response from year to year. The unavailability of such measurements over regional and larger spatial scales has been an impediment to the development of suitable land-surface parameterizations and closure of the land surface energy/water balance, even though certain field programs such as the First ISLSCP Field Experiment (FIFE) and others have been designed to bridge the gaps between scales. With inadequate verification of surface quantities at regional and larger scales, investigators have had to rely heavily on indirect methods of verification, such as trying to generalize measurements made over smaller scales, analyzing patterns of land use and vegetation and the use of precipitation indices or remotely-sensed vegetation indices (such as the normalized difference vegetation index, NDVI) as proxies for evapotranspiration and soil moisture.

In this research, scientists from the CIMSS have studied techniques for estimation of the land-surface sensible heating, evapotranspiration (ET) and characteristics of the land surface using remotely-sensed skin temperatures, in-situ data from the synoptic network and also promising new data which will become available with the launch of high-spectral resolution infrared sounding instruments, such as the Advanced Infrared Radiometer Sounder (AIRS) and the Geostationary High-Resolution Interferometer Sounder (GHIS). The goal of the research was to develop a system for evaluating the land surface sensible heating, evapotranspiration and potentially other surface characteristics which incorporates currently available in-situ and remote data sources and which will be flexible to the addition of new data or data reduction techniques as they become available. A guideline for the development of this prototype system was the framework of so-called optimal estimation and data assimilation techniques currently favored in operational numerical weather prediction (NWP). The optimal system relies on the data inputs which we have investigated for the evaluation of the surface energy and water balance. The addition of other data sources, as well as some promising and complementary data reduction approaches investigated by other researchers are planned as upgrades to the system.

II. Research Accomplishments

A. Overview

The overall objective of this research was to investigate methods for estimating land-surface evapotranspiration, sensible heating and potentially other surface characteristics from a combination of operational, in-situ and remote data sources. Energy balance approaches were predominantly utilized to evaluate the surface evapotranspiration and sensible heating. These energy balance methods generally involve using a data source to estimate the surface sensible heating, estimating the net radiation and soil flux using complementary data and methods, and subsequently evaluating evapotranspiration as a residual in the surface energy balance. Models of the Planetary Boundary Layer (PBL), surface and free atmosphere are used to interpret the various signals.

In Sections B and C of this report, we present the list of the in-situ and remote sensing data sources which we have investigated and those planned for later addition to the system. The list of data types includes both currently available data sources and several remote sensing data sources which are planned for the Earth Observing System (EOS) or other programs which have shown promising capabilities. In Section D, the concepts of optimal estimation are introduced and some encouraging preliminary results from a prototype system applied to the estimation of land surface properties are detailed.

B. In-Situ and Remote Sensing Information

1. Temporal Changes of Satellite-Measured Surface "Skin" Temperatures (DT_S)

Satellite-measured surface "skin" (radiometric) temperatures have been used by many researchers to quantify the land-surface sensible heat flux and evapotranspiration. They have the advantage of being available over wide geographical areas and their long time-history makes them applicable to retrospective studies. They are, of course, only usable under mostly clear-sky conditions. Diak and Stewart (1989) provided an error evaluation for the use of skin temperatures to quantify the daytime surface energy/moisture balance indicating that three or four levels of information on surface heating/ET were obtainable. Most research investigations have used remotely-measured ***absolute*** temperatures as a lower boundary condition in a surface layer or surface layer/PBL model to estimate surface sensible heating and latent heating through energy balance considerations.

After numerous published research investigations, there are still many inconsistencies in the quality of results reported by various researchers and important differences between the models and methods used to estimate surface exchanges using these remote sensing measurements. A basic problem with the use of skin temperatures is that for a given energy balance the so-called "aerodynamic" temperature (a construct temperature which produces the measured surface sensible heat flux when inverted through surface layer theory) depends on surface type and nature of the overlying atmosphere. Both the variations in remotely-sensed temperatures due to the viewing geometry of the radiometer and the relationship of the remotely-measured temperature to this aerodynamic temperature further complicate the problem of estimating the surface sensible heat flux and evapotranspiration..

In recent work (Diak and Whipple, 1993a), we have evaluated daytime sensible and latent heating totals for five days at the FIFE site using the ***temporal changes*** of GOES skin temperatures (DT_S). Wetzel et al. (1984) demonstrated that the mid-morning temporal change of surface temperature was a strong signal of the surface energy balance and soil moisture. Importantly, the use of these temporal changes mitigates problems involved with using ***absolute*** temperatures which are caused by errors in sensor calibration, atmospheric corrections and surface emissivity estimates. The use of these changes may also have some advantages within the surface/PBL models which are commonly used to "invert" the remote temperature measurements and estimate fluxes. Physical and dynamical models of the surface and atmosphere are usually better at predicting differences than absolute values. Potentially then, ***model biases*** are also reduced by using the models within the framework of predicting temporal differences. Our FIFE results (shown in Fig. 1), which were made using temporal changes of surface skin temperature measured from a geostationary satellite as interpreted by a PBL model are encouraging (Diak and Whipple, 1993a). The standard errors in 12-hour (daytime) sensible heating estimates are within about 1.5 $MJ\text{-}m^{-2}$ of the FIFE surface-based measurements for the days which we investigated for this mixed prairie environment (a typical combined sensible and latent heating total for a clear summer day in mid-latitudes is about 15 $MJ\text{-}m^{-2}$). This level of information is somewhat better than projected in our prior study (Diak and Stewart, 1989) and would be of value in the investigation of the land-surface energy balance.

There are also some preliminary indications from measurements made at the FIFE site of the changes of remotely-sensed temperatures with time and viewing angle (see Hall et al., 1992, Fig. 10a, data from Vining and Blad, 1992), that the use of temporal changes may also reduce problems associated with angle of view. Some additional pertinent results from the FIFE using the Cupid model (Norman et al., 1990) are shown in Fig. 2(a-b). A comparison between measured and modeled directional brightness temperatures is shown in Fig. 2a to support the validity of the model and show the importance of directional effects. Predictions of DT_S between 0900 and 1500 (local time) are shown as a function of viewing angle in Fig. 2b. Clearly from these preliminary results, DT_S is less susceptible to view angle effects than is absolute temperature.

The nature and quality of ancillary data required for a remote sensing data source is always an important question in evaluating its potential contribution. To estimate the surface sensible heating and evapotranspiration using surface skin temperatures, information on the temperature, wind speed and humidity of the lower atmosphere is required to serve as upper boundary conditions in surface layer or PBL models. Many investigators using surface skin temperatures to estimate the surface energy balance, including ourselves, have gone to full PBL models or PBL data sources, rather than using hourly reports from the National Weather Service (NWS) network of stations or other measurements made at low levels as upper boundary conditions. The use of these NWS or other low-level data, typically recorded at a height of 2m, means that the "signal" of the surface sensible heating, the surface-air temperature gradient, is evaluated over a small vertical distance and is susceptible to noise and errors of scale. In our methods using DT_S, we have used radiosonde information at a particular synoptic station location as initial conditions in a surface layer/mixed layer PBL model to evaluate the surface energy balance. The effects of temperature and moisture advection on the use of DT_S via a three-dimensional forecast model (the CIMSS 3-d model, see Diak et al., 1992) and other techniques has been examined in Diak and Whipple (1993b), but is in need of further investigation.

2. Temporal Changes of the Height of the Planetary Boundary Layer (DH)

The daytime change in time of the height of the PBL (DH), to date measured from radiosonde reports, is a sensitive indicator of the surface sensible heating which we have used in Diak (1990), Diak and Whipple (1993b) and Diak and Whipple (1993c) very successfully to quantify the surface sensible heating and evapotranspiration. This sensitivity of DH to the surface energy balance is evident in the equations describing the change of the PBL height with time (Driedonks, 1982a) and has been well-documented in both theoretical (Driedonks, 1982b) and applied studies (Chou and Atlas, 1982; Diak and Stewart, 1989; Boers and Eloranta, 1984).

In Diak (1990), we were able to quantify the sharp gradient in moisture availability across the Central United States using DH measurements from the synoptic network. In Diak and Whipple (1993b), a follow-up study was accomplished using a larger data base and the sensitivity of the methods and procedures to compensate for the effects of advection were detailed. A useful finding which emerged from this investigation is that surface flux estimates made using DH measurements are not greatly affected by moderate values of advection since it is ***differential temperature advection in the vertical*** (within and above the PBL) which modulates PBL growth for a given surface heating condition. In these two studies we projected that the 12-hour (daytime) surface sensible heating and evapotranspiration totals could be estimated with an accuracy of about 2 MJ-m^{-2} using DH measurements.

In Diak and Whipple (1993c), we were able to use co-located radiosonde measurements and surface flux measurements at the FIFE site to make more detailed estimates of how well surface sensible heating and evapotranspiration can be estimated using radiosonde evaluations of DH. This comparison gave RMS accuracies of 1.2 and 1.5 MJ-m^{-2}, respectively, for the 12-hour sensible heating and evapotranspiration totals, which was a better result than the initial error projections. We were also able to clearly observe a rapid "dry down" (a rapid increase in the Bowen ratio due to a long period without rainfall) which occurred in the summer of 1989 at the FIFE site (see Fig. 1). An unanticipated result was that the accuracy of the technique for estimating the surface sensible heating did not change much between clear and cloudy days. It was earlier thought that the circulations and latent heat release associated with clouds would adversely affect such an evaluation. The result signifies that the change in the PBL height could be used to quantify surface sensible heating under some cloudy circumstances and possibly evapotranspiration, if other terms in the surface energy budget under cloudy conditions can be estimated with reasonable accuracy. The level of accuracy of the techniques under clear conditions and the fact that the data apply to horizontal scales of tens of kilometers (Norman et al., 1993) makes radiosonde sites usable as "calibration targets" for remote sensing techniques for the surface energy balance.

When used in combination with satellite-measured skin temperatures (DT_s), there is also the potential to say something about the character of the land surface. In Diak (1990) and Diak and Whipple (1993b), we used the combination of data to derive an "effective" roughness at the sites of investigation. This capability is a result of having two data components (DT_s and DH), both of which contain information on the surface energy balance and the transfer characteristics of the surface. Variations in the roughness of the surface influence DH through variations in mechanically-induced turbulence and the subsequent growth of the PBL. Roughness influences DT_s through its effects on transfer coefficients in the surface layer. The roughness evaluated in these studies was termed "effective" because of the complexity of the surface model from which it was derived, where the ratio of vegetation to bare soil and other canopy variables were not explicitly accounted for, but were implicit in the Z_0 results. Future possibilities exploiting such combinations of data types to simultaneously evaluate land surface sensible heating /evapotranspiration and characteristics of the land surface will be addressed in Section D.

Our results using FIFE information indicate that DH may be a useful indicator of the surface sensible heating even in some cloudy circumstances. Further studies should be done to establish whether estimating the surface sensible heating and evapotranspiration under cloudy circumstances is feasible at an accuracy level which would be of use. In addition to using DH measurements to estimate the surface sensible heating (H), this will involve estimating the soil flux (G) and net radiation (R_n) terms in the energy budget equation of the surface and deriving the latent heating (λE) term as a residual (the standard "energy balance" methodology, but for cloudy conditions). The soil flux term is generally small under cloudy conditions and can probably be estimated reasonably well. The net radiation term consists of net shortwave and net longwave components. Models for estimating incident and net shortwave radiation using satellite-measured visible data are well-proven, show RMS accuracy on daily insolation typically between five and ten percent (Diak and Gautier, 1983) and could be applied in this work to estimate the net shortwave radiation. Models used to estimate net longwave radiation under cloudy conditions show large relative errors compared to the daily longwave radiation budget, but these errors are not prohibitively large in an absolute sense. While we expect that there will be some degradation in the evaluation of evapotranspiration under cloudy conditions, since it will not be possible to evaluate the net radiation as well as when it is clear, it is possible that the cloudy results would still have a usable level of skill.

At this writing, the prospects for the Laser Atmospheric Sounder Altimeter (LASA) as part of the EOS suite of instruments are somewhat undetermined. The original specifications for this instrument, however, suggested that it would be possible to measure the height of the PBL within about 50m (Curran, 1987), an accuracy level which is more than adequate for estimating the surface sensible heating and evapotranspiration from DH methods. This would make the use of DH data away from radiosonde locations feasible, should a suitable time interval of observation from one or more instruments be possible.

3. High Spectral Resolution Infrared Radiances from Future Sounding Instruments

Diak and Stewart (1989) suggested that ***temporal changes of atmospheric radiances*** (radiances which have their origin in the atmosphere) resulting from diurnal heating and the resulting change in PBL temperature and structure could serve as a "calorimeter" for the lower atmosphere, a measure of the sensible heating input from the surface. This proposed technique for evaluating the surface energy budget can be regarded as a so-called "integral" method, that is, a method which relies on the evaluation of bulk properties of the PBL or their time changes (Norman et al., 1993), but here accomplished using a remote sensing data source rather than in-situ measurements.

The High-Resolution Interferometer Sounder (HIS) is an instrument developed at the Space Science and Engineering Center at the University of Wisconsin. The instrument version developed for high-altitude flights on the NASA ER-2 aircraft measures infrared radiation between 590-2750 cm^{-1} (approximately 17 - 3.7 μm) in about four thousand spectral channels at a spectral resolution between .35 and .70 cm^{-1}. The geostationary satellite HIS (GHIS) is being studied as a replacement for the filter-wheel-type (low spectral resolution) sounding instruments on board the current meteorological geostationary satellite series (Smith et al., 1990) and is also providing information which will help in the development of the Advanced Infrared Radiometer Sounder (AIRS, a grating spectrometer with similar spectral characteristics to the HIS), which will be an important component of NASA's instrument suite for the upcoming EOS program. The important characteristic of these instruments for surface energy budget evaluations is that for the first time it will be possible to measure and differentiate infrared radiation components emanating both from the surface and the lower atmosphere. The HIS and AIRS instruments will also offer very "clean" window channels with which to view the surface and thus will provide an improved determination of surface skin temperatures. While such instruments are not projected to be launched until the end of the decade, their potential for remote sensing of surface sensible and latent heating (to be detailed) is promising and suggests that advance research on their capabilities should be performed.

In Diak et al. (1993a) and Diak et al. (1993b), we examined the temporal changes of HIS radiances as a means to estimate the surface fluxes of heat and moisture. Because previous HIS measurements have concentrated on covering as wide a geographical area as possible (for purposes of deriving atmospheric soundings for numerical weather prediction purposes), rather than sampling the same location at multiple times, the first experiments using the HIS radiances to derive surface quantities had to be done in simulation. Details on procedures and the results of these studies are given in Diak et al. (1993a) and the conclusions are only summarized here. Table 1 shows regression results for the time differences in HIS radiances versus surface energy budget quantities in the experiments described in Diak et al. (1993a). The table is subdivided into regression results for the total (surface + atmospheric) radiances as well as separate results for the surface and atmospheric component terms.

Table 1

Regression Statistics for Model Variables vs. Eigenvector Coefficients

Variable	**Total Radiance**		**Surface Radiance**		**Atm. Radiance**	
	R	$\mathbf{R^2}$	**R**	$\mathbf{R^2}$	**R**	$\mathbf{R^2}$
H	.87	.75	.71	.51	.87	.76
λE	.87	.76	.85	.73	.91	.83
G	.90	.81	.91	.83	.89	.79
H/S_n	.89	.76	.73	.53	.87	.76
$\lambda E/S_n$	.91	.83	.85	.72	.91	.94
G/S_n	.91	.83	.92	.85	.90	.81
DH/S_n	.88	.78	.64	.41	.89	.80
H/R_n	.90	.81	.76	.57	.91	.82
$\lambda E/R_n$	.93	.85	.87	.75	.91	.83
G/R_n	.92	.85	.92	.85	.90	.81
DH/R_n	.93	.86	.70	.48	.93	.87

Table 1. Shown are the correlation coefficients (R) and explained variances (R^2) for the regression of the eigenvector coefficients ($\underline{X}$) of various HIS radiance time-change covariance matrices on the energy budget constituents of sensible heating (H), latent heating (λE), submedium conduction (G), as well as these three quantities normalized by the net solar flux (S_n) and net radiation (R_n). Also shown are statistics for the 12-hour rise of the PBL height (DH) normalized by S_n and R_n.

The radiance signals arising from the lower atmosphere clearly have a higher correlation with the surface fluxes than does the surface radiance (surface temperature) component and thus are most important to the improved power of this remote sensing method. This investigation indicated that evaluations of sensible and latent heating by these procedures were relatively insensitive to differences in the measured value of skin temperature which would be possible for the same energy balance due to differences in atmospheric conditions, surface character or angle of view. The method is susceptible to errors caused by horizontal temperature advection in the PBL, as are most integral methods, but correction procedures for such errors using forecast model output or other data have proven successful (Diak and Whipple, 1993b; Hipps et al., 1993) and would likely be successful applied to the HIS procedures as well.

This high spectral resolution method offers the possibility of partitioning the available energy (net radiation minus the soil heat flux) into evapotranspiration and sensible heat with no explicit adjustments for the local atmosphere or surface characteristics, or even for that matter taking the local conditions explicitly into account in any way. The sensible and latent heating evaluations detailed in Diak et al (1993b) were made by simply using a time difference of two synthesized radiance measurements, which this is a very powerful characteristic of the observing system. It results from the fact that all atmospheres heated from the bottom show similar temporal changes in temperature (radiance) for a given energy input.

When AIRS or GHIS data becomes available at suitable time intervals, the procedures discussed above using the high spectral resolution information (containing information on both surface temperature changes and atmospheric changes) would replace the DT_S component of the data system. Research to be conducted regarding the future use of these high spectral resolution data should be as follows;

- Follow-up studies on the use of high spectral resolution data need to be performed. If appropriate HIS data from field programs becomes available, they can be utilized for this purpose. Without real data, however, we can still add to our knowledge through further simulation studies by using information from field programs such as the FIFE, where there were concurrent measurements of atmospheric profiles (used to synthesize the HIS data) and surface fluxes.

- It is likely that the basic set of statistics for retrievals of surface sensible heating and evapotranspiration using the AIRS/HIS total radiance changes can be improved. In general, to improve the AIRS/HIS retrieval of these energy balance components via the eigenvalue procedures which we have been described, sample locations can grouped by region, season, etc., in order to account for the possible variation in the local atmospheric and energy budget climatologies.

- Similar to several of the other data types which have been discussed, the effects of temperature and moisture advection on the AIRS/HIS procedures will need to be evaluated.

C. Other Potential Surface Energy Balance Signals - In-Situ Measurements of Air Temperature (DT_{air})

In recent investigations, Mahfouf (1991), Bouttier et al. (1993a) and Bouttier et al. (1993b) have demonstrated the value of low-level measurements of air temperature and humidity, posed in the framework of forecast model error statistics (the difference between measurements and model predictions), as a signal of the surface sensible heating, evapotranspiration and soil moisture. Model predictions of near-surface values of temperature and relative humidity are sensitive to the soil moisture in the model and the resulting energy balance of the surface. If errors in the model-predicted surface sensible and latent heating are dominant in the prediction errors for these low-level variables, it can be intuitively seen that a value of surface sensible heating which is too high (soil moisture too low) will result in a prediction of low-level air temperature which is too warm compared to measurements, and a humidity prediction which is too dry. A value of surface sensible heating which is too low (soil moisture too high) will have the opposite results on the low-level prediction of temperature and humidity.

Using these low-level measurements and resulting forecast model error statistics as a signal, Mahfouf (1991) developed techniques to retrieve soil moisture information and adjust the model soil moisture state based on that information. Further investigations (Bouttier et al., 1993a; Bouttier et al., 1993b) described a sensitivity analysis and optimization of these methods and their implementation in a mesoscale model. In-situ measurements of this general nature can be researched and incorporated into the surface energy balance estimation procedures. We anticipate again that putting these data components into the framework of ***temporal changes*** would have natural advantages, similar to those described for the DT_S data. This air temperature and humidity information will be most useful for land regions which are well-sampled by such in-situ data sources.

Two such DT_{air} data types could immediately be considered for incorporation into the optimal system. These are:

- ***Hourly low-level measurements of temperature*** from the synoptic network take advantage of a relatively high spatial and temporal data density, but since the measurements are recorded at a height of only a few meters they are subject to local effects and errors of scale. Using these data as ***temporal changes*** may well reduce these sorts of errors. Since the data is taken at hourly intervals, many choices of observation interval are possible, which could even be varied with local conditions (length of day, etc.) in order to maximize the signal to noise.

- ***Temporal change of air temperature through the depth of the boundary layer***, evaluated from radiosonde reports. Such "integral" signals and methods (Norman et al., 1993) have been demonstrated to be practical for evaluating sensible heating and evapotranspiration at the surface (Brutsaert and Sugita, 1991; Hipps et al., 1993). While often these signals require corrections to account for the effects of temperature and moisture advection, procedures have been developed for this purpose using radiosonde reports and/or forecast model information (Hipps et al., 1993; Diak and Whipple, 1993b) which appear to be effective. While radiosonde reports do not have the advantage of high spatial and temporal density as do the hourly surface reports, the methodology of using the measurements as both a vertical integral (through the depth of the PBL) and a temporal difference are an advantage in maximizing signal to noise and make the measurements representative of a larger spatial scale than just the point radiosonde location. At this writing, such measurements are being incorporated into the surface energy budget "retrieval" algorithm to be described in the next section.

D. Optimal Estimation of Surface Quantities and Issues Concerning the Combination of Data Sources

The general objective of optimal estimation procedures is to obtain the best statistical estimate of a quantity (or quantities) given the information inherent in the data source(s), the relative reliabilities of the methods which interpret the data (here models of the surface and atmosphere) and lastly, the quality of information available on these quantities of interest from prior information (such as their climatological values or an estimate from a previous time). The theories and techniques are widely used in meteorological analysis systems and the mathematics are similar to the so-called "maximum likelihood" procedures used to retrieve atmospheric profiles of temperature and moisture given the information provided by satellite sounding instruments. Such an estimation or retrieval algorithm (Eyre, 1989) is detailed in the appendix to illustrate how the techniques have been applied to the retrieval of two surface quantities, the surface Bowen ratio (B_0) and the effective surface roughness length (Z_0) from the temporal change of surface skin temperature (DT_s) and the temporal change of the PBL height (DH).

A prototype retrieval system utilizing these principals has been developed at the CIMSS for this project. The system follows the mathematics of Eq. (1) in the Appendix and its current features are as follows;

- Retrievals are performed on the grid location of the CIMSS Subsynoptic Scale Forecast Model (SSM), horizontal spacing ≈ 80 km.
- The temporal changes of PBL heights (DH) and temporal changes of surface skin temperature (DT_s) are the data sources.
- Retrieval variables are the surface Bowen ratio (B_0) and "effective" roughness (Z_0).

- DH data is diagnosed by automated procedures (developed under this project) at radiosonde locations. A 1-d PBL model is used at radiosonde locations to establish other required parameters (the K matrix, "background" values of DH and DT_S, etc., see the Appendix). DH and the other parameters are analyzed to the SSM grid.
- DT_S data and a cloudy/clear mask are diagnosed by automated procedures (developed under this project) from GOES data. Currently, surface retrievals are only performed at clear locations.

The first results from this system for June 1988 (the summer of the Midwest drought) are shown in Fig. 3 (a-c) and are encouraging. Figs. 3a and 3b show the DT_S and DH data on the SSM grid for clear regions of the Midwest and eastern Great Plains region on 8 June. Interesting features of these figures are the coincident high values of DT_S and DH in the general region of the Iowa-Illinois border and coincident minima in the eastern region of South Dakota. The daytime (12-hour average) surface Bowen ratio (B_0) retrieved from this data combination is shown in Fig. 3c, and a relative maxima exists in the Iowa-Illinois region, where there were relatively high values of DH and DT_S, and a minimum in the retrieved Bowen ratio is evident in the area of the coincident low DT_S and DH values previously described. The lower values of retrieved B_0 in South Dakota are supported by a relative maximum of the Antecedent Precipitation Index (API) in that region due to significant rainfall in the several days preceding 8 June. The B_0 maxima in the Iowa-Illinois region is supported by the existence of relative minima in API which existed on June 8 at that location.

This estimation or retrieval framework is flexible to the addition of new sources of information and retrieval variables, provided that physical or statistical models exist to interpret the measurements. Further suggested improvements and refinements are as follows;

- In-situ measurements of air temperature of the nature described in Section C above should be added to the information data base and retrieval algorithm. The addition of the radiosonde measurements described in that section is in progress.
- For the optimal estimation procedures for land surface variables, there is much to be gained through addressing the "predictability" component of such a system (the "forward model error" component of the E matrix detailed in the Appendix) to establish predictability estimates which dynamically account for the local surface regime and/or the local atmospheric conditions at a retrieval location. This predictability component of an optimal estimation system establishes how well we can determine observational variables when retrieval variables are known. For example, even if the surface energy balance terms and roughness were known perfectly, we still could not predict DT_S and DH perfectly

because of various forecast model errors and model simplifications, errors in ancillary information, etc., and this needs to be reflected in the predictability estimates for the system.

While these errors are situation dependent, there are many atmospheric/surface situations where the predictability estimate can be refined. This will serve to both establish the general quality of retrievals of surface sensible heating and evapotranspiration under various conditions and also, importantly, allow for objectively emphasizing the "best" data source or sources (the data types which possesses the best signal to noise ratio) for a given situation. For example, our previous work has shown that model-predicted values of DT_S are of reduced value for estimating surface sensible heating and evapotranspiration when there is substantial horizontal temperature advection. Similarly, the signal of in-situ measurements of air temperature (DT_{air}) will be more error-prone in advective situations (Bouttier et al., 1993a). The signal of DH, however, is more robust under these circumstances, deteriorating instead when there is large ***differential*** (in the vertical) advection of temperature. It is thus expected that under many situations of temperature advection, that an optimal system would emphasize the DH data in the retrieval process when DT_S data, DT_{air} measurements and DH data are all available.

- The potential retrieval and/or application of other land surface characteristics should be applied to the system. Earlier, a basic example of this was discussed, which was the estimation of an "effective" roughness of the surface using DT_S and DH data, both of which contain information on the surface energy balance and the transfer characteristics of the surface. Our experience suggests that extending beyond this single level of information on the surface character (evaluating some of the sub-components of the effective roughness, such as the vegetation cover fraction, etc.) using exclusively the information sources which have been discussed will be difficult. Independent measurements of such surface characteristics as the fraction of vegetative coverage versus bare soil, etc. would be valuable in further refining the estimates of sensible heating and evapotranspiration at a given location through a better general description of the surface. NDVI is known to be closely related to the fraction of green vegetative cover (Hall et al., 1992) and the fraction of total vegetative cover is important in relating aerodynamic temperature to the radiative temperature. These relationships should be further investigated and applied in the estimation framework.

III. PUBLICATIONS ACKNOWLEDGING SUPPORT FROM NAGW-1858

A. Refereed

Diak, G. R., R. M. Rabin, M. S. Whipple, C. M. Neale and K. P. Gallo, 1994: Regional evapotranspiration and sensible heat fluxes evaluated from satellite and in-situ data compared to SSM/I measurements over the U.S. Great Plains. In preparation. To be submitted to special issue Rem. Sens. Rev. on land-surface thermal remote sensing. Guest editor for this issue, G. Diak.

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APPENDIX

Example of an Optimal Estimation System applied to the Retrieval of Land-Surface Quantities

A simple optimal estimation or "retrieval" algorithm (Eyre, 1989) is detailed here to illustrate how the techniques are applied to the retrieval of two surface quantities, the surface Bowen ratio (B_0) and the effective surface roughness length (Z_0) from two data sources, the temporal change of surface skin temperature (DT_s) and the temporal change of the PBL height (DH). To begin this example, we introduce the important concept of the "forward" model, which is the physical or statistical model used to estimate the measurement variables from the retrieval variables. In the example to be illustrated, it is the surface/PBL model which predicts DT_s and DH as a function of a prescribed surface B_0 and Z_0.

In matrix form, a one-dimensional (one point on a latitude-longitude plane) linear optimal estimation algorithm can be written (Eyre, 1989).

$$x = x_b + C * K^T * (K * C * K^T + E)^{-1} * (y_m - y_{x(b)}) \qquad (1)$$

where;

- x = a column vector, the elements of which are the quantities to be estimated (B_0, Z_0)
- x_b = a column vector with "background" or prior information values of B_0 and Z_0 from climatology other sources
- C = a matrix of error covariances of the background quantities of B_0 and Z_0 contained in x_b
- K = a matrix of derivatives of the measurement quantities (DT_s, DH) with regard to the estimated quantities (B_0,Z_0) from the forward model (e.g., $\delta(DT_s)/\ \delta B_0$, etc.)
- E = a matrix of errors in measurement quantities (DT_s, DH) which are the sum of measurement errors plus errors in the physical or statistical "forward" models which produce estimates in the measurement variables (DT_s, DH) from the retrieval quantities B_0 and Z_0.
- y_m = a column vector of measurement quantities (DT_s, DH)
- $y_{x(b)}$ = a column vector of estimates of measurement quantities (DT_s, DH) made from the background values of the estimate quantities (B_0, Z_0) and the forward model

Superscript T indicates a matrix transpose and superscript -1 a matrix inverse.

The principles expressed in Eq. 1 are very straightforward. In this equation, the "signal" or forcing is the term $(y_m - y_{x(b)})$, which is the measurement values of the quantities DH and DT_s minus a background value of those same quantities evaluated from the forward model and prior information on B_0 and Z_0 $(y_{x(b)})$. The K matrix contains information on the derivatives of the measurement quantities with respect to the retrieval quantities obtained from the forward model and thus indicate how the retrieval values B_0 and Z_0 should be adjusted given such a signal. For example, in the case of the measurement quantity DH and retrieval quantity B_0, $\delta(DH)/\ \delta(B_0)$ is almost always positive (a higher value of the Bowen ratio and sensible heating produce higher values of the planetary boundary layer height), indicating that a positive value of the signal in DH (measured greater than prior estimate) should result in a positive adjustment to the Bowen ratio in the retrieval process.

The matrix C contains error covariances of the background information on B_0 and Z_0, The diagonal of this matrix is an estimate of the error variances of these background values. In the retrieval process, these act as constraints, holding the retrieved values closer to the background values when the background values are thought to be of high reliability. The E matrix contains error variances in the measurement quantities DH and DT_s which arise both from pure measurement errors plus errors in the forward model which predicts DH and DT_s from B_0 and Z_0. These error variances also act as constraints on the retrieval process, dictating that the signal in a measurement quantity should be greater the errors before there is confidence in making an adjustment to the retrieval quantities. The linear retrieval process outlined in Eq. 1 can become non-linear if some of the derivatives (K) change rapidly as a function of some of the retrieval variables (x). In this case, a modified, iterative version of Eq. 1 replaces the linear form shown above (see Eyre, 1989).

FIGURES

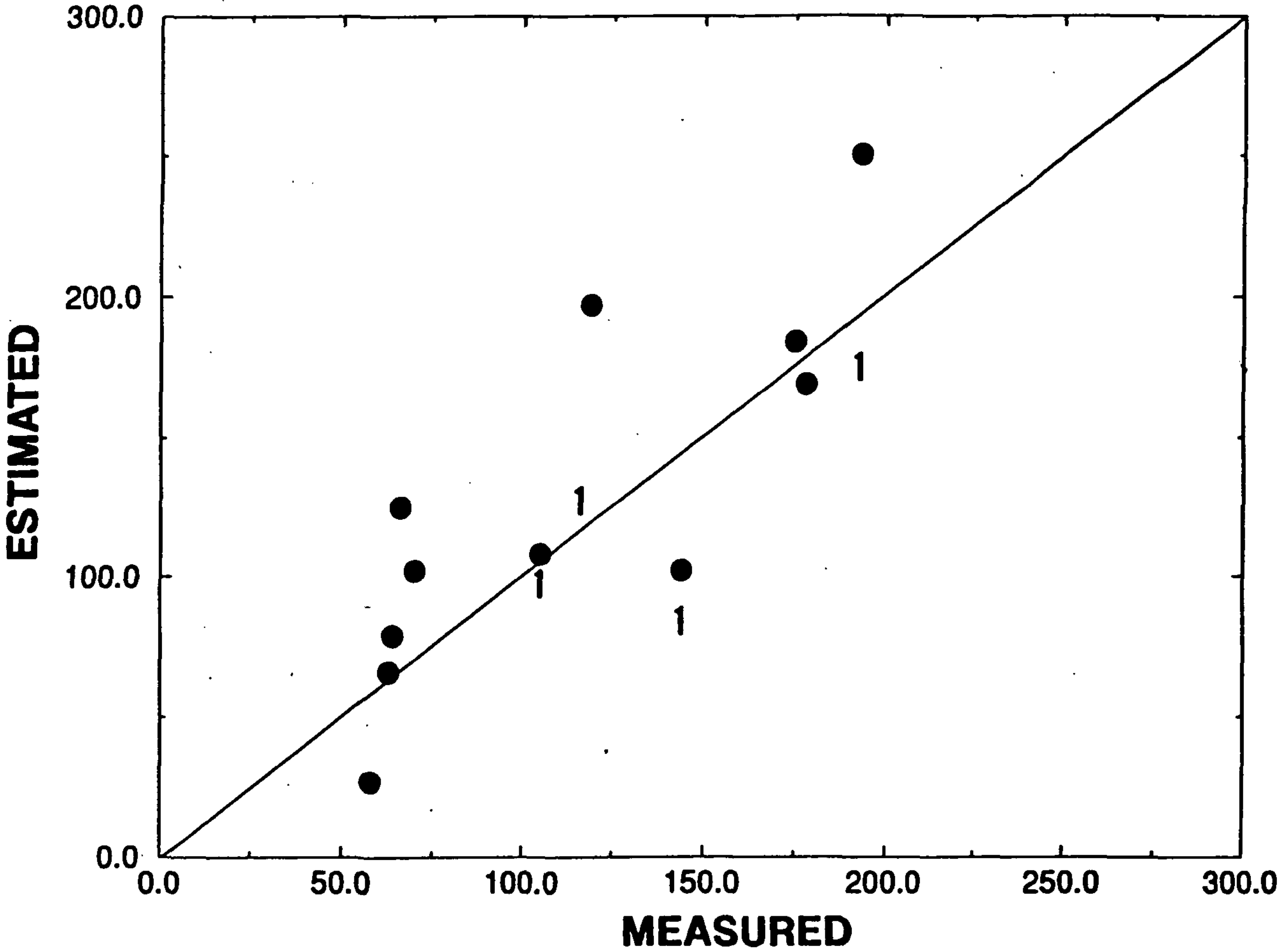
Figure Captions

1 Comparison of estimates 12-hour (daytime) averages of sensible energy flux density ($W\text{-}m^{-2}$) made during the FIFE with an average of in-situ surface flux measurements made at the FIFE site. The solid dots are estimates which have been made using DH data from radiosonde reports at the FIFE site, while the plotted number "1"s are estimates which have been made using DT_S data measured from geostationary satellite on clear days.

2 (A.) Comparison between predictions from the Cupid model and infrared thermometer measurements (MMR) for FIFE day 156 in 1987.

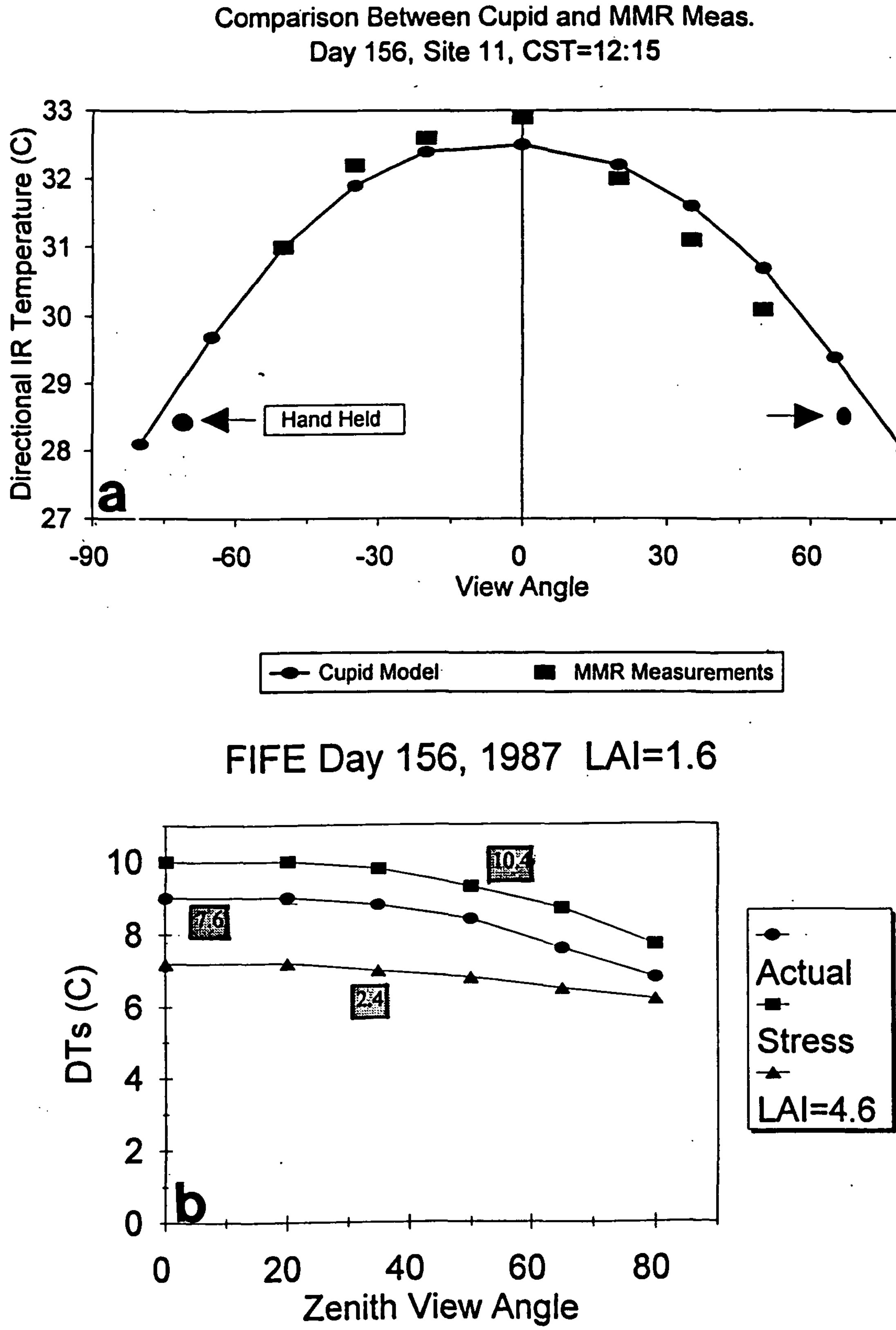
(B) The dependence of DT_S (evaluated between 0900 to 1500 local time) on view angle for three conditions on day 156: 1) the actual conditions measured on that day, 2) a simulated mild soil water deficit (Stress), and 3) a dense canopy with leaf area index (LAI) of 4.6 instead of the actual 1.6.The simulation does not include interaction with the PBL (atmospheric boundary conditions for the Cupid model are prescribed). The numbers on the curves are the predicted 24-hour sensible heat fluxes ($MJ\text{-}m^{-2}$) for each case.

3. Shown are measured values of DT_S (C, Fig. 3a) and DH (m, Fig. 3b) for clear areas of the central United States on 8 June, 1988. Fig. 3c shows the 12-hour average surface Bowen ratio (dimensionless) derived from these data in the prototype optimal estimation system.



SENSIBLE ENERGY FLUX DENSITY (W/m**2)

FIG. 1



Comparison Between Cupid and MMR Meas.
Day 156, Site 11, CST=12:15
Directional IR Temperature (C)
33
32
31
30
29
28
27
Hand Held
a
-90
-60
-30
0
30
60
90
View Angle
Cupid Model
MMR Measurements
FIFE Day 156, 1987 LAI=1.6
10.4
7.6
2.4
DTs (C)
10
8
6
4
2
0
b
0
20
40
60
80
Zenith View Angle
Actual
Stress
LAI=4.6

FIG. 2

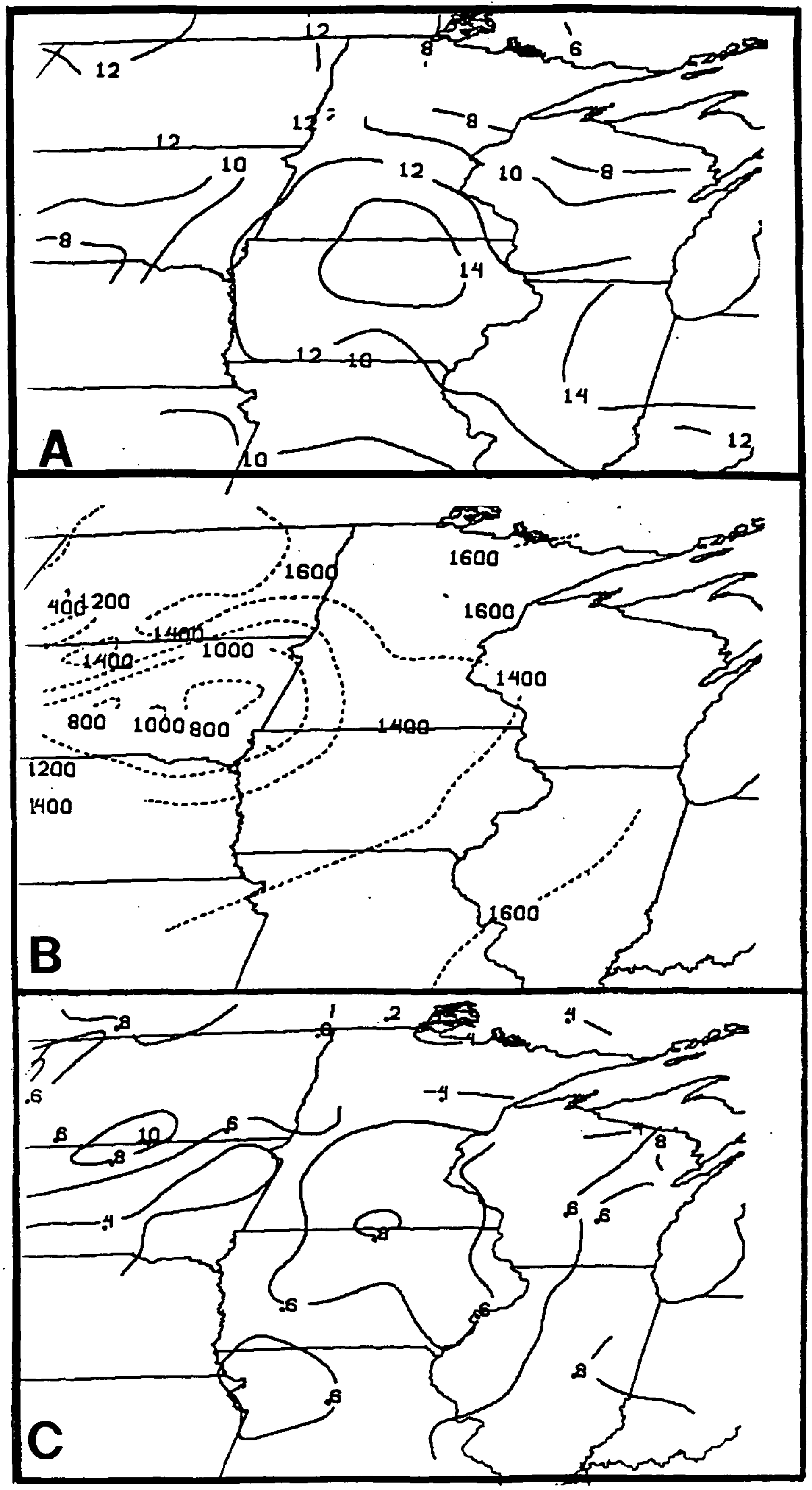


FIG. 3