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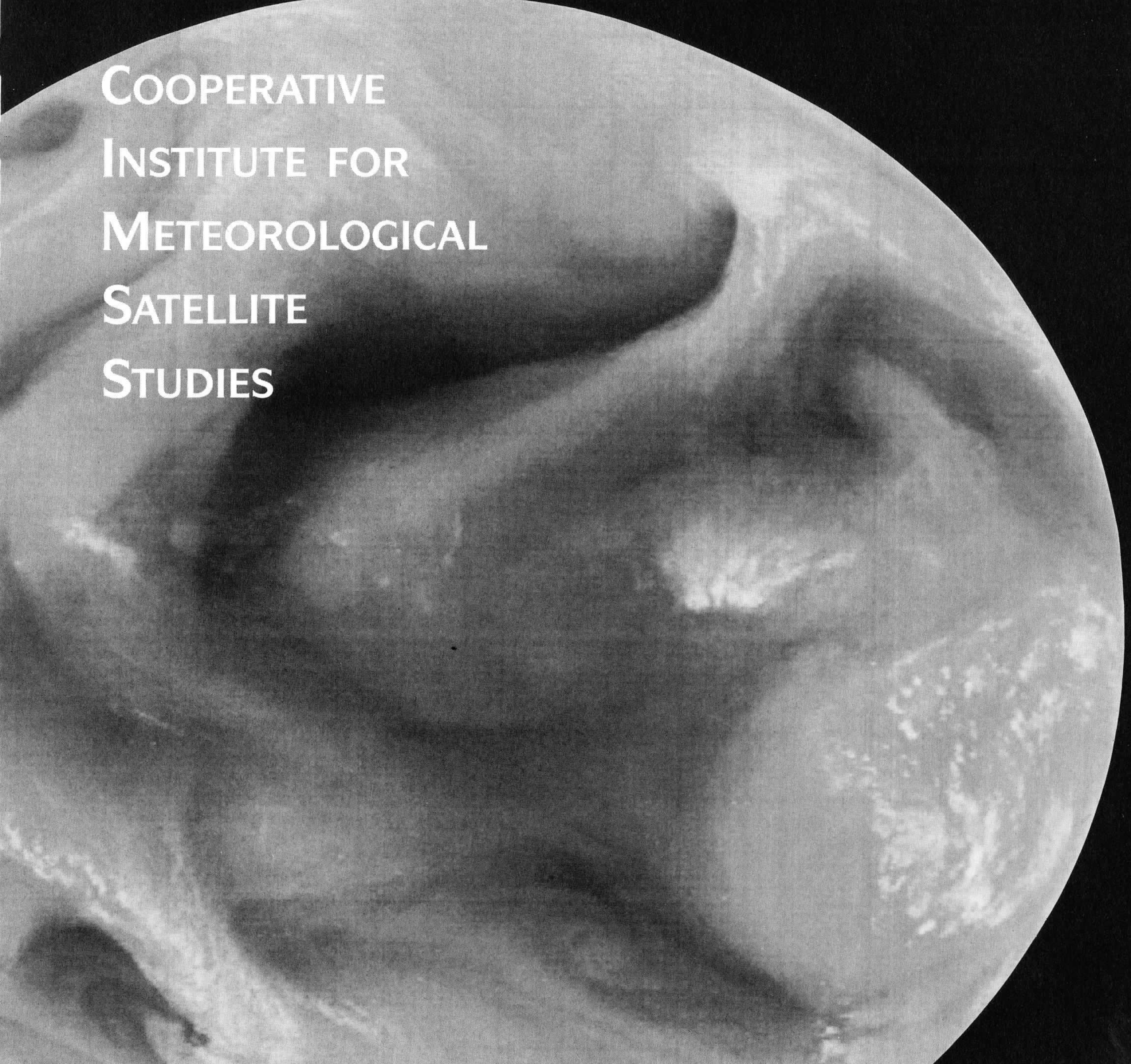
Final Report
NASA Grant NAG5-3493

Evapotranspiration and Sensible Heating Evaluated from Satellite and In Situ Data Using an Optimal Estimation Approach

A REPORT from the

COOPERATIVE
INSTITUTE FOR
METEOROLOGICAL
SATELLITE
STUDIES



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Evapotranspiration and Sensible Heating Evaluated from Satellite and In Situ Data Using an Optimal Estimation Approach

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1. Introduction

A primary objective of this proposed work was *to provide improved monitoring and modeling tools for evaluating of evapotranspiration and sensible heating at the land surface.* These quantities are important *upper* boundary conditions for hydrologic models, and have equal importance as a *lower* boundary conditions for atmospheric models at all space and time scales. The *monitoring* component of the program relied on the development of a remote sensing method for evaluating land-surface fluxes that has been extensively tested in this work. The remote sensing method (an **I**nversion of an **A**tmosphere-**L**and **EX**change prediction model [ALEX], referred to as ALEXI) employs satellite measurements of the time-change of land-surface temperature, satellite-based vegetation indices (currently AVHRR-NDVI, in the future MODIS) and a modicum of complementary operational surface and atmospheric information to estimate the land-surface fluxes of water and heat (Anderson et al. 1997; Mecikalski et al. 1999). It has been tested against in-situ flux measurements from the FIFE and Monsoon '90 experiments, as well as over a regional scale using flux measurements from the SGP '97 program, and is currently undergoing further tests using data from the Little Washita Watershed during SGP '97 and the Washita 1992 Experiments. A simplified version of this scheme the "Double Time Difference" methodology (Norman et al. 2000), has also been developed, yields good flux estimates, and is geared towards those users who need simpler procedures and a more modest database than that required for ALEXI flux evaluations

In the *modeling* component of the proposed research, a parameterization for the photosynthetic process based on principles of Light-Use Efficiency (LUE, defined as the ratio of net assimilation to absorbed photosynthetically-active radiation [APAR]; Monteith 1977; Norman and Arkebauer 1991) was developed and tested. LUE is a simple way to characterize plant productivity and has been measured for many different plant species. LUE has been found to be a fairly stable quantity within various vegetation classes when the vegetation is unstressed, but it varies between major vegetation types. The advantages of such an approach are that it is based on a *canopy-level* quantity, thus scaling effects are incorporated into the measurement of canopy LUE, and that it requires relatively few parameter specifications and ground-based measurements as input. This makes it well suited for large-scale remote-sensing-driven applications.

For example, in our soil-canopy prediction scheme (ALEX), LUE replaces 15 vegetation-dependent parameters required by the Simple Biosphere Model, version 2 (SiB2) and allows an analytical solution for canopy resistance, thereby significantly improving computational efficiency and reducing input data requirements without sacrificing generality. It has been incorporated into, and is undergoing tests within the UW Cooperative Institute for Meteorological Satellite Studies (CIMSS) mesoscale modeling system (currently run in real time at resolutions between 80 and 15 km for real-time agricultural applications, see Diak et al. 1998).

2. ALEXI - A Scheme Evaluating Land-Surface Fluxes

An **A**tmospheric-**L**and **EX**change **I**nverse model (ALEXI) has been developed to diagnose surface fluxes, given thermal infrared remote sensing inputs, remotely-sensed vegetation data, plus a modicum of in-situ data and land-surface characteristics. This inversion (originally called the Two-Source Time-Integrated Model, TSTIM, Anderson et al. 1997), uses the time rate of change in surface brightness temperature as an indicator of the land-surface energy balance. The rise morning radiometric temperature, as measured by ground-based infrared thermometry or from a satellite platform (e.g., Geostationary Operation Environmental Satellites, GOES), guides the partitioning of surface fluxes into sensible and latent heating components.

Given an estimate of vegetation cover, derived from remote sensing spectral measurements (AVHRR-NDVI; Sellers et al. 1996b; Carlson and Ripley 1997), the surface brightness temperature measurements are decomposed into their soil and canopy contributions, allowing further partitioning of fluxes between the soil and canopy components of the scene. Energy closure for the system is accomplished using a atmospheric boundary layer (ABL) height-energy relationship with an ABL height that is diagnosed in ALEXI. This ABL height is estimated using an air temperature (typically at 50-m height) computed by ALEXI from the component soil and canopy temperatures and a simple model of the ABL (McNaughton and Spriggs 1986).

With a few important modifications, the equation set used in ALEXI is nearly identical to that comprising the *predictive* version of the land-surface scheme (ALEX, Anderson et al. 1999). ALEX is currently operational in the CIMSS mesoscale model and is the forecasting basis for a number of real-time agricultural products (Diak et al. 1998; Anderson et al. 1999). Some of the modifications are designed to reduce the number of required model input parameters and/or simplify time-dependent elements of the predictive model version (the soil heat flux and ABL components) for the purpose of computational efficiency in the inverse mode (avoiding costly integration of time-dependent equations). An energy closure using the characteristics of the ABL has proven advantageous in prior remote-sensing work (Diak 1990; Diak and Whipple 1993; Diak and Whipple 1995). Many problems encountered in earlier thermal IR flux estimation methods are mitigated in ALEXI. A primary strength of ALEXI for remote-sensing applications is that it requires a modicum of ground-based input; *in particular, the need for ancillary measurements of local air temperature is eliminated with the use of an energy closure based in the characteristics of the ABL.* The errors associated with evaluating fluxes using a surface-air temperature gradient evaluated over a short vertical distance (typically 2m, as is characteristic of many other schemes) are reduced.

Furthermore, because the model uses the *time difference* in brightness temperature rather than absolute temperature measures, it is relatively insensitive to time-independent biases inherent in infrared satellite observations of the Earth's surface. This reduces the need for high accuracy in sensor calibration, in the estimation of atmospheric corrections to surface brightness temperature to obtain the surface radiometric temperature and also in the specification of surface emissivity. Sensitivity tests presented by Anderson et al. (1997) show that a 6° C additive bias in brightness temperature affects sensible heat estimates by only ~ 6%. The effect of sensor view angle on apparent surface temperature is explicitly built into ALEXI, thus radiometric temperatures obtained at any reasonable angle of view can be used. Such angular variations of measured brightness temperatures with view angle can be large (> 5° C) and have a deleterious effect on flux estimates made using surface brightness temperatures (Hall et al. 1992). Explicitly accounting for this angle dependence increases the feasibility of using thermal IR observations from geosynchronous satellites and other remote instruments with off-nadir sensor viewing angles.

ALEXI has been tested with data collected during three field experiments and has been found to perform well in a variety of vegetative regimes. Comparisons between modeled and measured fluxes from the FIFE (Sellers et al. 1988) and Monsoon '90 field experiments yield differences comparable to those achieved by other flux models and to typical errors in the flux measurements themselves. Flux evaluations over a regional scale at 10-km resolution, using GOES thermal IR data, have been detailed in Mecikalski et al (1999). The results of this Mecikalski et al. (1999) work were regional-scale evaluations of land surface latent heating for several days in summer 1997 during the joint USDA/NASA Southern Great Plains Experiment (SGP '97). Comparisons between flux estimates from ALEXI and in-situ measurements made at several sites in the SGP '97 region, showed good agreement.

3. The Development of Statistical Interpolation SI-ALEXI

3.1. Statistical Interpolation (SI) Methods and SI-ALEXI

The general objective of SI methods is to achieve the best statistical estimate of a quantity (for example, air temperature), given the information inherent in its measurement, and also the quality of any prior (background or "guess") information that is available. For example, when working with air temperature, this prior information could come from a numerical forecast model or even from the climatology of a region. SI techniques are widely used in numerical meteorology in two- and three-dimensional applications to produce numerical analyses for the initialization of forecast models. *An important attribute of SI is that as new sources of information become available, they can be easily incorporated into an existing model without changing the modeling framework.*

The form of SI adapted to the ALEXI model has its foundation in methods used to derive vertical profiles of atmospheric temperature and moisture using atmospheric radiance measurements made by the atmospheric sounding instruments on meteorological satellites (so-called atmospheric "retrieval" methods). Such techniques have been outlined by Eyre (1990) and in a somewhat different and more advanced framework by Ma et al. (1999). The method to be outlined here has already been used by Diak et al. (1995) and Rabin et al. (2000) to estimate surface fluxes using a land-surface model with different (and more primitive) characteristics than ALEXI.

The prototype SI version of ALEXI is the multi-dimensional (multiple retrieved quantities, multiple observational types) equivalent to the usual one-dimensional SI equation. An extra layer of complexity is added, however, because the *quantities that we measure are not the same as those we wish to estimate or "retrieve."* For example, in the most basic version of ALEXI, we measure brightness temperatures and use these to retrieve the land-surface energy balance components. This adds the requirement of a transform or mapping function to go between observational space (e.g., brightness temperatures) and retrieval space (energy-balance-related variables), a so-called "forward" model. In SI-ALEXI, the forward model is a simplified version of the *predictive* form of ALEXI (ALEX, Anderson et al. 1999).

The important characteristics of SI-ALEXI (and SI methods in general) are:

- The use of multiple observational data types (e.g., brightness temperatures, air temperatures, microwave soil moisture information) for an improved estimate of retrieved quantities (surface energy balance components), provided a physical or statistical "forward" model exists to make the transform between each observational variable and retrieval variables;
- Weighting each observational data type (and its respective "forward" model) by inherent errors and relative information content;
- Using prior or "guess" information (model output, land-surface characteristics, vegetation amounts, etc.) and the reliability of this information relative to measurements in the retrieval procedure.

The principles of the SI-ALEXI method are straightforward. The 'signals' or 'forcings' are the measured values of quantities such as radiometric temperatures, minus estimates of the same quantities produced using guess surface parameters as input to the forward model. Partial derivatives (relative sensitivities) of the measurement quantities with respect to retrieval quantities determine to what relative degree each retrieval variable is adjusted from its guess value given these signals. For example, in ALEXI a higher measurement value of surface radiometric temperature than is calculated from the guess state would most often indicate that the actual sensible heating total is higher than expected, requiring adjustments to the retrieval quantities in ALEXI that determine sensible heating.

Error covariances of the guess information act as constraints, holding the variables retrieved in ALEXI closer to the guess values when confidence in the guess is high, aiding in quality control of ALEXI results. Total errors of the ALEXI measurement quantities are the sum of simple errors of measurement (for example, calibration errors in a satellite radiometer), plus errors in the forward model (ALEX) used to map retrieval quantities into observational space. These errors also act as constraints on the retrieval process, dictating that the signal in measurement quantities should be greater than errors (signal should be greater than noise) before significant adjustments are made to the guess state.

3.2. Current Capabilities

To date, the prototype SI-ALEXI version uses measurements of the time differences of both brightness and air temperatures (these air temperatures are from the synoptic network) to estimate the sensible and latent heat fluxes at the land surface at a 10-km scale. Previous studies have used absolute (as opposed to time-difference) shelter-level air temperature (and humidity) measurements to estimate soil water status (Mahfouf 1991; Bouttier et al. 1993a and 1993b). Our first tests show, however, that air temperature measurements by themselves are inadequate to resolve detailed land-surface features in fluxes and soil water status. Hourly measurements of air temperature and humidity are made at relatively low horizontal resolution (optimistically, 100 km) and are most generally taken at airports, locations which often are at a local minimum in elevation and with less vegetation than the surrounding regions. We might then expect that the surface energy balance evaluated using shelter-level information alone would show a high bias in sensible heat and be relatively smooth due to the wide horizontal spacing of hourly observations. In several experiments when time differences of air temperatures evaluated from the synoptic network were objectively analyzed and used by themselves in SI-ALEXI to estimate the surface energy balance (e.g., no satellite brightness temperature input), this was in fact the case. Therefore, we have taken the approach of using such air temperature analyses as "guess" information in SI-ALEXI and allowing the infrared brightness temperatures and vegetation information to add small-scale features to the distribution of land-surface fluxes; this includes the capabilities of removing biases in the air-temperature-generated flux data set. Examples using the prototype SI-ALEXI demonstrated that the use of air temperatures alone produced sensible heating results that are of larger magnitude (in most regions) and much smoother than those obtained when brightness temperatures are also incorporated.

Looking towards potential future capabilities of passive microwave information (most specifically, L-band [1.4 GHz]) for estimating surface-layer soil water and the land-surface energy balance, a "forward" microwave model (estimating microwave brightness temperatures from soil moisture, vegetation amounts and soil and meteorological conditions) has already been written and tested (Liou et al. 1997), as has the corresponding inverse model (the inversion to estimate soil moisture from microwave brightness temperatures). ALEXI in its current form (using infrared brightness temperatures and shelter-level air temperature measurements) produces an estimate of the soil evaporation flux that can be inverted to provide a value of surface-layer soil water (Kustas 1998). We anticipate that the microwave soil moisture information will be complementary to infrared brightness temperatures in that vegetation canopies up to moderate density are semi-transparent in the microwave. Also, microwave data evaluates soil moisture, while IR data infers the surface energy budget, information that may be complementary if used in the correct manner.

Thus, microwave data assimilated into SI-ALEXI can provide soil water and soil evaporation information under conditions that are limiting using infrared data alone. A verification database for microwave studies was gathered during the joint USDA-NASA Southern Great Plains program of 1997 in which all Co-Investigators were participants. This possibility will be investigated in future NASA-funded work.

4. The "Double Time Difference" (DTD) Simplified Approach to Surface Flux Evaluation

We used the equations of Anderson et al. (1997) to form a double difference of radiometric and air temperatures so that an estimate of sensible heat flux can be obtained from measurements of surface radiometric temperature, air temperature, wind speed, vegetation height, cover, type and approximate leaf size. The derivation of this methodology is discussed in Norman et al. (2000). Its advantages are a more modest database than is used in ALEXI and rapid evaluation of areal fluxes. A drawback is that the flux evaluations are probably not as accurate as from the full ALEXI model.

To illustrate the application of the DTD approach to a large region, GOES and AVHRR (Advanced Very-High-Resolution Radiometer) satellite observations were combined with surface synoptic data on 12 June 1995, a day chosen by Mecikalski et al. (1999). The AVHRR data was used to calculate a NDVI (Normalized Difference Vegetation Index) and estimate a vegetative-cover fraction by the method of Carlson et al. (1995). GOES thermal images were obtained 1.5 and 5.5 hours after sunrise and combined with near-surface air temperature and wind speed from the surface weather station nearest the pixel of interest. The map of latent heat looks remarkably like the map produced by the more complex ALEXI technique (Mecikalski et al. 1999).

While there were differences between ALEXI and the DTD method, general patterns are very similar. The DTD method has the advantage in requiring only several minutes of computer time to generate regional output and a database and solution procedure much simpler than ALEXI for users with reduced resources. Another possible application is to use a pass of this DTD technique to provide "guess" energy budget values for ALEXI to facilitate convergence and reduce ALEXI's computer requirements.

5. Light-Use-Efficiency (LUE) Investigations and the Predictive (ALEX) Model

5.1. Background

With recent advances in computing power and data access, transfer, and storage capabilities, it is becoming increasingly feasible to model surface fluxes over large regions in a real-time mode. The Internet now provides near real-time access to a variety of satellite images and spatially distributed surface weather observations that supply valuable constraints to regional-scale flux evaluations. Digital maps of land-surface characteristics crucial to flux prediction, such as vegetation cover, surface albedo, land use, topography, and soil type are available over the network, and maps of time-composite vegetation indices are updated for the conterminous United States on a biweekly basis (see http://edcwww.cr.usgs.gov). As new information sources come on line, the capacity for data sharing and data assimilation in surface modeling efforts will continue to increase.

The **A**tmosphere-**L**and **EX**change (ALEX) model introduced here was developed to take advantage of these newly enhanced data streams, and to put these data into practical use in the meteorological and agronomic sectors. The ALEX model was designed to be conceptually simple and versatile, yet robust over a variety of surface conditions so that it can be easily adapted to various specific applications. Most importantly, ALEX is computationally efficient, a critical attribute for large-scale or real-time applications.

While drawing features from existing land-surface parameterizations, such as the Cupid model (Norman, 1979; Norman and Campbell 1983; Norman and Polley 1989) and the Simple Biophysical Model (SiB2; Sellers et al. 1996), ALEX is unique in that it incorporates an analytical submodel for estimating bulk stomatal resistance to gas exchange, used in specifying canopy transpiration and carbon assimilation fluxes. The simplicity of the full model equation set enables model inversion, so that ALEX can be run in a prognostic (forward) mode with upper boundary conditions set by surface measurements, or in a diagnostic (inverse, ALEXI, described above) mode, using inputs derived from remote sensing. The “reversible” nature of ALEX provides new opportunities for integrating satellite and conventional synoptic data in modeling surface phenomena.

In this report we describe the basic framework of the ALEX model that was developed. The analytical canopy resistance submodel of ALEX is described in greater detail by Anderson et al. (1999). Here we focus on modeling system fluxes of sensible, latent and soil heating. Model flux estimates were compared with micrometeorological measurements made in a tall-grass prairie site in Kansas and in a pasture/rangeland site in the Southern Great Plains of Oklahoma, and also with estimates from a more detailed soil-plant-atmosphere model. To demonstrate the utility of the ALEX model, we summarize current projects where ALEX is being applied operationally in the fields of agriculture, meteorology and hydrology.

5.2. The ALEX Model

ALEX, in its most basic form, is a two-source (soil and vegetation) model of heat, water and carbon exchange between a vegetated surface and the atmosphere. Details on ALEX are given in Anderson et al. (1999). Gradients in the corresponding state variables of temperature (T), vapor pressure (e), and CO_2 concentration (C) are modeled; these gradients drive fluxes regulated by the resistance (R) to mass and energy transport between pairs of nodes. The series-parallel resistance networks used in ALEX to define fluxes of sensible and latent heating allow both the soil and vegetation components of the system to modify the in-canopy air microclimate, simulating feedback mechanisms observed in nature. In ALEX the pathways for carbon transport soil and plant fluxes have been decoupled for computational simplicity, a reasonable approximation in most circumstances.

Upper boundary conditions are specified at some measurement height above the canopy. In this study, the canopy vegetation has been constrained to a single layer, although an understory or surface residue layer can be accommodated with minor modification. Temperature and moisture conditions at the soil surface form the interface between the above- and belowground model components. Belowground processes of infiltration and heat transfer are simulated with a one-dimensional, multi-layer numerical model that allows for discontinuities in soil thermal and hydraulic properties. The soil and canopy regimes interact in the plant rooting zone: the soil water profile is modified by root uptake, while transpiration and photosynthesis can be limited by soil water availability. All model input parameters and variables that must be specified at each modeling site are listed in Anderson et al (1999). Prognostic flux and state variables computed by the model are also tabulated in that reference.

Stomatal regulation of gas exchange in vegetation causes transpiration and photosynthetic carbon fluxes to be tightly coupled (Collatz et al. 1991). We have developed a simple, analytical model for stomatal resistance on the canopy scale (canopy resistance) that requires few parameters so that it is well suited to regional applications. This model is parameterized in terms of a quantity referred to as the canopy light-use efficiency (LUE), defined as the total carbon fixed into dry mass divided by the absorbed photosynthetically active radiation (APAR). Flux estimates from this model agree well with measurements acquired in a variety of vegetative and climatological regimes, and with estimates from more detailed and mechanistic photosynthetic models (Anderson et al. 1999). This model provides the transpiration estimates to both ALEXI and ALEX.

6. ALEX Model Validation

Anderson et al. (1999) evaluated the performance of the canopy resistance submodel against predictions from the more detailed physiological models of Collatz et al. (1991; 1992) and against measurements of carbon fluxes made during the First ISLSCP (International Satellite Land Surface Climatology Project) Field Experiment of 1987 (FIFE; Sellers et al., 1992) in 1987 and the Southern Great Plains Experiment of 1997 (SGP '97). In the cases studied, the analytical submodel in ALEX reproduced baseline fluxes well; it was also able to reasonably capture the effects on photosynthesis of a dry-down period that occurred before the 3rd Intensive Field Campaign (IFC) of FIFE '87.

Here we will concentrate on evaluating the reliability with which the ALEX model predicts surface fluxes of energy and water exchange. Model estimates of net radiation, sensible, latent and soil heating will be compared with flux measurements acquired during the FIFE '87 and SGP '97 field experiments. Where available, measurements of soil and canopy properties made in situ at the experiment site have been used; other parameters have been assigned values representative of the site soil and vegetation types. While the FIFE and SGP sites are similar in many respects, these two experiments reflect the response of different plant species to different climatological forcings; together they provide a useful test of the validity of the simple modeling approach presented here.

We also compare the results from the ALEX model with fluxes predicted, using identical inputs, by a more comprehensive, multi-layer soil-plant-atmosphere model (Cupid). Because soil and canopy fluxes are not commonly measured in isolation in the field, numerical experiments with detailed models provide a means for testing the partitioning of radiation, heat, and water fluxes generated by simpler models.

6.1. Comparison Datasets

6.1.a. Field Measurements - FIFE '87:

The FIFE experiment was conducted near the Konza Prairie Research Natural Area outside of Manhattan, Kansas. The flux measurements examined here were collected at FIFE Site 11 (Grid ID 4439); this site and the experimental procedures employed there are described in detail by Kim and Verma (1990a;1990b). The predominant soil type at the site is a Dwight silty clay loam, and the vegetation primarily warm season C_4 grasses. The site was burned annually, but not grazed in 1986 or 1987.

The flux measurement instrumentation at this site consisted of an eddy correlation system mounted at 2.25 m above ground, a net radiometer, and a soil heat flow transducer. Mean wind speed, air temperature and humidity were monitored at 2.25 m above ground, while PAR was monitored with quantum sensors mounted at 2 m. Carbon fluxes and sensible and latent heating were computed from the eddy covariance data, averaged over 30 minute intervals. Following Twine (1998), closure among daytime eddy correlation fluxes was enforced by modifying observed values of *H* and *LE* such that they summed to the available energy (*RN* - *G*) yet retained the observed Bowen ratio.

The measurements examined here were collected during each of the four 1987 IFCs, spanning the months of May through October and encompassing all of the major phenological stages of the native prairie development, from green-up through senescence. A severe dry-down occurred in July and into early August, significantly depressing carbon and latent heat fluxes at this site (see Kim and Verma, 1990b). LAI, soil moisture, and other time-dependent input data required by the ALEX model were obtained from the FIFE CD-ROM data collection (Strebel et al., 1994). Anderson et al. (1997) outline a methodology for estimating the fraction of green LAI in the prairie canopy based on measurements of live and dead plant dry weight collected periodically throughout the experiment.

6.1.b. Field measurements - SGP '97:

The SGP '97 measurements evaluated here were collected at a flux facility operated by the National Oceanic and Atmospheric Administration (NOAA), located in the Little Washita watershed in southwestern Oklahoma. This site occupies range and pastureland containing predominantly C_3 grass species, and the soil has been classified as a silt loam. The pasture just outside the instrumentation enclosure has been grazed, which may account for the high degree of soil compaction reflected in the measured bulk density of 1.6 $g\text{-}cm^{-3}$.

The instrumentation set deployed at this site was similar to that described by Baldocchi and Meyers (1991). Fluxes were measured with an eddy correlation system consisting of a sonic anemometer and an infrared gas analyzer mounted at 3 m above ground; a net radiometer and soil heat flux plates were also installed at the site. Mean air temperature, humidity, and wind speeds were monitored at 2 m. Fluxes were computed from covariance data averaged over 30 minute intervals. In this experiment, great care was taken in normalizing flux measurements to a common standard. First, net radiation measurements were normalized with respect to a roving radiometer; then energy closure was enforced for eddy covariance measurements using the observed Bowen ratio, as described above and by Twine (1998).

The data presented below were collected between 10 June and 19 July during the SGP '97 campaign. Available soil water appeared adequate to sustain high canopy transpiration and assimilation rates, and grasses were predominantly green during this period. Leaf area index was measured on 16 June at several locations around the flux station and was found to be quite variable due to grazing activity. The effective flux footprint will therefore depend to some extent on wind direction, so our use of an average LAI value will necessarily introduce some error into model flux estimates.

6.1c. Cupid Model simulations:

The Cupid model (Norman 1979; Norman and Campbell 1983) simulates the aboveground vertical transport of heat, water and carbon through a multi-layer vegetation canopy. Cupid couples energy budget analyses for foliar elements classified by inclination angle and depth within the canopy with turbulent transport theory to diagnose state and flux profiles within the canopy. The model includes a rigorous treatment of radiation transfer through the canopy, solving the system of equations describing radiative scattering and transmission in thin layers of leaf area (Norman, 1979). Soil surface and belowground water infiltration and heat conduction are simulated with a multi-layer soil model identical to the one implemented in ALEX. The canopy resistance to transpiration and carbon assimilation fluxes is modeled mechanistically (Norman and Polley, 1989), using an approach similar to that developed by Collatz et al. (1991; 1992).

6.2. Model Comparisons with Measurements from FIFE '87:

The results of statistical comparisons between model energy flux estimates generated with the ALEX model and measurements made during FIFE '87 are tabulated in Table 1. This table reports the root-mean-square-difference (RMSD) between the modeled and measured fluxes and its systematic and unsystematic components (RMSDs and RMSDu, respectively); the mean bias error (MBE) given by $\overline{P}-\overline{O}$, where $\overline{P}$ and $\overline{O}$ are the averages of the modeled and measured fluxes, respectively; and the coefficient of determination for the comparison (R^2). Both measured and modeled fluxes are at half-hour time steps.

In general, the agreement from both models (Cupid and ALEX) is quite good, given the wide range in weather and soil moisture conditions and phenological stages represented in this data set. The analytical equation set implemented in ALEX yields estimates of net radiation above the canopy that are essentially identical to those generated with the numerical radiative transfer scheme in Cupid. Estimates of midday net radiation from both models are biased high by approximately 70 W m^{-2}, perhaps due in part to uncertainties in the leaf and soil emission/absorption/reflection coefficients used in the models. Both models overestimate the observed amplitude of the soil heat flux curve (*G*) by about 25%.

FIFE '87						
Flux	**N**	MBE	RMSD	RMSDu	RMSDs	R^2
RN (W m^{-2})	721	23.5	48.0	26.8	39.9	0.99
LE (W m^{-2})	721	15.99	42.2	38.8	16.7	0.93
H (W m^{-2})	721	2.6	38.3	38.1	4.0	0.84
G (W m^{-2})	721	3.1	40.9	34.6	21.8	0.76
SGP '97						
Flux	N	MBE	RMSD	RMSDu	RMSDs	R^2
RN (W m^{-2})	1911	-6.9	27.8	16.1	22.7	0.99
LE (W m^{-2})	1899	0.1	40.3	40.3	1.9	0.93
H (W m^{-2})	1900	-5.7	42.0	19.7	37.2	0.80
G (W m^{-2})	1911	-9.4	43.2	33.4	27.4	0.81

Table 1: Statistical comparison between flux estimates from the ALEX model and measurements made during the FIFE '87 and SGP '97 field experiments.

For reference, the relative accuracy of the ALEX flux estimates can be compared to the expected errors in the measurements. In an intercomparison of flux measurement systems employed during FIFE '87, Nie et al. (1992) found 10% variations between measurements of net radiation, and 20% variations among daytime latent heat flux measurements. In comparison, errors in net radiation estimation from ALEX are on the order of 20%, or 10% when the systematic component of variation is excluded.

Daytime estimates of latent heat have an accuracy of 20%, comparable to the expected errors amongst the measurement systems themselves. A calibration in sand of 14 different commercially-available soil heat flux plates conducted by Twine (1998) revealed that the plates consistently underestimated the known flux under both saturated and dry conditions. Translated to thermal conductivities typical of the FIFE site, the expected bias is on the order of 5%. This may explain in part the disagreement between the modeled and measured diurnal soil flux amplitudes.

To assess the skill with which ALEX partitions system fluxes between the soil and canopy regimes, flux component estimates from the ALEX model were compared with Cupid model predictions. The agreement in the partitioning of net radiation between the soil and canopy reflects the relative accuracy of the analytical canopy extinction model implemented in ALEX in comparison with the rigorous numerical treatment in Cupid. The simplified representation of in-canopy extinction utilized in the analytical model somewhat overestimates the net radiation transmitted to the soil surface, but in general the agreement in partitioning is good. Estimates of canopy transpiration agree well with the exception of day 211 during the 3rd IFC, at the peak of the 1987 dry down period. On this day, the soil moisture constraints built into the Cupid model induced a more drastic reduction in stomatal conductance than those in ALEX. Examination of system latent heat (*LE*) estimates showed that the ALEX model better reproduces observed water fluxes on this day.

Overall, the good comparison between results from the Cupid and ALEX models validates the simplified approach taken in ALEX.

6.3. Model Comparisons with Measurements from SGP '97:

Model estimates of the four system energy budget components from ALEX were compared with half hourly flux measurements made during SGP '97. The model accuracy is 30-45 Wm^{-2} for each component. As with the FIFE '87 data set, midday values of net radiation are somewhat overestimated by ALEX, and the amplitude of the soil heat flux curve has been exaggerated. The error in *G* has been absorbed predominantly into the sensible heating estimates, leaving the latent heat estimates relatively unbiased.

Twine (1998) has performed a careful intercomparison between flux measurement devices used during SGP '97. After normalization of net radiation measurements to the roving radiometer standard and enforcement of energy closure for eddy covariance flux measurements, variations between instruments of 5%, 10% and 20% were found for net radiation (day+night) and daytime latent and sensible heat, respectively. In comparison, the average errors in flux estimates from the ALEX model are 15% (10%), 20% (20%), and 55% (25%) for *RN*, *LE*, and *H*, respectively, based on the total (unsystematic) components of the RMSD. Roughly half the RMSD (excluding biases) for each flux can be explained by observational error.

7. ALEX in the CIMSS Mesoscale Model

The ALEX canopy and soil model has been running for almost two years, with good results, in the CIMSS Mesoscale Forecast system. It has provided superior predictions of lower atmospheric temperature and moisture versus an earlier, simpler parameterization. An ongoing object of new NASA-funded work will be to rely on environmental conditions from this model to provide ALEXI with atmospheric and radiation boundary conditions in a much more horizontally-detailed manner than can be achieved by the use of hourly and radiosonde data that are currently used for that purpose.

8. Contributions to the SGP '97 Program

The two project PIs (Norman and Diak) and a graduate student (Twine) were heavily involved in the SGP '97 Program in the summer of 1997. We maintained a "roving" set of measurements of surface turbulent fluxes and net radiation that will be used to quality control and verify flux measurements made at many site locations during the SGP. Each investigator who measured surface fluxes as part of the experiment has sent data to Tracy Twine and a summary of data collected and future needs was presented at the SGP meeting in March 1998. We also archived GOES-8 imager data in the visible and thermal infrared for almost all of the days of the SGP experiment, which are available to SGP investigators on request at no cost.

8. Conclusions

The accuracy of forecast models for weather and climate models depends on the faithfulness with which the land-surface submodels represent surface conditions. A sizable research effort, the Project for Intercomparison of Land Prediction Schemes (PILPS) was designed to evaluate results from various treatments of the land surface in a standardized manner. Excellent land-surface models exist, but they all depend on a cumulative water budget (storage change = precipitation - evapotranspiration - drainage - runoff) to estimate soil water availability and partition the available energy (net radiation minus soil heat flux) into sensible heat and latent heat. This cumulative water budget is very difficult to estimate on regional or continental scales because of large uncertainties in all the components. Thus, small biases in the model will accumulate to large errors over time. For example, a 1 mm/day bias (only 10-20% error in evapotranspiration) for two months will accumulate to an enormous error of about ½ of the maximum available soil water storage. Uncertainties in the horizontal distribution of precipitation, especially at 10 km, will cause further uncertainties in the soil water stored and may eventually cause large errors in the cumulative water budget. In addition to uncertainties associated with precipitation, the maximum available soil water (which depends on a combination of rooting depth and soil hydraulic properties) is very poorly known on the scale of a model grid square. Therefore, the accumulation of large errors in stored soil moisture is inevitable, even with high quality land-surface models, and the uncertainties are likely to be as variable as precipitation patterns.

The remote sensing scheme described (ALEXI) can be configured to map available soil water without needing any information about soil water storage characteristics or precipitation. ALEXI is based on *diagnosing* the current state of the surface and does not rely on a cumulative soil water budget. Therefore, the ALEXI scheme provides an excellent means to validate the land-surface components of weather and climate models. Future funded work will use the SI version of ALEXI along with an enhanced Pathfinder data to compile a climatology of evapotranspiration over North America at the 10-km grid scale, something that has never been accomplished.

The ability of ALEXI to map soil moisture conditions will improve estimates of carbon and water fluxes over large regions. The intimate connection between carbon dioxide uptake and transpiration water loss through stomatal conductance permits calculation of carbon dioxide flux that is consistent with the transpiration flux from ALEXI. Regional estimates of carbon dioxide uptake through photosynthesis are made routinely with predictive models, but they have never been compared to independent estimates based on remote sensing measurements as we will do. Under well-watered conditions, our estimates of carbon fixation should agree with other models. However, detecting the presence of water stress will be more reliable using ALEXI, so systematic differences between predictive models (which use the error-prone water budget approach) and ALEXI may occur. We believe that our approach will result in more reliable estimates of carbon uptake on the continental scale.

The goal of the new research will be to provide continental-scale, time-continuous estimates of heat, water and carbon dioxide fluxes to be incorporated into a Pathfinder database. Results from this research will be valuable for the following:

- Validating and improving climate and weather forecast models
- Generating a climatology of evaporation and transpiration on a 10-km grid over continental U.S.
- Improving our understanding of carbon cycling between terrestrial surfaces and the atmosphere.

9. Papers, Theses and Presentations Acknowledging NASA Grant NAG5-3493

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