SENSITIVITY OF EVAPOTRANSPIRATION IN A WHEAT FIELD, A FOREST, AND A GRASSLAND TO CHANGES IN CLIMATE AND DIRECT EFFECTS OF CARBON DIOXIDE

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Abstract. Micrometeorological and physiological measurements were used to develop Penman-Monteith models of evapotranspiration for a wheat field in eastern Nebraska, a forest in Tennessee, and a grassland in east-central Kansas. The model fit the measurements well over the periods of observation. Model sensitivities to changes in climatic and physiological parameters were then analyzed. The range of changes considered was established from recent general circulation model output and from review of recent plant physiological research. Finally, climate change scenarios produced by general circulation models for the locations and seasons matching the observed data were applied to the micrometeorological models. Simulation studies show that when all climatic and plant factors are considered, evapotranspiration estimates can differ greatly from those that consider only temperature. Depending on ecosystem and on climate and plant input used, evapotranspiration can differ from the control (no climate or plant change) by about –20 to +40%.

1. Introduction

Growing evidence suggests that the Earth's climate is being modified by anthropogenic and biogenic emissions of atmospheric carbon dioxide (CO_2) and other radiatively active trace gases (CH_4, N_2O, $CFCl_3$, CF_3Cl_2, etc.). By the time that CO_2 and other radiatively active trace gases produce a heating equivalent to that of a doubling of the pre-industrial concentration of CO_2, global temperature should increase by 1.5 to 5.5 °C (Dickinson, 1986). If such is the case, precipitation and evapotranspiration patterns will be altered, and hydrological conditions will change throughout the world.

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Here, we concern ourselves with the question of how evapotranspiration may be affected by climatic change. *Evapotranspiration, ET*, is a compound term used to describe two processes that occur simultaneously – *evaporation* from the soil surface and the canopy when it is wet, and *transpiration*, which is vaporization at the leaf surface of water extracted from the soil by the plant. For evapotranspiration to occur three prerequisites are necessary: a source of water, energy to drive the phase change of the water, and a sink for water, i.e., a moisture deficit in the air above the ground. *ET* can be expressed either in terms of mass of water evaporated, or in energy terms as the latent heat flux, *LE*. In what follows we use *ET* and *LE* interchangeably.

The question of how climatic change may alter *ET* is complicated for a number of reasons. The greenhouse effect is expected to be accompanied not only by changes in temperature, but also in cloudiness – and hence radiation, windiness, and humidity as well, all of which affect the three prerequisites described above. These same climatic changes can alter plant growth leading to larger or smaller plants, to more or less plant cover of the ground, and to deeper or shallower rooting – all of which also affect *ET*. Additionally, the balance between precipitation and *ET* determines how much can be transpired. It is also important to note that one of the major radiatively active trace gases, carbon dioxide, affects plant physiological conditions and, in particular, plant growth and the resistance to the passage of water through the plant into the atmosphere. In any analysis of the possible impacts of climatic change on *ET*, all these factors must be considered.

If either precipitation or evapotranspiration changes, the amount of water stored in the soil, the amount that penetrates to depths below the root zone, and the amount that runs off into rivers and streams must also change, with consequent effects on hydrology. In most prior studies of the hydrological consequences of climatic change *ET* is considered either a function of temperature (e.g., Revelle and Waggoner, 1983; Gleick, 1987), or a function of the carbon dioxide effects on plant resistance (e.g., Idso and Brazel, 1984; Aston, 1984). In a recent analysis of the possible hydrological consequences of climatic change on a Belgian watershed, Bultot et al. (1988) devote considerable analytic attention to climatic effects, but choose not to deal with the direct effects of CO_2 on plant behavior. Here, we attempt to evaluate the impacts of all of the changes described above.

Our approach is as follows: After establishing a credible range of climatic changes and physiological responses to carbon dioxide enrichment (cf., Rosenberg *et al.*, 1989), we select a model that permits consideration of each of the important changes identified. The model is then calibrated by comparing its predictions of *ET* rates to those measured in three ecosystems (control cases) – an agricultural field, a deciduous forest, and a grassland. The climatic and plant factors are considered to be independent. The changes in those factors are applied to the model over the credible range previously determined for each one of them, thus establishing the sensitivity of the dependent variable, *ET*, to single and multiple climatic and plant factors. We then estimate the impact on *ET* of climatic change scenarios based on three atmospheric general circulation models. Finally, we assess the applicability of our resulting model predictions to a wider range of conditions than is represented by our test cases.

2. Methodology

Our purpose is to simulate the effects of a climatic change induced by increased levels of radiatively active trace gases on the latent heat flux considering both the climatic and the physiological impacts of a climatic change. The Penman-Monteith equation (hereafter P-M), which combines an energy balance approach with a catenary treatment of water vapor diffusion through the plant and into the atmosphere (van den Honert, 1948), is chosen as the basis of our model. The variables found in the P-M equation are temperature, net radiation, soil heat flux, humidity, and wind speed, as well as a set of parameters representing the structure and the physiology of the plant.

In addition to incorporating micrometeorological and physiological parameters, the P-M approach has other advantages. The properties of the P-M equation have been well studied (e.g., Saxton, 1975; Beven, 1979). The P-M method has been successfully used to estimate evapotranspiration from crops and forests (Rosenberg *et al.* 1983). Finally, the P-M equation has been found suitable for simulation studies (e.g., Stewart, 1984). The P-M approach is best used at the local level, and with time scales of the order of a day.

A standard formulation of the P-M equation (Monteith, 1965) for the latent heat flux, *LE*, expressed here in W m^{-2}, is the following:

$$LE = \frac{s(R_n + S) + \rho_a C_p (e_s - e)/r_a}{s + \gamma\left(\frac{r_a + r_c}{r_a}\right)} \tag{1}$$

where L is the latent heat of vaporization, in J kg^{-1}; E is the flux of evaporated water, in kg m^{-2} s^{-1}; R_n is the net radiation, in W m^{-2}; S is the soil heat flux, in W m^{-2}; ρ_a is the density of dry air, in kg m^{-3}; r_a is the aerodynamic resistance, in s m^{-1}; r_c is the canopy (or bulk physiological) resistance, in s m^{-1}; C_p is the specific heat of dry air at constant pressure, in J kg^{-1} K^{-1}; e_s is the saturation partial pressure of water vapor (hereafter the "saturation vapor pressure") at leaf temperature – but here we take air temperature as a proxy for leaf temperature, and e is the actual vapor pressure in the air above the canopy, both in Pa; and, s and γ are the derivative of the saturation vapor pressure with respect to temperature and the psychrometric constant, respectively, both in Pa K^{-1}. (A comprehensive list of the variables, their definition, and their units may be found in Appendix 2.)

Air temperature, T_a, is an adequate proxy for leaf temperature, T_l, in the case of the forest which is well coupled (aerodynamically) with the air above the canopy. On advective days, we can expect that $T_a > T_l$, and on non-advective days, that $T_a < T_l$, in the herbaceous species case. ($|T_a - T_l|$ is generally of the order of a few degrees C.) In our datasets, we encounter few hours of advection. Direct measurements of T_l are lacking, but it is reasonable to assume that our analysis may underestimate temperature effects.

The value of the canopy resistance is obtained differently for each ecosystem due to the different types of data available. In the grassland case, we used literature values of stomatal resistances (Jones, 1983) to compute the canopy resistance. The grassland model was tested against measured *LE* and used without adjustment in the sensitivity studies and the simulation.

For the forest model, we used the canopy resistance values obtained by Verma *et al.* (1986) which were calculated by inverting a P-M equation with different parameterizations. This model was tested against measured *LE* and used without adjustment in the sensitivity studies and the simulations.

Our methodological approach was different in the case of the wheat. We first tested the performance of the wheat model against measured *LE* using a single average value of stomatal resistance for the whole observation period. This value was computed from hourly porometer measurements of the stomatal resistance of sunlit leaves for given days. Then, we inverted the P-M equation to obtain more realistic values of the stomatal resistance – in essence fitting the model to the observations. We used this latter value in the sensitivity studies and simulations. We refer to the average stomatal resistance computed from the measured hourly values as $\bar{r}_s$ and to the hourly canopy resistance obtained by inverting the P-M equation as r_c.

As discussed above, the methods of measurement, particularly of plant parameters, differ from one study to the next, making it necessary to parameterize certain inputs to the P-M equation differently for each ecosystem. A detailed description of the model and the parameterizations for each ecosystem may be found in Appendix 1. In summary, the three models were calibrated with local data. And, the wheat and the grassland models were validated using independant data.

3. Origin of the Data

For more than two decades, scientists of the University of Nebraska's Center for Agricultural Meteorology and Climatology (CAMaC) have used aerodynamic and Bowen ratio energy balance micrometeorological methods to measure *ET* in agricultural fields. These methods were calibrated against precision weighing lysimeters (Rosenberg and Brown, 1970). In the past few years, instrumental systems have been perfected by this group for eddy correlation measurements of energy and mass balance in agricultural crops. These systems have recently been used to study the energy and mass balance in a deciduous forest and a grassland,

TABLE I: Location, soil, vegetation, and measurements at the experimental sites

	Winter wheat	Forest	Tall grass prairie
Location	Mead, NE	Oak Ridge, TN	Manhattan, KS
Latitude	40°51′ N	35°57′30″ N	39°03′ N
Longitude	96°45′ W	84°17′15″ W	96°32′ W
Altitude [m above m.s.l.]	359	365	480
Soil	Sharpsburg silty clay loam	n.a. n.a.	Dwight silty clay loam
Dominant species	*Triticum aestivum*	*Quercus* spp. *Carya* spp. *Pinus taeda*	*Andropogon gerardii* *Panicum virgatum* *Sorghatorum nutans*
Height of canopy [m]	from ~0.22 in May to ~0.85 in June	~22.0 Range: 17–26	~0.5
LAI [m^2 m^{-2}]	4.6–0.1	~4.9	~2.0
WBI [m^2 m^{-2}]	n.a.	0.6	n.a.
Observation period	20 May–24 June 1985	2–9 August 1984	29 July–6 August 1986
No. of collection days	10	6	7
ET measurement method	Bowen ratio	eddy correlation	eddy correlation
Climatological deviation	wetter than average	normal	wetter than average

Legend: LAI: Leaf Area Index; WBI: Woody Biomass Index (see text for definition).
References: wheat: Dr. Shashi B. Verma, Center for Agricultural Meteorology and Climatology (CAMaC), University of Nebraska, Lincoln 68583-0728, personal communication, September 1987; forest: Verma *et al.*, 1986; and, grassland: Verma *et al.*, 1987.

as well. The forest and grassland data and a similar set for a wheat field serve as the basis for the analysis presented here of the impacts of climatic change and CO_2 enrichment on evapotranspiration rates. The sites and data sets are summarized in Table I. Climate and plant conditions for days of high and low *LE* flux are shown for each ecosystem in Table II.

3.1. *The Wheat Field*

A four hectare wheat field and large areas of adjacent land at the University of Nebraska's Field Laboratory near Mead, Nebraska (40°51′ N; 96°45′; 359 m above m.s.l.) were planted with winter wheat (*Triticum aestivum L.*) in the fall of 1984. Soil in these fields is Sharpsburg silty clay loam. The canopy increased from a height of about 0.22 m in early May of 1985 to a height of about 0.85 m in late June. Over the same period, the green leaf area index decreased from 4.6 to 0.1.

The data were collected at regular intervals from May 20 to June 24, a period encompassing the end of inflorescence, the anthesis, milk development, and

TABLE II: Midday (1000–1600 hr) climate and plant conditions on days of high and low evapotranspiration in the wheat, grassland and forest ecosystems

Climate and Plant Conditions	Units	Wheat, 1985		Grassland, 1986		Forest, 1984	
		High flux (8 June)	Low flux (June 13)	High flux (June 30)	Low flux (Aug. 5)	High flux (Aug. 6)	Low flux (Aug. 8)
Net radiation	W m^{-2}	565.0	529.0	490.0	342.0	494.3	321.3
Temperature	°C	36.0	24.0	35.5	24.0	28.1	28.5
Vapor pressure	kPa	2.85	1.35	2.05	2.24	2.41	2.69
Wind speed	m s^{-1}	2.66	2.74	2.50	2.50	1.44	0.75
Aerial resistance	s m^{-1}	20.6	72.3	43.2	43.2	23.6	43.7
Canopy resistance	s m^{-1}	55.3	105.8	100.	100.	175.7	88.8
Leaf area index		1.0	0.1	2.0	2.0	4.9	4.9
Measured latent heat flux	W m^{-2}	600.0	330.0	357.0	143.0	305.0	177.0

dough development growth stages. A Bowen ratio-energy balance method (Rosenberg *et al.*, 1983) was used to measure latent heat flux. For this purpose, wind speed, temperature, and vapor pressure were measured at 1.25 and 2.25 m above the ground. Net radiation was also recorded. The measurements were summarized hourly. Leaf area index and plant height were measured daily. On given days, hourly stomatal resistance measurements of sunlit leaves were made in the field using porometers.[1] 1985 was a wetter than normal year in eastern Nebraska.

3.2. *The Forest*

The Oak Ridge forest, a fully-leafed deciduous forest, is situated in eastern Tennessee (35°57′30″ N; 84°17′15″ W; 365 m above m.s.l.). The research site was covered by an uneven-aged stand of oak (*Quercus* spp.) and hickory (*Carya* spp.), with only small inclusions of loblolly pine (*Pinus taeda L.*) and extended for several kilometers in all directions. The average height of the canopy was 22 m, but because of the uneven age structure and mixed-species composition of the stand, crown heights ranged between 17 and 26 m. The leaf area index (LAI) and the woody biomass index (WBI) – the projected area of branches and twigs per unit surface area of ground – were about 4.9 and 0.6, respectively. For further details on the canopy structure see Hutchison *et al.* (1986).

The measurements were made from August 2 to August 9, 1984. Meteorological parameters were measured at 28 m above the ground. The vertical flux of water vapor was measured with eddy correlation instruments at that same height. In addition, the canopy resistance and the canopy heat storage capacity were computed. Climatologically, 1984 was a near-normal year in eastern Tennessee. For a more complete discussion of the measurements and calculations see Verma *et al.* (1986).

3.3. *The Tall Grass Prairie*

The Konza prairie is located near Manhattan in northeastern Kansas (39°03′ N; 96°32′ W; 480 m above m.s.l.). Soil at the site is mainly Dwight silty clay loam. The vegetation was dominated by big bluestem (*Andropogon gerardii*), switchgrass (*Panicum virgatum*), and indiangrass (*Sorghastorum nutans*). The experimental area was burned in early spring to improve the mix of grasses and forbs. The area had been lightly grazed for several years, but was not grazed during the experiment. The average height was 0.5 m and the leaf area index was 2.0.

Data were collected from July 29 to August 6, 1986. The meteorological parameters were measured 2.25 m above the ground. The fluxes of water vapor

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[1] Dr. Shashi B. Verma, *Center for Agricultural Meteorology and Climatology, University of Nebraska, Lincoln 68583-0728, U.S.A.*, personal communication, September 1987.

were measured using the eddy correlation technique. 1986 was a wetter than normal year in northeastern Kansas. A detailed account of the experiment may be found in Verma *et al.* (1988).

4. Model Performance

In this section, we evaluate the performance of the P-M model as adapted for use with the wheat field, forest, and grassland data; we assess the sensitivity of each model to changes in various climatic and plant growth parameters; and we present and discuss the results of a series of climatic change simulations.

4.1. *The Model Results*

Each of the ecosystem adaptations of the model was used to compute latent heat flux hourly values, daily averages, and averages over the whole observation period. The daily averages were calculated using midday values (i.e., 10–16 hr). Indeed, preliminary simulation results show that the largest relative changes in *LE* occurred in the morning, though their absolute magnitude was small. More importantly, morning data and model results are less instructive than midday values because of very large stomatal resistances, small fluxes, and the frequent presence of dew. The total ecosystem average was calculated from the daily averages over all days for which complete data sets were available – i.e., ten days for the wheat, six for the forest, and seven for the tall grass prairie.

4.2. *Model Performance*

As a first step the P-M model as parameterized (see Appendix 1) was used to estimate *ET* for each day of study in each ecosystem. As previously explained, the wheat model was fitted to the observations by inverting the P-M equation and using measured values of *LE* at the simulation stage. To assess the performance of the P-M equation in the wheat case before fitting the model to the observations, the single average stomatal resistance, $\bar{r}_s$, was used for all days.

All three models track the diurnal cycle relatively closely (sample days are shown in Figures 1a–c). Though daily mean wind speeds were used in the grassland model, since hourly data were unavailable, the grassland model does almost as well as the forest model and better than the wheat model on a daily average basis (cf., Figure 2).

Review of the data indicates that the wheat model systematically overestimates evapotranspiration at the beginning of the growing season and underestimates it towards the end. This is probably because the average value of the stomatal resistance, $\bar{r}_s$, is too high at the beginning of the season and too low at the end. The forest model and the grassland model do better and no systematic biases are apparent. The coefficients of correlation between measured and

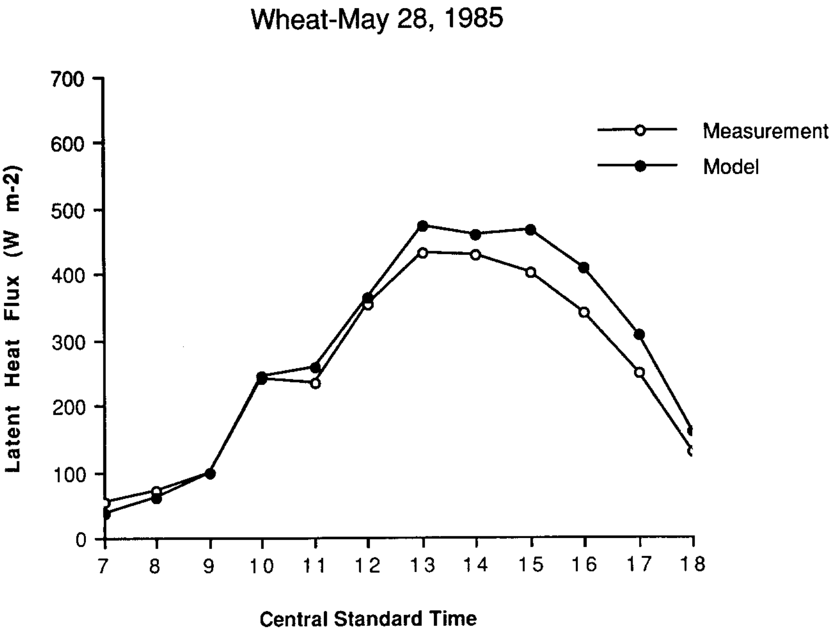

Fig. 1a. Bowen ratio-energy balance measurements of latent heat flux in a wheat field at Mead, NE, and Penman-Monteith estimates (model) using field measurements of climate and plant conditions on May 28, 1985.

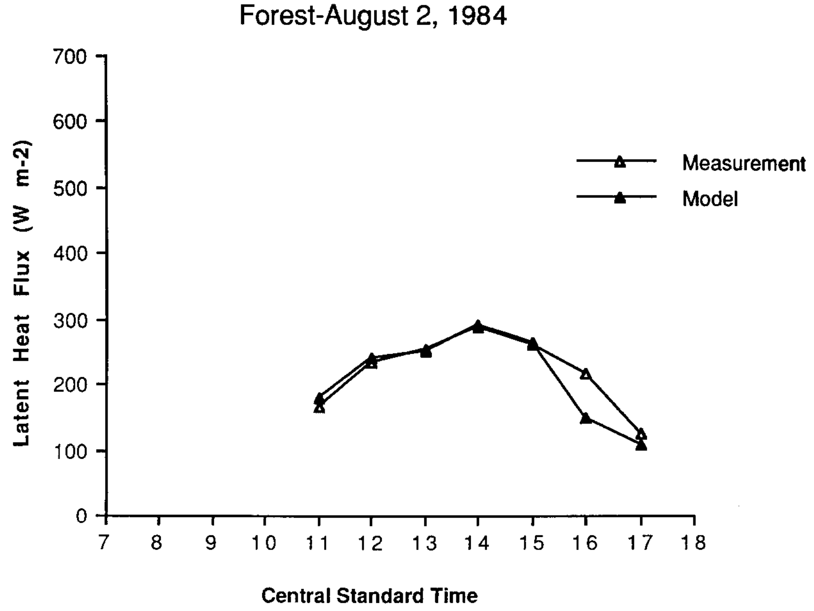

Fig. 1b. Eddy correlation measurements of latent heat flux in a forest at Oak Ridge, TN, and Penman-Monteith estimates (model) using field measurements of climate and plant conditions on August 2, 1984.

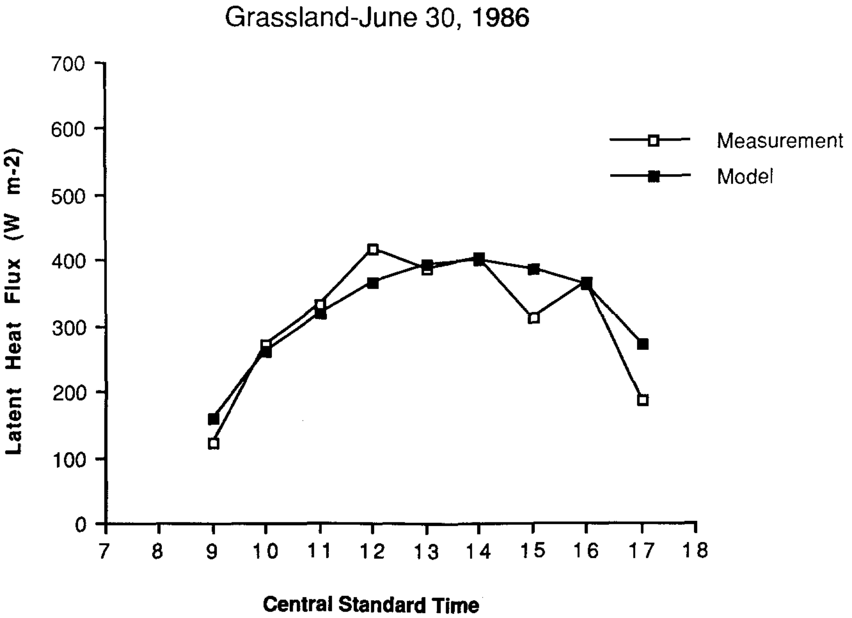

Fig. 1c. Eddy correlation measurements of latent heat flux in a grassland at Konza Prairie, KS, and Penman-Monteith estimates (model) using field measurements of climate and plant conditions on June 30, 1986.

modeled daily values, r^2, are 0.44, 0.76, and 0.67 for the wheat, the forest, and the grassland respectively. Hence, the fit of the model to the observations prior to tuning is variable. Over the observation period, the relative difference between model results and observations prior to tuning is –4% for the wheat field, +4% for the forest, and +7% for the grassland.

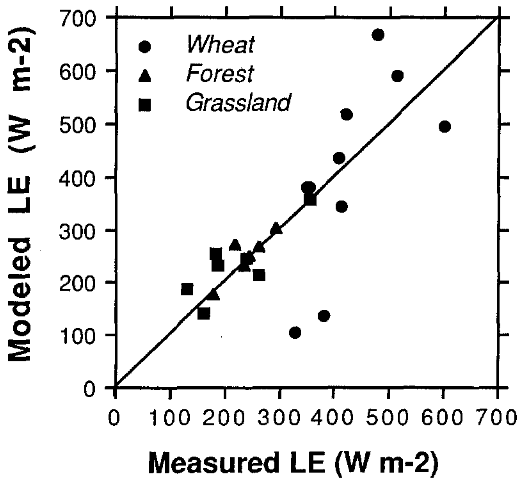

Fig. 2. Measured and Penman-Monteith-modeled latent heat flux in wheat, forest, and grassland.

5. Results of the Simulations

First, we study the sensitivity of evapotranspiration to climatic and plant factors. Then, we simulated and analyzed climatic change scenarios.

5.1. *ET Sensitivity to Climatic and Plant Factors: Results*

A control case was established for each day in each ecosystem by calculating the *LE* flux with the P-M model using actual weather and values of the plant parameters (i.e., temperature, net radiation, air humidity, wind speed, leaf area index, characteristic leaf dimension, and stomatal resistance). Then, each factor was changed, one at a time, so that the sensitivity of *ET* to each individual climatic and plant factor could be tested. Next, the sensitivity of *ET* to changes in pairs and groups of climatic and plant factors was examined.

5.1.1. *Single Factor Changes*

In calculating *ET* sensitivity to climate and plant factors, a wide range of possible changes was considered. In choosing the range of climatic changes, we were guided by Schneider *et al.* (1989). For the physiological changes, we used the values found in Rosenberg *et al.* (1989). The range of temperature change, ΔT, tested (–10K to +10K) is admittedly extreme. Other changes considered were: net radiation, ΔR_n, from –30 to +30%; absolute humidity, Δe, from –20 to +20%; wind speed, Δu, from –20 to +20%; leaf area index, ΔLAI, from –30 to +30%; and stomatal resistance, Δr_s, from –60 to +60%. (Note that we assume that stomatal and canopy resistances are linearly related; a given percentage changes in r_s produces an identical change in r_c, but r_c changes independently from r_s when *LAI* changes.) We make the assumption that the leaves grow larger. Thus, changes in the characteristic dimension, *d*, were taken as proportional to the square root of the ratio of the altered to unaltered leaf area index. An alternative assumption is that the size of the leaves is unchanged, but that there are more of them, so that *d* is constant, but *LAI* still increases. In any event, the sensitivity studies show that, within the range of changes corresponding to the changes in *LAI*, the effect of the characteristic dimension on the aerodynamic resistance is negligible. Hence, the effect of *d* on *LE* is negligible, as well.

To examine single factor changes, graphs were drawn representing the percentage change in *LE* caused by a percentage change in a given parameter, *P* – where *P* represents R_n, r_s, or any other variable (cf., Figures 3–7). The slope of each curve is $\partial(\ln LE)/\partial(\ln P)$. The steeper the slope, i.e., the larger $|\partial(\ln LE)/\partial(\ln P)|$, the greater the sensitivity of *LE* to *P*. Because it uses dimensionless ratios, this approach enables us to compare the relative impacts on *LE* of physical parameters expressed in different units. Temperature is not plotted along with the other variables because it refers to a *state* of the physical system

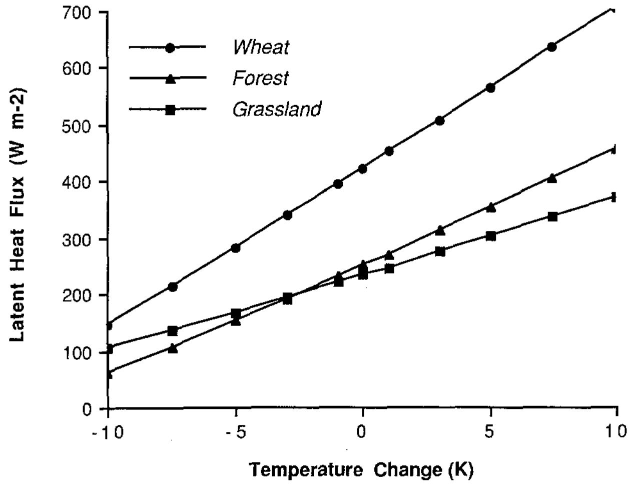

Fig. 3. Sensitivity of latent heat flux estimates by the Penman-Monteith models for wheat, forest, and grassland to departures from present temperature.

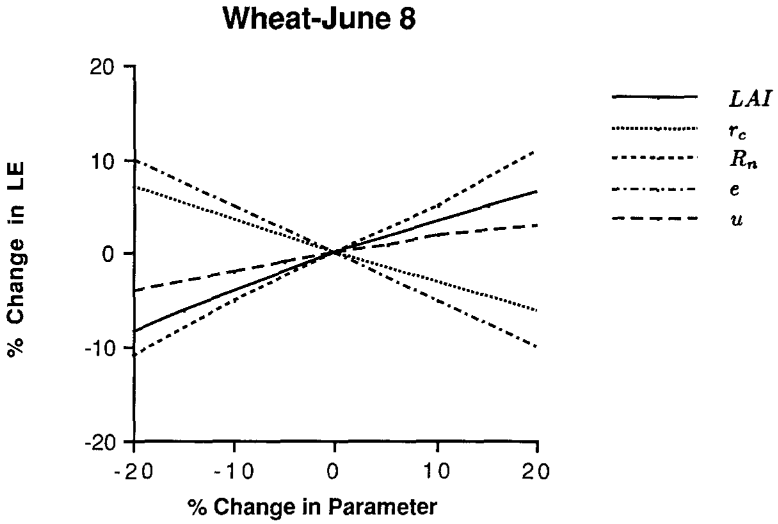

Fig. 4. Sensitivity of latent heat flux in a wheat field to changes in leaf area, stomatal resistance, net radiation, and humidity on June 8, 1985. Unperturbed *LE* flux (0,0) point was 600 W m^{-2}.

rather than a *physical quantity* in that system. Its different meaning implies, in particular, that temperature differences make physical sense whereas quotients, and for that matter percentage changes, do not.

The sensitivity of *LE* varied with the microclimatological conditions. The only generalization that we can make is that the impact of changes in wind speed, *u*, was minor in most of the simulations. For that reason, changes in wind speed are not considered in the tables that follow. Temperature has a large

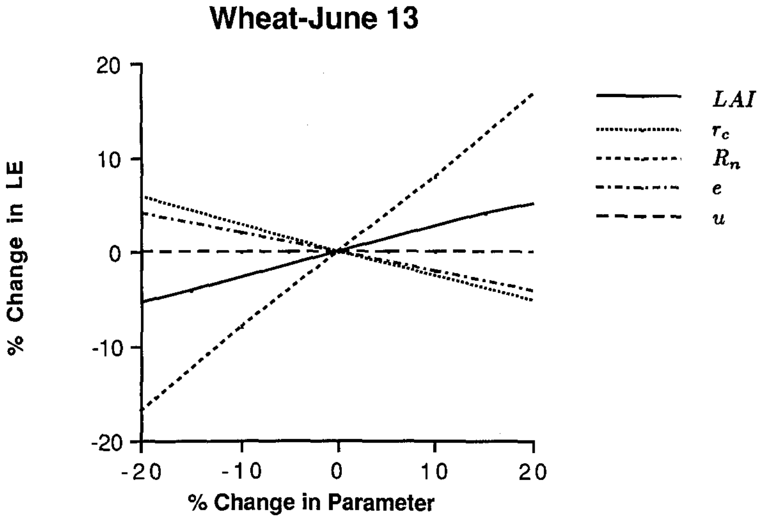

Fig. 5. Sensitivity of latent heat flux in a wheat field to changes in leaf area, stomatal resistance, net radiation, and humidity on June 13, 1985. Unperturbed *LE* flux (0,0) point was 330 W m^{-2}.

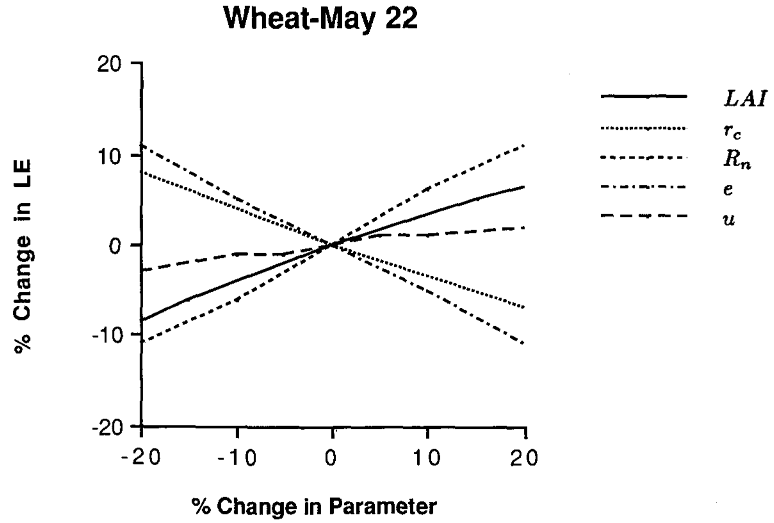

Fig. 6. Sensitivity of latent heat flux in a wheat field to changes in leaf area, stomatal resistance, net radiation, and humidity on May 22, 1985. Unperturbed *LE* flux (0,0) point on this day with no sensible heat advection was 420 W m^{-2}.

impact on *LE* (cf., Figure 3). The relative sensitivity of *LE* to R_n, r_s, e, and *LAI* is variable, but net radiation and humidity dominate in most cases.

The sensitivity of *ET* to the individual climatic and plant behavior changes, over the range of changes tested in the model is illustrated in Figures 4 and 5, for the days of highest and lowest *ET* in the wheat crop.

Changes in R_n had the greatest influence on June 13, the low flux day (about 330 W m^{-2}) with intermittent passages of clouds (see Table II and Figure 5).

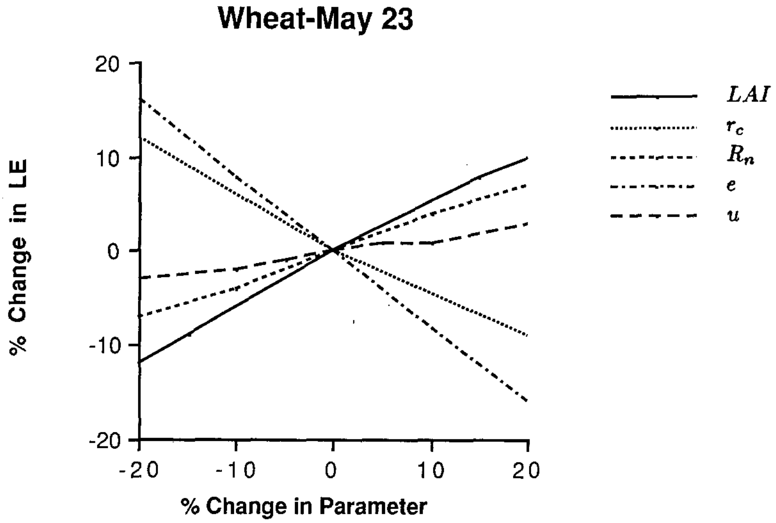

Fig. 7. Sensitivity of latent heat flux in a wheat field to changes in leaf area, stomatal resistance, net radiation, and humidity on May 23, 1985. Unperturbed *LE* flux (0,0) point on this day with significant sensible heat advection was 476 W m^{-2}.

Next in importance, in descending order of sensitivity, were r_s, *e*, *LAI*, and *u*. *LE* was much less responsive to R_n on June 8, the high flux day (600 W m^{-2}) which was sunny, although R_n was still the predominant factor. On that day, *e*, r_s, *LAI*, and *u* were the next most important factors. Note that the response of *LE* to r_s was the only one that was markedly curvilinear.

Another interesting comparison appears in Figures 6 and 7. On May 23 sensible heat advection was significant, contributing 53 W m^{-2} to the latent heat flux of 476 W m^{-2} between 10 and 16 h. On that day changes in R_n were of diminished importance and changes in windspeed were more important than usual. Nonetheless, *u* still was the factor of least importance. The sensitivity of *LE* to r_s was greatest on this day. By contrast, May 22 was a day with no advection of sensible heat and an *LE* flux of about 420 W m^{-2}; r_s was the factor of greatest importance on this day too, but the role of R_n was greater than under advective circumstances. The role played by advection was not studied for the forest and the grassland for lack of advective days during the observation period.

5.1.2. *Two Factor Changes*

The combined effects of temperature and stomatal resistance were examined first. Then, setting ΔT equal to +3K, the effects of ΔLAI versus Δr_s and Δr_s versus Δe were examined. Changes in windiness were ignored in the following studies due to the low sensitivity of the latent heat flux to changes in wind speed.

Figure 8 is a three-dimensional representation of the *ET* response (in terms of latent heat flux) in the three ecosystems when temperature and stomatal

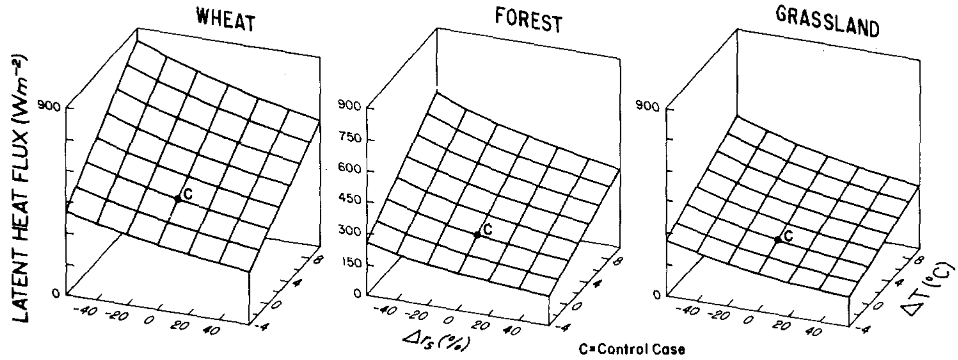

Fig. 8. Changes in latent heat flux in (a) wheat, (b) forest, and (c) grassland in response to simultaneous incremental changes in air temperature and stomatal resistance.

resistance are varied simultaneously. These response surfaces are calculated for the case of the 'mean' day in each ecosystem; hence the responses to change are intermediate between those that occur on high flux and low flux days. The response to temperature change is linear at each level of r_s change although the slopes steepen in all ecosystems with decreasing r_s. The curvilinearity of the *LE* response to decreasing r_s is evident in all three ecosystems and is greatest in the forest case. The degree of curvilinearity of this response changes little with increasing temperature.

5.1.3. *Multiple Factor Changes*

Tables III–V illustrate the range of changes in *LE* flux that could occur in each of the ecosystems on days of high and days of low flux as climatic and plant factors are varied singly and jointly. In these tables only the effect of a 3 °C temperature increase is shown on line 2. Changes in the other factors are those we consider reasonable on the basis of our literature review (Rosenberg *et al.*, 1989). Thus, in the wheat crop (Table III) on June 8 – a clear, hot day (see Table II for weather and plant conditions) – a 3 °C temperature rise increases *LE* flux from 600 to 692 W m^{-2} or 15% (line 2). If only *LAI* is increased by 15% with no other change, *LE* flux is increased by 5%. A 40% increase in r_s alone reduces *LE* flux by 11%. Both increased and decreased vapor pressure are considered, the former reducing and the latter increasing *LE* flux each by 5%.

The lower half of Table III considers multiple factor changes (lines 9–22). For wheat, the strongest increase in *LE* (26%) occurs when R_n is increased and e decreased (line 12). The effect of these climatic changes is reduced to 19% when plant factors are considered (line 20).

The impact of a 3 °C temperature increase on *LE* flux in wheat is less in both percentage and absolute terms on the cool, cloudy day, June 13 (see Table III). One sees in these sets of computations how, when all factors are considered, the

TABLE III: Simulated effects of climate change and CO_2-enrichment on summertime evapotranspiration in a wheat field (Mead, NE)

	Change in					High flux day (8 June)		Low flux day (13 June)		Avg. all days (10 days)		Notes
Line no.	T (K)	R_n (%)	e (%)	r_s (%)	LAI (%)	LE (W m^{-2})	Change (%)	LE (W m^{-2})	Change (%)	LE (W m^{-2})	Change (%)	
1	0	0	0	0	0	600		330		423		1) No climate change
2	3	0	0	0	0	692	15	367	11	508	20	2) Temperature increase only
3	0	10	0	0	0	631	5	358	8	449	6	3) Single factor changes
4	0	−10	0	0	0	568	−5	302	−8	398	−6	
5	0	0	10	0	0	570	−5	323	−2	395	−7	
6	0	0	−10	0	0	630	5	337	2	451	7	
7	0	0	0	40	0	532	−11	300	−9	373	−12	
8	0	0	0	0	15	631	5	342	4	444	5	
9	3	10	0	0	0	725	21	397	20	536	27	4) Temperature and net radiation change
10	3	−10	0	0	0	659	10	337	2	481	14	
11	3	10	10	0	0	698	16	390	18	510	20	5) Temperature, net radiation, and humidity change
12	3	10	−10	0	0	753	26	403	22	562	33	
13	3	−10	10	0	0	631	5	331	0	455	7	
14	3	−10	−10	0	0	686	14	344	4	507	20	
15	3	10	10	40	0	624	4	357	8	453	7	6) (5) + stomatal resistance increase
16	3	10	−10	40	0	673	12	368	12	499	18	
17	3	−10	10	40	0	564	−6	303	−8	404	−5	
18	3	−10	−10	40	0	613	2	314	−5	450	6	
19	3	10	10	40	15	659	10	370	12	478	13	7) (6) + leaf area index increase
20	3	10	−10	40	15	712	19	383	16	527	24	
21	3	−10	10	40	15	597	0	316	−4	427	1	
22	3	−10	−10	40	15	650	8	328	−1	476	12	

TABLE IV: Simulated effects of climate change and CO_2-enrichment on summertime evapotranspiration in a forest (Oak Ridge, TN)

	Change in					High flux day (6 August)		Low flux day (8 August)		Avg. all days (6 days)		Notes
Line no.	T (K)	R_n (%)	e (%)	r_s (%)	LAI (%)	LE (W m^{-2})	Change (%)	LE (W m^{-2})	Change (%)	LE (W m^{-2})	Change (%)	
1	0	0	0	0	0	305		177		250		1) No climate change
2	3	0	0	0	0	376	23	218	23	311	24	2) Temperature increase only
3	0	10	0	0	0	325	7	192	9	268	7	3) Single factor changes
4	0	−10	0	0	0	284	−7	162	−9	232	−7	
5	0	0	10	0	0	281	−8	162	−8	230	−8	
6	0	0	−10	0	0	328	8	192	8	271	8	
7	0	0	0	40	0	258	−15	154	−13	211	−16	
8	0	0	0	0	15	324	6	187	5	266	6	
9	3	10	0	0	0	398	31	235	33	330	32	4) Temperature and net radiation change
10	3	−10	0	0	0	354	16	202	14	292	17	
11	3	10	10	0	0	376	23	221	25	311	24	5) Temperature, net radiation, and humidity change
12	3	10	−10	0	0	420	38	248	40	350	40	
13	3	−10	10	0	0	332	9	188	6	272	9	
14	3	−10	−10	0	0	375	23	216	22	311	24	
15	3	10	10	40	0	321	5	193	9	265	6	6) (5) + stomatal resistance increase
16	3	10	−10	40	0	359	18	218	23	298	19	
17	3	−10	10	40	0	283	−7	165	−7	232	−7	
18	3	−10	−10	40	0	320	5	189	7	264	6	
19	3	10	10	40	15	344	13	205	16	284	13	7) (6) + leaf area index increase
20	3	10	−10	40	15	384	26	231	30	319	27	
21	3	−10	10	40	15	303	0	175	−1	248	−1	
22	3	−10	−10	40	15	344	13	201	13	284	13	

TABLE V: Simulated effects of climate change and CO_2-enrichment on summertime evapotranspiration in a grassland (Konza Prairie, KS)

	Change in					High flux day (30 June)		Low flux day (5 August)		Avg. all days (7 days)		Notes
Line no.	T (K)	R_n (%)	e (%)	r_s (%)	LAI (%)	LE ($W\ m^{-2}$)	Change (%)	LE ($W\ m^{-2}$)	Change (%)	LE ($W\ m^{-2}$)	Change (%)	
1	0	0	0	0	0	357		143		233		1) No climate change
2	3	0	0	0	0	401	12	180	26	274	17	2) Temperature increase only
3	0	10	0	0	0	380	6	154	8	250	7	3) Single factor changes
4	0	−10	0	0	0	334	−6	131	−8	216	−7	
5	0	0	10	0	0	348	−2	131	−8	223	−4	
6	0	0	−10	0	0	365	2	155	8	243	4	
7	0	0	0	40	0	304	−15	117	−18	194	−17	
8	0	0	0	0	15	378	6	153	7	249	7	
9	3	10	0	0	0	425	19	193	35	292	25	4) Temperature and net radiation change
10	3	−10	0	0	0	376	5	167	17	255	10	
11	3	10	10	0	0	417	17	182	27	283	21	5) Temperature, net radiation, and humidity change
12	3	10	−10	0	0	433	21	204	43	302	29	
13	3	−10	10	0	0	368	3	156	9	246	6	
14	3	−10	−10	0	0	384	8	178	25	265	14	
15	3	10	10	40	0	359	1	151	6	238	2	6) (5) + stomatal resistance increase
16	3	10	−10	40	0	373	4	169	19	254	9	
17	3	−10	10	40	0	317	−11	129	−9	207	−11	
18	3	−10	−10	40	0	330	−7	148	4	223	−4	
19	3	10	10	40	15	383	7	163	14	256	10	7) (6) + leaf area index increase
20	3	10	−10	40	15	398	12	183	28	273	17	
21	3	−10	10	40	15	338	−5	140	−2	223	−4	
22	3	−10	−10	40	15	353	−1	160	12	240	3	

sensitivity of *LE* to climate and plant changes can considerably alter the effects of temperature alone.

Temperature increase alone has a strong impact on *LE* flux in the forest on all days (Table IV). The impact of other factors tends to dampen the response (in percentage terms) more on the high flux than on the low flux day. A 3 °C temperature rise in the grassland increases *LE* by 12 and 26% on the high flux and low flux days, respectively (Table V). These responses are modified when the multiple factor changes are considered.

The physiological changes represented in Tables III–V are those believed most likely. However, it is possible that leaf area index, instead of increasing as a result of CO_2 fertilization, could decrease if leaf abscision occurs because of increased water stress. It is also conceivable that canopy resistance could increase by only 20% if plants respond to increased heat load by transpiring more, or it could increase by as much as 60% because of decreases in stomatal density. These alternative physiological changes are examined in Table VI under two different climatic change scenarios. Scenario I represents conditions where changes in all climatic variables act to increase evaporative demand. Under Scenario II, the impact of increased temperature on *ET* is partially offset by changes in other climatic factors.

If leaf area decreases and canopy resistance increases, both factors will act to reduce evapotranspiration. As is shown in Table VI, a 15% reduction in the *LAI* of wheat under Scenario I (line 6) reduces the climate-induced increase in *ET* (line 1) from 33% to 25%. This effect is accentuated by a simultaneous increase in canopy resistance, to the extent that the impact of climatic change on *ET* is nearly offset by these combined physiological effects when r_c is increased by 60% (line 12).

Conversely, if CO_2 fertilization causes *LAI* to increase, increased evapotranspiration will result (line 5). This response can be mitigated by increased canopy resistance. Lines 7, 9, and 11 show the combined effects of increased leaf area (+15%) and a range of changes in canopy resistance under Climate Scenario I. For wheat, the effect of increased *LAI* on *ET* will be halved if r_c is 60% greater (line 11). Although the magnitude of the changes discussed above vary somewhat among ecosystems, the general patterns are similar.

The impact of these physiological changes is much the same under both climate change scenarios. However, because the impact of climate alone is very large in Scenario I, even fairly large physiological changes in the plant cannot counteract the effects of climate, *ET* is increased. Under Scenario II, where evaporative demand is lower, plant changes can more than compensate the effects of climate, and actually reduce *ET* below the control (or, 'no change') case.

TABLE VI: Simulated effects of climate change and a range of possible CO_2-enrichment-induced plant responses on evapotranspiration rates in a wheat field (Mead, NE), a forest (Oak Ridge, TN), a grassland (Konza Prairie, KS) in summer

	Change in					Wheat		Forest (avg. all days)		Grassland		Notes
Line no.	T (K)	R_n (%)	e (%)	r_s (%)	*LAI* (%)	*LE* ($W\ m^{-2}$)	Change (%)	*LE* ($W\ m^{-2}$)	Change (%)	*LE* ($W\ m^{-2}$)	Change (%)	
												Climate Change Scenario I
1	3	10	−10	0	0	562	33	350	40	302	29	1) Climate change only
2	3	10	−10	20	0	528	25	321	28	276	18	2) Climate change + stomatal resistance increase
3	3	10	−10	40	0	499	18	298	19	254	9	
4	3	10	−10	60	0	473	12	277	11	235	1	
5	3	10	−10	0	15	589	39	372	49	321	38	3) Climate change + leaf area index increase/ decrease
6	3	10	−10	0	−15	530	25	324	30	279	20	
7	3	10	−10	20	15	556	31	343	37	295	27	4) Climate change + change in stomatal resistance and leaf area index
8	3	10	−10	20	−15	496	17	297	19	253	9	
9	3	10	−10	40	15	527	24	319	27	273	17	
10	3	10	−10	40	−15	466	10	273	9	232	−1	
11	3	10	−10	60	15	501	18	298	19	254	9	
12	3	10	−10	60	−15	440	4	254	1	214	−8	

	Change in					Wheat		Forest (avg. all days)		Grassland		Notes
Line no.	T (K)	R_n (%)	e (%)	r_s (%)	*LAI* (%)	*LE* (W m^{-2})	Change (%)	*LE* (W m^{-2})	Change (%)	*LE* (W m^{-2})	Change (%)	
												Climate Change Scenario II
13	3	−10	10	0	0	455	7	272	9	246	6	1) Climate change only
14	3	−10	10	20	0	428	1	250	0	225	−3	2) Climate change + stomatal resistance increase
15	3	−10	10	40	0	404	−5	232	−7	207	−11	
16	3	−10	10	60	0	383	−10	216	−14	192	−18	
17	3	−10	10	0	15	477	13	290	16	262	12	3) Climate change + leaf area index increase/ decrease
18	3	−10	10	0	−15	429	1	253	1	227	−2	
19	3	−10	10	20	15	450	6	267	7	241	3	4) Climate change + change in stomatal resistance and leaf area index
20	3	−10	10	20	−15	401	−5	231	−8	206	−11	
21	3	−10	10	40	15	427	1	248	−1	223	−4	
22	3	−10	10	40	−15	377	−11	213	−15	189	−19	
23	3	−10	10	60	15	406	−4	232	−7	208	−11	
24	3	−10	10	60	−15	356	−16	197	−2	174	−2	

5.2. *Climatic Change Scenarios*

To further investigate the effects of a climatic change due to a 'greenhouse' warming on *ET* and get an order of magnitude sense of the changes involved, we use the predictions of three global climatic models (GCMs) to force the P-M models. We use results from the Geophysical Fluid Dynamics Laboratory (GFDL), the Goddard Institute for Space Studies (GISS), and the National Center for Atmospheric Research (NCAR) GCMs. The GCM predictions are for the grid point nearest the location of each ecosystem and for the months (GFDL and GISS) and season (NCAR) corresponding to the time of the year when the *LE* measurements were made. (Note that the grid points of the three models do not correspond exactly.) Results are shown in Table VII. We used values found in Rosenberg *et al.* (1989) for the expected physiological responses to changes in carbon dioxide concentrations. The results of the GFDL (Manabe and Wetherald, 1983), GISS (Hansen *et al.*, 1983), and NCAR (Washington and Meehl, 1984) CO_2 doubling experiments provide the information on climatic change.

LE fluxes are computed in Table VII for the average day in each ecosystem. 'Control' means latent heat flux with no climate change. The first line for each GCM considers only the effect of its predicted temperature change on *LE* rate; the second line considers all climatic changes predicted by the model for the same location and season, and the third line considers all climatic factors plus changes in plant behavior caused by elevated CO_2 concentration.

Overall, the predicted increases in *LE* due to temperature change alone vary greatly in response to the considerable difference in temperature changes projected by the GCMs. In all cases, predicted *LE* is decreased significantly when other climatic factors are considered (e.g., GFDL from 42% in wheat for temperature alone to 28%; GISS, 28% in grassland to 15%). In the one case where a temperature decrease is predicted (NCAR, wheat) *LE* is decreased still more when all climatic changes are considered. The inclusion of increasing stomatal resistance in the model further reduces *ET* despite the counteracting effects of greater *LAI*.

As in the latter part of Section 5.1.3., we computed the climatic change scenarios with a wide range of values of r_c and *LAI*. From those additional calculations (not displayed), it appears that 'extreme' combinations of changes in r_c and *LAI*, i.e., (+60; –15) and (+20; +15) can affect the sign of ΔLE.

6. Discussion and Conclusions

The results of the simulations reported in the foregoing sections cannot be taken as the final word on the question of how and to what extent *ET* will be affected by a greenhouse-induced climatic change and the CO_2-induced changes in plant growth and stomatal response. The results of the previous sections are clearly

TABLE VII: Impacts of climatic changes predicted using GFDL, GISS, and NCAR GCM output, with and without expected changes in *LAI* and r_s on calculated latent heat flux, *LE*, for three ecosystems in summer

GCM	ΔT [K]	ΔR_n [%]	Δe [%]	Δu [%]	ΔLAI [%]	Δr_s [%]	LE [W m^{-2}]	Change [%]
Wheat Field, Mead, Nebraska (May–June)								
Control	–	–	–	–	–	–	423	–
GFDL	6.3	–	–	–	–	–	601	42
	6.3	14	24	–36	–	–	544	28
	6.3	14	24	–36	15	40	520	23
GISS	3.6	–	–	–	–	–	525	24
	3.6	0	30	26	–	–	462	9
	3.6	0	30	26	15	40	430	2
NCAR	–1.1	–	–	–	–	–	392	–7
	–1.1	0	22	100	–	–	326	–23
	–1.1	0	22	100	15	40	295	–30
Forest, Oak Ridge, Tennessee (August)								
Control	–	–	–	–	–	–	250	–
GFDL	4.8	–	–	–	–	–	348	39
	4.8	–2	14	28	–	–	322	29
	4.8	–2	14	28	15	40	292	17
GISS	2.2	–	–	–	–	–	295	18
	2.2	2	23	–49	–	–	268	7
	2.2	2	23	–49	15	40	250	0
NCAR	1.5	–	–	–	–	–	281	12
	1.5	0	5	26	–	–	269	7
	1.5	0	5	26	15	40	242	–3
Grassland, Konza Prairie, Kansas (July–August)								
Control	–	–	–	–	–	–	233	–
GFDL	4.3	–	–	–	–	–	292	25
	4.3	4	20	12	–	–	279	20
	4.3	4	20	12	15	40	252	8
GISS	4.7	–	–	–	–	–	297	28
	4.7	2	34	7	–	–	269	15
	4.7	2	34	7	15	40	243	4
NCAR	0.5	–	–	–	–	–	240	3
	0.5	0	14	39	–	–	215	–8
	0.5	0	14	39	15	40	191	–18

ΔT: change in temperature; ΔR_n: change in net radiation; Δe: change in absolute humidity; Δu: change in wind speed; ΔLAI: change in leaf area index; Δr_s: change in stomatal resistance.
Note: For NCAR, no irradiance data being available, $\Delta R_n = 0$.

dependent on the model employed and on the parameterizations used to adapt the model for use with each of the three ecosystems. So, let us first review some of the assumptions underlying the use of the P-M model for the applications described above.

6.1. *Modeling Rationale*

The objective of the present study was to increase our understanding of how evapotranspiration could be affected by global change. Given this objective, our approach was to perform a sensitivity analysis using a model whose data demands can be met with actual field observations, modeling only well understood phenomena, avoiding synergisms when unknowns remain, and changing one factor at the time.

We recognize that such an approach can only provide partial answers to the question we are asking. Proceeding hierarchically, a possible next step is to perform offline studies, forcing land-surface schemes like those developed by Dickinson (1984) and Sellers *et al.* (1986) with GCM data. Then, it would be interesting to close the land-surface/atmosphere feedback loop, and simulate changes in climate using a land-surface fully coupled to the atmosphere. Finally, changes in landscape characteristics due to changes in vegetation composition should be included. This is the direction in which our present research is leading.

6.2. *Modeling Assumptions*

The P-M approach used in this study does not explicitly incorporate soil moisture effects, though they can be significant. Three points should be made regarding this modeling decision. First, the inclusion of a soil moisture submodel and a model of water storage in vegetation for the forest would require a large amount of data. Our aim in this work has been to rely as much as possible on local reliable observations and as little as possible on literature data. Second, for the control cases, we can assume that water was not limiting given that the wheat and grassland data represent wetter than normal years. The forest data apply to a climatologically normal year – which at Oak Ridge means adequate water supply. Third, by inverting P-M to obtain the stomatal resistance, in the wheat and the forest cases, we incorporate possible soil moisture effects on stomatal behavior to some extent.

Our analysis does not consider explicitly the likelihood that changes in precipitation will alter availability of water and, hence, the magnitude of ET. In forests, especially, changes in precipitation will affect interception losses. These commonly range from 10 to 25% of annual precipitation in deciduous forests – like that at Oak Ridge, and 15 to 40% in coniferous forests (Rutter, 1975). Therefore, everything else being equal, the actual evapotranspiration could be significantly different from what the model predicts.

Stomatal behavior is complex and many unknowns remain (Farquhar, 1986). At this point, we simply impose stomatal resistance values and do not consider how these might be affected by root-to-shoot communication, feedforwards, or feedbacks. We do not adjust for stomatal resistance response to saturation vapor pressure deficit, because of remaining questions pertaining to the behavior of existing formulations, such as that of Choudhury and Monteith (1986) (Paw U and Gao, 1988). We give changes in r_s that are both positive and negative. Soil moisture shortage and increased vapor pressure deficit would further increase r_s. Climatic changes that would diminish it are also possible.

In addition, we do not include the differential impacts of soil moisture stress and CO_2 enrichment on growth. Kimball (1985) reviewed 18 studies of growth under doubled CO_2 concentrations with and without water stress and noticed that, in the case without water stress, growth was stimulated by about 43% and that, in the case with water stress, growth was stimulated by about 76%. Hence, in relative terms, plants benefit more from CO_2 enrichment when under stress. Further, and perhaps most important, we cannot be completely confident that the simulated responses of ET to changes in stomatal resistance would actually occur in fields and forests exposed to a future CO_2 enriched atmosphere since most of the data on stomatal behavior comes from greenhouse and growth chamber studies (e.g., Morison, 1987). CO_2 enrichment in the open air has not yet been accomplished for long enough to establish to what extent the stomatal closure actually occurs and whether it is transitory or persistent. Finally, anatomical adaptations to climatic change and CO_2 enrichment of the atmosphere over the long term cannot be ruled out. As shown by Woodward (1987a), the observed stomatal density of leaves of eight temperate arboreal species in an herbarium collection decreased by 40% over the last 200 yr, during which time the CO_2 concentration increased by 60 ppm. This interesting study is only suggestive. Most likely, the leaves collected were not highly transpiring sunlit leaves at the top of the canopy.

Carbon dioxide enrichment affects plant growth and thus the ability to cast shade. We include leaf area index effects, but we do not consider light interception effects, which in the case of the forest could have measurable impacts on the growth of the understory (Woodward, 1987b).

The combined effects of climate warming and CO_2 enrichment are likely to alter the length of the growing season of most plants. This effect will be most noticeable in crops. However, we did not include this change in our simulations.

In our analysis, we have assumed an unchanging species composition of the vegetation. However, in unmanaged ecosystems especially, the short-term responses to evolving climatic disturbances and the longer term adaptations to a new climate will affect vegetation dynamics. As numerous forest hydrology studies suggest (e.g., Hibbert, 1967; Hall, 1971; Bosch and Hewlett, 1982), changes in vegetation cover are likely to alter evapotranspiration significantly.

6.3. *On the Control of Regional Evapotranspiration*

Are our results applicable beyond the boundaries of our fields? Equivalently, to what extent does local stomatal behavior regulate regional evapotranspiration?

As pointed out by Jarvis and McNaughton (1986), this second question is the object of a long standing debate between plant physiologists and climatologists – the former concluding that transpiration is strongly regulated by stomata and the latter concluding that it is not, neither paying serious attention to the scale at which they are working.

Jarvis and McNaughton (McNaughton and Jarvis, 1983; Jarvis and McNaughton, 1986) define a factor, Ω_c, determining the degree to which transpiration is decoupled from the stomatal behavior. The formulation of the Ω_c factor may not be exact (Paw U and Gao, 1988), its derivation being based on the generally accepted, but theoretically incorrect, concept of equilibrium evapotranspiration and the assumption that the canopy is in radiative equilibrium with its environment. However, the general conclusion reached by Jarvis and McNaughton, that tall vegetation has a greater control over its transpiration than shorter vegetation, still holds. Our 'base case' results are consistent with this postulation.

6.4. *On the Use of GCM Predictions of Regional Climatic Change*

As can be seen by examining our GCM-based scenarios and as is frequently noted in the literature (e.g., Mitchell, 1988), predictions of regional climate change vary greatly from one GCM to another. In the present exercise, we use GCM results only to define possible climatic forcings.

A second caveat is that the experimental plots upon which we base our calculations are infinitesimal in comparison to GCM grid cells which encompass thousands of square kilometers. The phenomena taking place at those highly contrasted scales are likely to be different.

Finally, we assume that changes in surface characteristics and surface fluxes are small enough not to affect general circulation, though on a global scale one can expect such feedbacks to be present (e.g., Shukla and Mintz, 1982).

6.5. *Conclusion*

This study indicates that a biophysical approach to estimating the effects of climatic change and CO_2 enrichment on ET is appropriate and useful. The P-M models developed for each ecosystem fit the field data reasonably well.

An impact is the product of a forcing and a sensitivity. The studies that we performed on the wheat, deciduous forest, and tall grass prairie ecosystems enabled us to assess the impact of a climatic change on evapotranspiration, by examining on the one hand the magnitudes of the external forcings that can be expected and, on the other, the model sensitivity to those changes.

To some extent, the temperature effect can be compensated by stomatal responses and increases in absolute humidity. This is so because of the sensitivity of evapotranspiration to those factors and the ranges within which they are likely to vary in the event of a climatic change. It is thus appropriate to formulate evapotranspiration not only in terms of temperature, but also in terms which include other microclimate factors, as well as some plant physiological considerations.

We are cognizant of the high degree of uncertainty in regional GCM output. The regional results that we use present 'greenhouse' climatic change scenarios. They cover a wide range because of the contrasting regional scale predictions of the GFDL, GISS, and NCAR GCMs. Nonetheless, the results based on scenarios incorporating the most likely micrometeorological and physiological changes indicate that changes in evapotranspiration could be moderate and, in some instances, insignificant. But, if one allows for significant decreases in leaf area index, which seems unlikely but possible, the latent heat flux is generally greatly reduced. Evapotranspiration could have less of an impact on runoff, for instance, than was previously predicted by Revelle and Waggoner (1983) and Gleick (1986), for example. However, increases in runoff resulting from decreases in evapotranspiration due to stomatal closure (Aston, 1984; Idso and Brazel, 1984) still seem unlikely.

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Appendix 1. Model Description

The appendix describes the model and, in particular, the physical constants, the treatment of the soil and the canopy heat fluxes, the parameterization of the temperature-dependent properties of air and water, and the calculation of the aerodynamic and canopy resistances.

1. Physical Constants

For the purpose of the present simulation, we assumed that the density of dry air, ρ_a, and the specific heat of dry air at constant pressure, C_p, are constant and use their values at 20 °C; hence, $\rho_a = 1.204$ kg m^{-3} and $C_p = 1010$ J kg^{-1} K^{-1} (e.g., Jones, 1983).

2. The Soil and the Canopy Heat Fluxes

S represents the soil heat flux in the wheat and the grassland cases. In the forest case, the soil heat flux was incorporated in the value of the net radiation, R_n (Verma *et al.*, 1986), as,

$$S = 0.036\, R_n,$$

and the parameter S in the P-M equation is replaced by G, the forest canopy heat storage term, in W m^{-2}.

3. The Temperature-Dependent Properties of Air and Water

In this section, we present the parameterizations of the latent heat of vaporization, the psychrometric constant, and the saturation vapor pressure and its derivative with respect to temperature.

3.1. *The Latent Heat of Vaporization*

For the latent heat of vaporization, L, we used the approximation found in Verstraete (1985), derived from first principles by Dufour and Van Mieghem (1973):

$$L(t) = (2.50084 - 0.00234t)\, 10^6,$$

where t is the temperature in degrees Celsius.

3.2. *The Psychrometric Constant*

The psychrometric constant (Monteith, 1973), γ, is defined as:

$$\gamma = \frac{C_p P}{L\varepsilon},$$

where P is the atmospheric pressure in Pa; and, ε is the dimensionless ratio of the molecular weight of water to the effective molecular weight of dry air ($\varepsilon = 0.622$). In the grassland case, measured values of atmospheric pressure were used. In the wheat and forest models, we took $P = 10^5$ Pa.

3.3. *The Saturation Vapor Pressure and its Derivative*

Saturation vapor pressure, e_s, was obtained using the approximation provided by Dufour and Van Mieghem (1975):

$$\log(e_s(T)10^{-2}) = 23.95717 - \frac{2{,}954.98}{T} - 5.07026\log(T),$$

where T is the temperature in K.

By definition (e.g., Monteith, 1973), the slope of the saturation vapor pressure curve, s, is the derivative of saturation vapor pressure with respect to temperature, so that,

$$s(T) = \frac{1}{T}\left[\frac{6{,}804.10}{T} - 5.07026\right]e_s(T).$$

4. The Aerodynamic Resistance

The aerodynamic resistance, r_a, is the sum in series of the bulk leaf boundary resistance, r_B, and the external aerodynamic resistance between the canopy and the air at height z, r_H:

$$r_a = r_B + r_H.$$

4.1. *The Bulk Leaf Boundary Resistance*

Taking the derivation by Thom (1972) for the canopy resistance as an analogy and, in effect, using an approach similar to Sellers *et al.* (1987), we defined the bulk leaf boundary resistance, r_B, as,

$$r_B = \frac{r_l}{LAI},$$

where r_l, the leaf boundary layer resistance, was computed with the formulation suggested by Jones (1983):

$$r_l = \frac{1}{6.62c}\left(\frac{d}{u}\right)^{1/2} 10^3,$$

where d is the characteristic dimension of the leaves in m; u, the horizontal wind speed in m s^{-1}; and, c, a dimensionless constant which, in the turbulent case assumed here, can be taken as $c = 1.5$.

4.2. *The External Aerodynamic Resistance*

The external aerodynamic resistance was derived using the equation for the sensible heat flux, and the wind speed and temperature profiles.

The sensible heat flux, H, in W m^{-2}, through a boundary layer is described by the general heat transfer equation,

$$H = -\frac{\rho_a C_p}{r_H}(T_2 - T_1), \tag{A1}$$

where T_1 and T_2 are the temperatures in K at heights z_1 and z_2 ($z_2 > z_1$).

At the evaporating surface, where it was assumed that $u = 0$ and $T = T_1$, the wind speed and the temperature profiles can be written following Brutsaert (1982) as:

$$u = \frac{u_*}{k}\left[\ln\left(\frac{z - d_0}{z_M}\right) - \Psi_M(\zeta)\right], \tag{A2}$$

and,

$$T_2 - T_1 = -\frac{H}{k u_* \rho_a C_p}\left[\ln\left(\frac{z - d_0}{z_H}\right) - \Psi_H(\zeta)\right], \tag{A3}$$

where u_* is the friction velocity in m s^{-1}; k, the von Kármán constant, taken as equal to 0.4; z, the height at which temperature is measured, in m; d_0, the zero plane displacement for the surface, in m; z_M and z_H, the roughness lengths for momentum and heat, respectively, in m; ζ, the dimensionless Monin-Obukov stability parameter; and, Ψ_M and Ψ_H, the dimensionless profile correction functions for momentum and heat, respectively.

Combining equations (A1), (A2), and (A3), we get:

$$r_H = \frac{1}{k^2 u}\left[\ln\left(\frac{z - d_0}{z_M}\right) - \Psi_M(\zeta)\right]\left[\ln\left(\frac{z - d_0}{z_H}\right) - \Psi_H(\zeta)\right]. \tag{A4}$$

Let us now examine the factors needed to compute the value of r_H. For the wheat field and the tall grass prairie cases, we rely on Brutsaert's (1982) review of empirical formulations for the zero plane displacement, d_0, and the roughness length for momentum, z_M, to determine the most appropriate formulation:

$$d_0 = \frac{2}{3}h$$

and

$$z_M = \frac{h}{7.6},$$

where h is the height of the vegetation, in m.

For the forest, the zero plane displacement and the roughness length for momentum are obtained using coefficients calculated in 1986 by Baldocchi *et al.*,[4] for the same site:

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[4] Dr. Dennis D. Baldocchi, *Atmospheric Turbulence and Diffusion Division/NOAA/ARL, P.O. Box E, Oak Ridge, TN 37831, U.S.A.*, personal communication, October 1987.

$$d_0 = 0.98\,h$$

and

$$z_M = 0.18\,h.$$

The roughness length for heat, z_H, can be related to the roughness length for momentum, z_M, in the following way (Campbell, 1977):

$$z_H = 0.2\,z_M.$$

The Monin-Obukov stability parameter, ζ, is defined (Brutsaert, 1982) as:

$$\zeta = -\frac{(z-d_0)kgH}{u_*^3 \rho_a C_p T_1} \tag{A5}$$

where g is the acceleration due to gravity in m s^{-2}. We take g equal to 9.81 m s^{-2}.

The formulations of the profile correction functions for momentum and heat depend on the atmospheric stability. Let us refer to θ_1 and θ_2 as the potential temperatures (e.g., Brutsaert, 1982) at heights z_1 and z_2 ($z_2 > z_1$). Following Brutsaert (1982), in unstable conditions (ζ, $\theta_2 - \theta_1 < 0$), the profile correction functions for momentum and heat can be expressed as,

$$\Psi_M = 2\ln\left[\frac{1+(1-16\zeta)^{1/4}}{2}\right] + 2\ln\left[\frac{1+(1-16\zeta)^{1/2}}{2}\right] - 2\arctan[(1-16\zeta)^{1/4}] + \frac{\pi}{2}$$

and

$$\Psi_H = 2\ln\left[\frac{1+(1-16\zeta)^{1/2}}{2}\right],$$

and, in stable conditions (ζ, $\theta_2 - \theta_1 > 0$), as

$$\Psi_M = \Psi_H = -5\zeta.$$

Equations (A5), (A2), and (A3) can be combined so as to have ζ as the only unknown:

$$\zeta\left[\ln\left(\frac{z-d_0}{z_H}\right) - \Psi_H(\zeta)\right]\left[\frac{ku}{\left[\ln\left(\frac{z-d_0}{z_H}\right) - \Psi_H(\zeta)\right]}\right]^2 + (z-d_0)kg\left[1 - \frac{T_2}{T_1}\right] = 0. \tag{A6}$$

We solved equation (A6) for ζ using the Van Wijngaarden-Dekker-Brent method (Press *et al.*, 1986), a numerical approach to root finding which combines root bracketing, bisection, and inverse quadratic interpolation. The profile correction functions for heat and momentum were set to zero in the forest and the grassland cases for lack of sufficient data to compute them. The error introduced is small (e.g., Campbell, 1985).

5. The Canopy Resistance

As explained above, we obtained the canopy resistance values by different means for each ecosystem. In the wheat case, we used an average stomatal resistance, $\bar{r}_s$, when assessing the model performance, and a canopy resistance, r_c, obtained by inverting the P-M equation (Equation 1) in the sensitivity studies and the simulations:

$$r_c = \frac{s(R_n + S) + \rho_a C_p(e_s - e) - (s + \gamma)LEr_H}{\gamma LE} .$$

For the forest, we used the canopy resistance values computed independently by Verma *et al.* (1986). However to obtain those values, Verma *et al.* inverted the P-M equation, using their own parameterizations and taking measured *LE* as an input. Hence, though the model was not fitted to the observations, the forest model is not totally independent from them. For the grassland, we used literature values of stomatal resistances for grasses (Jones, 1983). The canopy resistance was computed by averaging the stomatal resistance, r_s, over the leaf area index:

$$r_c = \frac{r_s}{LAI}$$

where $r_s = (r_{ad} \cdot r_{ab})/(r_{ad} + r_{ab})$; and, r_{ad} and r_{ab} are the average stomatal resistances of the adaxial and abaxial sides of the leaf, respectively. In making this leaf area index-weighted estimation, we followed a standard practice, albeit one that has been shown by Finnigan and Raupach (1987) to be less than perfectly accurate.

Appendix 2. Variable List, Definitions, and Units

The variables as well as their definition and units are listed in Table VIII.

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TABLE VIII: Variable definition

Variable	Definition	Units
c	dimensionless constant ($c = 1.5$)	–
C_p	specific heat of dry air at constant pressure	J kg^{-1} K^{-1}
d	characteristic dimension of the leaves	m
d_0	zero plane displacement for the surface	m
e	actual vapor pressure in the air above the canopy	Pa
e_s	saturation partial pressure of water vapor	Pa
E	flux of evaporated water	kg m^{-2} s^{-1}
g	acceleration due to gravity ($g = 9.81$)	m s^{-2}
h	height of the vegetation	m
k	von Kármán constant ($k = 0.4$)	–
L	latent heat of vaporization	J kg^{-1}
P	atmospheric pressure	Pa
r_a	aerodynamic resistance	s m^{-1}
r_{ab}	average abaxial stomatal resistances of the leaf	s m^{-1}
r_{ad}	average adaxial stomatal resistances of the leaf	s m^{-1}
r_B	bulk leaf boundary resistance	s m^{-1}
r_c	canopy (or bulk physiological) resistance	s m^{-1}
r_l	leaf boundary layer resistance	s m^{-1}
r_s	stomatal resistances of the leaf	s m^{-1}
$\bar{r}_s$	average stomatal resistances of the leaf	s m^{-1}
R_n	net radiation	W m^{-2}
s	derivative of the saturation vapor pressure with respect to temperature	Pa K^{-1}
S	soil heat flux	W m^{-2}
t	temperature	°C
T	temperature	K
T_a	air temperature	K
T_l	leaf temperature	K
T_1	temperature at height z_1	K
T_2	temperature at height z_2	K
u	horizontal wind speed	m s^{-1}
u_*	friction velocity	m s^{-1}
z	height at which temperature is measured	m
z_H	roughness length for heat	m
z_M	roughness length for momentum	m
γ	psychrometric constant	Pa K^{-1}
ε	dimensionless ratio of the molecular weight of water to the effective molecular weight of dry air ($\varepsilon = 0.622$)	–
ζ	dimensionless Monin-Obukow stability parameter	–
θ_1	potential temperature at height z_1	K
θ_2	potential temperature at height z_2	K
ρ_a	density of air	kg m^{-3}
Ψ_H	profile correction function for heat	–
Ψ_M	profile correction function for momentum	–

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