Extrapolation of synoptic meteorological data in mountainous terrain and its use for simulating forest evapotranspiration and photosynthesis

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A model for calculating daily microclimate conditions in mountainous terrain is presented. Maximum–minimum daily air temperatures, precipitation, and dew point are extrapolated from valley stations to adjacent mountain slopes, after making elevation- and aspect-related corrections. The model (MT-CLIM) produces estimates of daily incoming shortwave radiation, air temperature, humidity and vapor pressure deficit, and precipitation for any mountain study site. MT-CLIM was tested against measured meteorological data on six study sites consisting of three north–south slope pairs in western Montana. Correlations between predicted and observed daily conditions on the six study sites for the period April–November 1983 were air temperature, $R^2 = 0.88–0.92$ with standard errors <0.48°C; relative humidity $R^2 = 0.63–0.72$ with standard errors <15%; radiation $R^2 = 0.60–0.78$ with standard errors $<100\ \mathrm{W\ m^{-2}}$. To test the utility of the model, data from MT-CLIM were used to run the DAYSTRANS/PSN model of evapotranspiration (ET) and photosynthesis (PSN) for western coniferous forests. Seasonal ET calculated from MT-CLIM data deviated by less than 5% from ET calculated from measured meteorological conditions on the six sites. Estimates of seasonal PSN agreed to within 10% of estimates derived from measured meteorological data on all sites except one. For each of the north–south slope study pairs, the combined MT-CLIM DAYTRANS/PSN simulation predicted that north slopes would have higher (5–31%) seasonal PSN than the comparable south slopes, which agrees with observed patterns of forest productivity in this semiarid region.

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Cet article décrit un modèle permettant le calcul des valeurs microclimatiques journalières dans les terrains montagneux. Après avoir apporté des corrections reliées à l'altitude et à l'exposition, les valeurs journalières de la température maximale, de la température minimale, du point de rosée et de la précipitation sur les pentes de montagnes sont calculées à partir de valeurs observées dans les vallées voisines. Le modèle (MT-CLIM) évalue le rayonnement solaire incident journalier, la température de l'air, l'humidité et le déficit de tension de vapeur et la précipitation pour n'importe quel site d'étude en montagne. Le modèle MT-CLIM a été vérifié à partir des données météorologiques mesurées à six sites d'études, trois exposés au nord et trois au sud, dans l'ouest du Montana. Les coefficients de corrélation entre les valeurs journalières prédites et observées sur les six sites d'étude pour la période d'avril à novembre 1983 ont été: pour la température de l'air, $R^2 = 0{,}88$ à $0{,}92$ avec une erreur standard <0,48°; pour l'humidité relative, $R^2 = 0{,}63$ à $0{,}72$ avec une erreur standard <15%; pour le rayonnement, $R^2 = 0{,}60$ à $0{,}78$ avec une erreur standard $<100\ \mathrm{W\ m^{-2}}$. Afin de vérifier l'utilité du modèle, les données de MT-CLIM ont servi de données d'entrées au modèle DAYTRANS/PSN qui calcule l'évapotranspiration (ET) et la photosynthèse (PSN) pour les forêts de conifères de l'ouest. Les valeurs calculées de l'évapotranspiration saisonnière à partir des données de MT-CLIM montrent une différence inférieure à 5% des valuers calculées en utilisant les observations météorologiques des six sites. Les estimés de la photosynthèse saisonnière correspondent à moins de 10% près aux estimés obtenus à l'aide des données météorologiques mesurées sur tous les sites, sauf un. Pour chacune des paires de sites, exposition nord et exposition sud, la simulation obtenue en combinant MT-CLIM et DAYTRANS/PSN a prévu que les pentes exposées au nord auraient une valeur plus élevée (de 5 à 31%) de la photosynthèse saisonnière que les pentes correspondantes exposées au sud, ce qui concorde avec les patrons observés de la productivité des forêts dans cette région semi-aride.

[Traduit par la revue]

Introduction

Meteorological conditions drive numerous ecological processes: photosynthesis, evapotranspiration, respiration, decomposition, etc. To calculate rates of these processes, air and soil temperature, incoming shortwave radiation, humidity, and precipitation data are needed for the site of interest. However, the use of meteorological data for ecological modeling has been hindered by two fundamental problems. First, meteorological data are rarely available for the exact location of interest. Second, meteorological data may be needed at varying time scales, from minutes to years, depending on the use to be made of the data. Additionally, humidity is rarely available from routine sources, and incoming shortwave radiation is typically recorded only at major airports. When working on a single intensive research site the logical remedy is to establish one's own meteorological station, collect the data needed, and analyze the data in a format optimal to one's task. However, many ecological questions are now being addressed over larger areas, from watersheds and regions to global issues that require meteorological data on virtually a continuous spatial scale, precluding individual data gathering efforts. Rarely are the routine products available from organizations such as the U.S. National Weather Service (NWS) of the National Oceanic and Atmospheric Administration optimum for the needs of the individual scientist. Consequently, use of these products usually entails reanalysis for the specific task at hand. Our goal of calculating forest evapotranspiration and photosynthesis over large areas has lead us to confront the above problems. The structure and composition of western coniferous forests are markedly controlled by climatic and related topographic factors (Daubenmire 1956). Although it is understood that forest distributions in this region are generally produced by varying conditions of radiant energy, temperature and water availability, mechanistic understanding of the role of microclimate in controlling forest processes has been slow. In a previous paper (Running 1984*a*), hypothetical meteorological scenarios were used to study the possible role of microclimate in controlling seasonal evapotranspiration (ET) and photosynthesis (PSN) of coniferous forests in the northern Rocky Mountains. Interactions between water and energy limitations of ET and PSN were explored and related to microclimate scenarios that were presumed to reflect changes in elevation, slope and aspect, and regional climate in the western United States. Hypothetical meteorological scenarios were used because we did not have a way to measure or generate meteorological data for the variety of conditions that we wished to evaluate.

This paper presents the logic, equations, and first testing of a mountain microclimate simulator (MT-CLIM) that is designed to extrapolate routine NWS meteorological data to adjacent mountainous terrain. MT-CLIM is designed specifically to provide inputs to ecological models of forest ET and PSN such as DAYTRANS/PSN, and a significant part of the logic in MT-CLIM is chosen specifically to optimize the meteorological data for this purpose. The predicted microclimate conditions will be validated from measured meteorological data on three north and south slope pairs in the mountains of western Montana. Execution of the complete system, using MT-CLIM generated meteorological data to drive DAYTRANS/PSN on the three slope paired sites, provides our first test of the total logic of large scale estimation of forest ET and PSN using coupled models of microclimate and ecological processes.

Methods

MT-CLIM

MT-CLIM extrapolates meteorological variables from the point of measurement (referred to as the base station) to the study site of interest, making corrections for differences in elevation, slope, and aspect between the two sites and improving the time and spatial scaling of the data for computation of ecological processes in the vegetation of interest. The first step in the development of MT-CLIM was to determine which synoptic meteorological database to work with. The U.S. Forest Service National Fire Danger rating system (Furman and Brink 1975) has an extensive network of stations throughout the forested region of the western United States but only operates during the summer fire months. RAWS (Remote Automated Weather Stations) facilities are being established in mountainous areas throughout the west, but the data are not yet routinely available to users outside the federal agencies (Warren and Vance 1981). Consequently, our best alternative was the Climatological Data Summary compiled by the National Oceanic and Atmospheric Administration (National Climatic Center, Ashville, NC). Data are compiled monthly for each state, giving daily conditions of air temperature and precipitation at secondary stations, with the addition of dew point, cloud cover, sunshine duration, wind speed, and various other variables at major airport stations.

A flow chart of the components and basic logical flow of MT-CLIM is shown in Fig. 1. Daily meteorological data are received from the NWS station defined as the "base" station. Input requirements are maximum–minimum air temperature and precipitation for the 24-h period, with dew point also used if available. "Site" topographic factors are then required to define the area of interest for which meteorological data are needed. Typically in Montana, the base stations are at city airports in valley bottoms, and the forested sites are in adjacent mountains. Because only vertical (elevation related) corrections are made to the base station data, sites horizontally distant from a base station data source are more difficult to estimate with this type of logic if air masses, cloud cover and precipitation differ at the study site.

An important concept in ecological theory is the idea of "operational environment": i.e., defining environmental variables from the perspective of the plant process being considered (Mason and Langenheim 1957). For example, the definition of day length meteorologically is the period of time that part of the solar disc is above the horizon of a flat surface. However, the day length for net photosynthesis of a tree is more exactly defined as the period of time when the light compensation point is exceeded. In complex topography, this operational environment definition of day length is frequently 20% shorter than the meteorological day length. While physical benchmark definitions are of course necessary, optimizing the analysis of climatic control to specific plant processes is most accurately done with derived definitions of operational environment. Certain key components of MT-CLIM are optimized for gas exchange processes of conifer trees and will be identified as such.

The time scale of MT-CLIM is daily, chosen mainly because synoptic data are most readily available as average or total daily conditions. Additionally, we have found a 1-day time step to be an appropriate compromise for ecological modeling between the higher resolution hourly time steps that require large climatic data files (Running 1984*a*; Knight et al. 1985) and longer time scales, weekly to monthly and yearly, that progressively average out climatic fluctuations and miscalculate hydrologic partitions of the ecosystem (Nemani and Running 1985).

Four subroutines calculate the four meteorological variables of interest: air temperature, incoming shortwave radiation, humidity, and precipitation. We do not consider wind conditions partly because energy and gas exchange by conifer needles is insensitive to windspeed beyond a rather low threshold (i.e., 5 cm s^{-1}) (Smith 1980), and partly because general climatological principles for extrapolation in mountains are not available.

Shortwave radiation

The estimation of daily incoming shortwave radiation proved to be one of our most difficult tasks, because the NWS stations in Montana do not directly measure incoming radiant energy but collect data only from semiquantitative "sunshine recorders" or qualitatively from observer's cloud cover estimates. After attempting to work with these data to estimate incoming solar radiation (Satterlund and Means 1978; Running and Hungerford 1983), we finally decided on the algorithm of Bristow and Campbell (1984) that relates diurnal air temperature amplitude to atmospheric transmittance. Their analysis requires only daily maximum–minimum air temperatures, bypassing the unreliable, nonquantitative NWS cloud-cover data, and appears to be equally accurate, having been tested on three sites ranging from maritime to continental climates and accounting for 70 to 90% of the variability in daily incoming radiation on these sites. We first compute clear sky transmissivity for the elevation of the site of interest, assuming clear sky transmittance at mean sea level is 0.6 and increases 0.008 m^{-1} of elevation. Final atmospheric transmissivity is then calculated as an exponential function of diurnal temperature amplitude of the base station (Bristow and Campbell 1984).

Next, a potential radiation model derived from the logic of Garnier and Ohmura (1968), Buffo et al. (1972), and Swift (1976) is run. This model for direct and diffuse shortwave radiation incorporates the slope and aspect of the site of interest and truncates the direct beam solar irradiance by east and west horizons for the study site, rather than assuming a flat horizon. Potential above-atmosphere radiation is reduced by atmospheric transmissivity to produce a final estimate of incoming shortwave radiation to the site. The potential radiation model is also run for an equivalent flat surface at the site elevation to generate a ratio of flat surface to slope radiation absorbed, for later use in adjusting air temperature estimates for the site. Finally, the day length computed by the radiation submodel is calculated for the period of each day that incoming shortwave radiation exceeds 70 W m^{-2}. This is a threshold

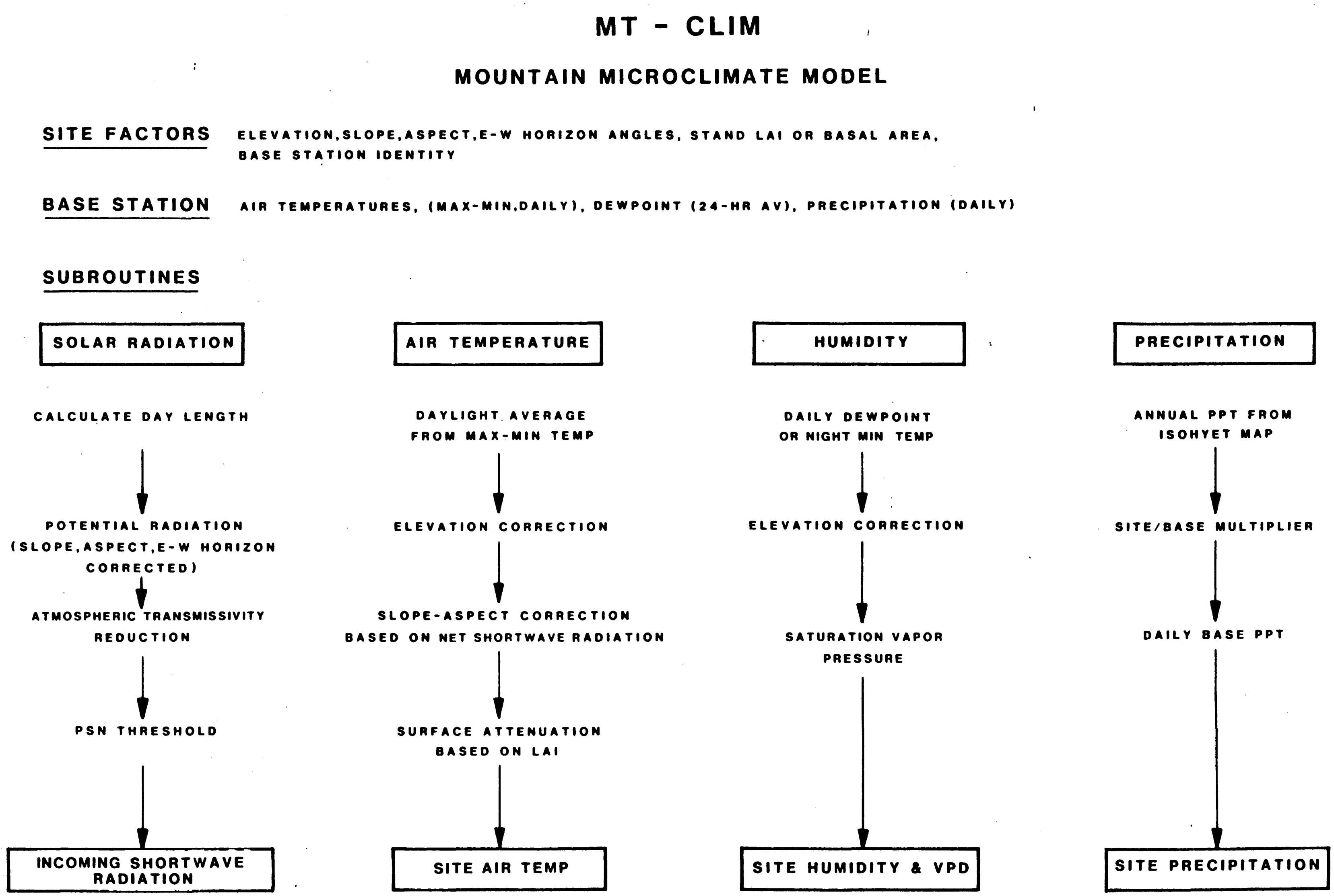

FIG. 1. Flowchart of the MT-CLIM model for estimating daily microclimate conditions in mountainous terrain. The site factors and base station variables shown are required inputs for the model. MT-CLIM was designed primarily to provide input data for forest ecosystem process models.

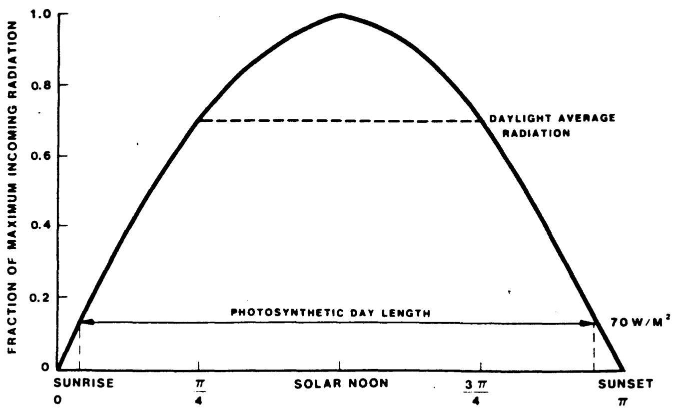

FIG. 2. An operational environment definition of day length for net photosynthesis, with the light compensation point for CO_2 fixation and maximum stomatal opening of a coniferous tree used to truncate day length. Daylight average radiation can also be estimated by integration of this approximated sine wave, as 0.707 × maximum radiation.

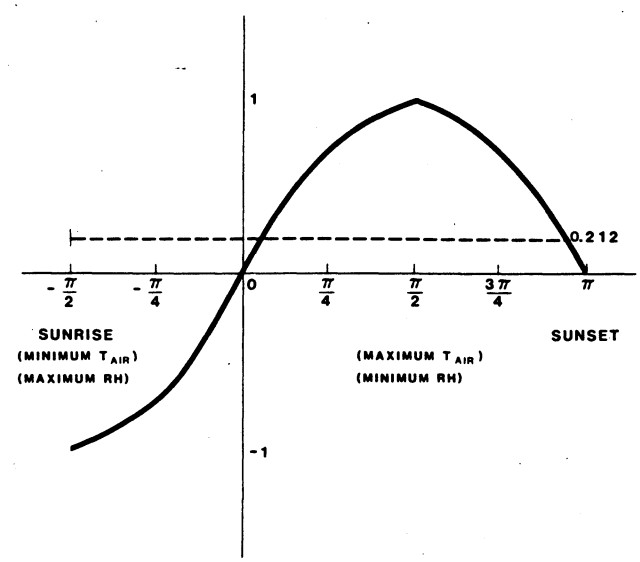

FIG. 3. The sine wave used to approximate daylight average temperature.

for conifer stomatal opening, transpiration, and positive net photosynthesis that we define to describe the operational environment of trees (Jarvis and Leverenz 1983). This threshold radiant energy value can easily be changed for different types of vegetation and produces an operational day length approximately 0.85 × physical day length. A clear sky radiation trace can be approximated by two quadrants of a sine wave which, when integrated, estimates daily average radiation equal to 0.707 × maximum radiation at solar noon (Fig. 2).

Air temperature

Daylight average air temperature is estimated by assuming the diurnal temperature trace to be a sine form, with the maximum and minimum points given by data from the base station (Fig. 3). Integrating the sine function over three quadrants (Parton and Logan 1981) yields the following equation for daylight weighted average air temperature:

[1] $T_{avg} = 0.212(T_{max} - T_{mean}) + T_{mean}$

which can be reduced to

$$T_{avg} = 0.606T_{max} + 0.394T_{min}$$

where

T_{avg} = weighted average daylight air temperature

T_{mean} = arithmetic mean $(T_{max} + T_{min})/2$ for a day

To test whether the sine form weighted air temperature (T_{avg}) is a more accurate measure of daylight air temperautre than the normally used arithmetic mean average air temperautre (T_{mean}), 120 days of hourly measured meteorological data from the Fraser Experimental Forest, Colorado, were used as a benchmark. Regressions of the T_{avg} and T_{mean} data against the hourly averaged daylight air temperatures were calculated and found to be

$$T_{ha} = -1.14 + 1.12T_{avg} \qquad R^2 = 0.93,\ n = 120 \text{ days}$$

and

$$T_{ha} = 0.74 + 1.20T_{mean} \qquad R^2 = 0.88,\ n = 120 \text{ days}$$

where

T_{ha} = hourly averaged daylight air temperature

The sine form weighted average more closely approximated the benchmark hourly averaged daylight air temperature as evidenced by a higher correlation coefficient and a slope closer to 1.0.

Daylight average air temperature is then corrected for elevation using a general lapse rate of $-6.0°C\ km^{-1}$ during the winter and $-7.0°C\ km^{-1}$ for summer, reduced by 10% on clear days, and increased by 10% on cloudy days (Finklin 1983). This lapse rate is less than the measured -7.0 to $-9.0°C\ km^{-1}$ lapse rates for western mountains (Baker 1944; Finklin 1983) because we are calculating daylight *average*, not maximum temperatures as is commonly done. The classification of clear and cloudy days is based on the ratio of potential to actual radiation as computed by the model. Days that have ratio values less than 0.5 are treated as cloudy. The ratio of slope to flat surface radiation computed in the radiation submodel is used as a multiplier to adjust air temperature for differences among slopes receiving different radiant energy inputs. This simple approach increases the air temperature on a south-facing slope and decreases temperature on a north-facing slope relative to a flat surface at that elevation. However, the magnitude of the temperature differential is a function of the characteristics of the energy exchange surfaces of the slopes (McNaughton and Jarvis 1983). Bare slopes can have maximum surface temperature differentials exceeding 10°C (Parker 1952), but closed canopy forests may exhibit virtually no slope related differences in surface temperature when the surface is an actively transpiring canopy (Kaufmann 1984; Sader 1986). Consequently, the predicted temperature is adjusted by a multiplier based on the leaf area index (LAI) of the study site. For example, if a south-facing surface of LAI = 1.0 receives twice the incoming radiation of a flat surface, air temperature is increased by 2.0°C, but the same site with a LAI = 5.0 would have no temperature increase. The temperature calculation is written generally as

[2] $T_{site} = T_{avg} \times f(\text{ELEV}) \times f(\text{SLOPE/FLAT}) \times f(\text{LAI})$

where

T_{site} = final calculated site temperature, °C

T_{avg} = Base station daylight average air temperature, °C

$f(\text{ELEV})$ = elevational lapse rate correction, $°C\ km^{-1}$

$f(\text{SLOPE/FLAT})$ = ratio of slope radiation to flat surface radiation

$f(\text{LAI})$ = site leaf area index correction, $°C\ LAI^{-1}$

Because NWS temperatures represent screen height (1.4 m) conditions, this logic will not calculate bare surface conditions well. However, evergreen canopies approximate screen height air temperatures because of the efficient turbulent mixing and vertical depth of the canopy energy absorbing surface (McNaughton and Jarvis 1983; Denmead and Bradley 1985).

Night average air temperature is estimated as the mean of daylight average and night minimum air temperatures.

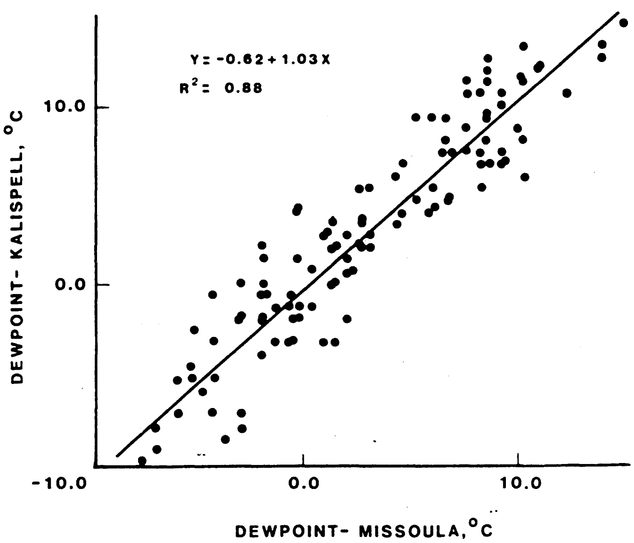

FIG. 4. The relationship between dew point measured at the Missoula airport and the Kalispell airport 250 km away, for 204 days from April to November 1983, as a test of regional equivalence of daily absolute humidity.

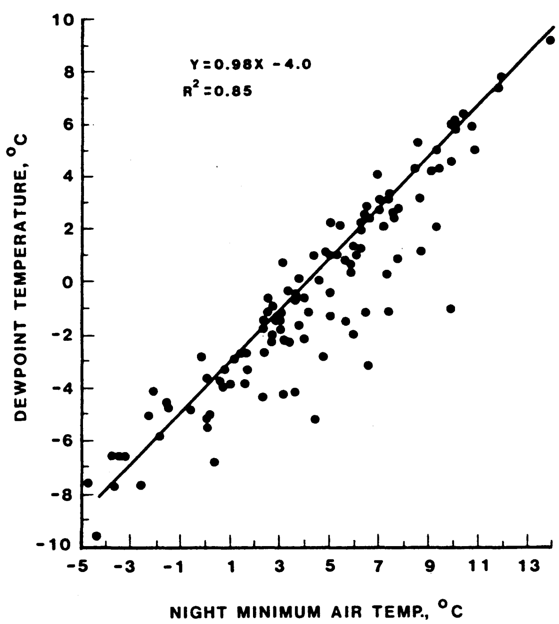

FIG. 5. The relationship between dew point and night minimum air temperature found for year days 65–299 in 1984 at Lubrecht Experimental Forest in western Montana. This test was done to determine how accurately dew point can be estimated from night minimum temperature if humidity data is not available.

Humidity

Primary NWS stations record dew point daily, providing a convenient starting point for humidity calculation. We assume dew point to be constant for the daylight period (Kaufmann 1984), and have found dew point to be relatively constant spatially on any given day over a relatively large area, giving us confidence in horizontal extrapolation of this humidity measurement (Fig. 4). Obviously, relative humidity is not constant over large areas because of temperature differences. If dew point data are not available, which is common, we assume the night minimum temperature to be equal to the daily dew point. We tested the relationship between night minimum temperature and dew point with two data sets, Lubrecht Experimental Forest 1984, shown in Fig. 5, and with Missoula NWS data for 204 days during the April–November period in 1983 (not shown). Results from the Missoula NWS data were nearly identical to the results from Lubrecht in Fig. 5, $R^2 = 0.88$, slope of 0.88°/°C and Y-intercept of 0.47°C. This logic deteriorates in arid environments where dew point is not reached regularly, yet even in central Montana a sufficiently strong relationship exists between night minimum temperature and dew point (Fig. 5).

Dew point, either measured or estimated from the base station, is then corrected for an elevational lapse rate of $-1.25°C\ km^{-1}$, modified slightly as a function of radiation load (Finklin 1983).

Finally, the estimated dew point for the site is combined with the estimated air temperature, to derive daylight averages of relative humidity, vapor pressure deficit, and absolute humidity deficit using equations of Murray (1967).

Precipitation

Precipitation in mountainous terrain is highly variable in both timing and duration, and we felt a mechanistic submodel at daily resolution was not possible within the scope of this work (Finklin 1983). As a simple alternative, we first calculate a ratio of annual precipitation of the site:base from annual isohyet maps for Montana. This site:base ratio is multiplied by the measured base station precipitation whenever daily precipitation occurs to provide an estimated daily precipitation for the study site. We did not attempt to validate this subroutine.

DAYTRANS/PSN

One purpose of MT-CLIM is to provide a meteorological data base to drive ecosystem process models such as DAYTRANS/PSN, a daily resolution model of a tree water balance developed over the last 10 years (Waring and Running 1976; Running 1984*a*, 1984*b*), coupled with the photosynthesis equations in FAST-P, a model of conifer gas exchange developed by the Swedish Coniferous Forest Project (Lohammar et al. 1980). DAYTRANS/PSN first calculates a hydrologic mass balance for a stand or single tree, including precipitation and snowpack inputs and surface runoff, evaporation, transpiration, and groundwater seepage outputs. From this soil water balance a measure of leaf water potential is derived. The average leaf conductance (k_l) of the canopy is calculated with controls by leaf water potential, incoming shortwave radiation attenuated through the canopy, humidity, and air temperature, including a special frost reduction (Running 1984*b*). Transpiration is calculated using the Penman–Monteith equation with the aerodynamic resistance fixed at $r_a = 5.0\ s\ m^{-1}$ and the radiation component divided by projected LAI to approximate radiation absorption through a multilayered canopy.

The photosynthesis routine combines the CO_2 concentration difference between ambient air and leaf mesophyll with a radiation and temperature controlled mesophyll conductance and the stomatal conductance generated by DAYTRANS (Lohammar et al. 1980). Net daily photosynthesis is calculated by subtracting a temperature-controlled night respiration component from the daylight net photosynthesis (Emmingham and Waring 1977). Further documentation is available in Running (1984*a*, 1984*b*) and Lohammar et al. (1980).

To compare microclimate effects on gas exchange processes, a "standard tree" was modeled that was identical for all sites. This tree was 10 m tall with LAI = 6.0 and 28.6 cm of available water in the rooting zone. Physiological parameters were developed primarily from work on *Pseudotsuga menziesii* in Oregon (Running 1976) and *Pinus contorta* in Colorado (Running 1980). DAYTRANS/PSN was initialized with snowpacks measured at the time meteorological data collection began. The snowpack water equivalents and date of measurement were as follows: Ambrose N = 14.6 cm and Ambrose S = 7.3 cm on yearday (YD) 91, Schwartz N = 37.6 cm and Schwartz S = 0 cm on YD 91, Ninemile N = 0 cm and Ninemile S estimated soil moisture depletion of 7.1 cm at the initiation of the simulation on YD 149 (Table 1).

Study sites

To test the accuracy of the MT-CLIM calculations, three paired north–south slope study sites in western Montana were chosen that were separated horizontally by 90 km around the Missoula airport, used as the base station (Table 1). Each site was at least 500 m above the base station elevation. Each pair of north and south facing slopes has a

TABLE 1. General characteristics of the study sites

Site	Aspect (deg.)	Slope (%)	Elevation (m)	Distance to base (km)
Ambrose				
N	350	40	1830	48
S	195	50	1830	48
Ninemile				
N	330	40	1700	39
S	170	50	1700	39
Schwartz				
N	40	40	1525	32
S	190	55	1525	32
Missoula Base Station	0	0	972	0

common ridgeline and represents the logical extremes of microclimate conditions for the area. The sites were all old clear-cuts regrown with complete vegetation cover of shrubs and young conifers. On each site a Stevenson screen was mounted 1.4 m above the soil surface approximately 200 m below the ridgeline on each slope side. All six sites were instrumented with electronic air temperature and humidity sensors recording hourly on either Omnidata Datapods or Campbell CR-21 digital dataloggers. On either the north or south slope of each pair a pyranometer and tipping bucket rain gauge were installed with output recorded hourly by the datalogger.

Data collection commenced when spring snowmelt allowed us to reach the sites: on March 31 at Schwartz, April 1 at Ambrose, and May 25 at Ninemile. We attempted to initiate data collection at the beginning of physiological activity of the trees, which we felt was critical for defining the total operational growing season of trees on these sites. Meteorological data collection continued until October 25 on all sites, at which point night temperatures were regularly below freezing, a threshold that terminates gas exchange in conifers (Tranquillini 1979, Graham and Running 1984).

Data analysis was conducted in three phases. First, hourly data from the dataloggers were summarized to daily average air temperature, incoming shortwave radiation, and relative humidity for each of the six study sites. To integrate these data to a more complete measure of relative slope microclimate differences, potential evapotranspiration was calculated for each site using the Penman–Monteith equation. A conifer forest with a dry canopy of stomatal resistance fixed at a minimum 500.0 s m^{-1}, and aerodynamic resistance fixed at 5.0 s m^{-1} was defined as the energy exchange surface. A particularly useful analysis of the concept of potential evaporation can be found in Lee (1978). He illustrates that potential evaporation is conceptually meaningless unless defined for a specific surface with given energy and mass exchange characteristics.

Second, we ran MT-CLIM daily for the summer for each of the six sites, using the Missoula airport NWS records as the base station. The measurements of daily averaged temperature, radiation, and humidity from the six sites were compared against estimated conditions from MT-CLIM for each day of the summer period using simple linear regression analysis of predicted data versus observed. Finally, we ran paired DAY TRANS/PSN simulations for each site, driving the model first with the field measured data and second with the MT-CLIM estimated meteorological data to test the erosion in accuracy that would occur from substituting estimated data for measured data.

Results and discussion

Site microclimates

The three sites with north–south slope pairs were chosen to represent easily comparable extremes in local microclimate for testing the versatility of MT-CLIM. Table 2 summarizes the relationships between air temperature, incoming shortwave radiation, and relative humidity measured on each study site and those variables predicted by MT-CLIM. These seasonal averages incorporate ranges of daily air temperature from −10.5 to 36°C and relative humidity from 13 to 100%. The seasonal microclimates of the three sites were very similar and illustrate that topographically induced changes in microclimate on one mountain slope can be equal in magnitude to regional differences found over hundreds of kilometres. Seasonal average daylight air temperatures were very similar, less than 2.0°C different between north- and south-facing slopes despite their substantially different radiation loads. Similarly small differences in topographically related surface temperatures have been found before (Kaufmann 1984; Sader 1986). Seasonal average relative humidity differences were equally small, less than 10% in all cases between slope pairs. The Schwartz Creek site actually showed no difference between north and south slopes in air temperature or relative humidity, despite the marked difference in incoming radiation to the two slopes. These seasonal averages obscure the fact that instantaneous differences in temperature exceeding 10°C were measured between the slope pairs on hot, cloudless, still afternoons, even on the Schwartz site.

Potential evapotranspiration

The field meteorological measurements were used to calculate potential evapotranspiration (PET) on the three paired study sites. Incoming shortwave radiation was only measured on one of each slope pair, so estimates for the opposing slope were derived from ratios of potential radiation for the two slopes. Seasonal PET behaved as expected on two of the slope pairs, the south-facing slopes having 17 and 44% higher PET than the north-facing counterpart (Fig. 6). These substantial differences in PET on the slope pairs at Ambrose and Ninemile occur despite the modest differences in north-south slope seasonal air temperature and relative humidity shown in Table 2. The calculation of PET with the Penman–Monteith equation integrates the effects of air temperature, humidity, and radiation into a single measure of microclimate that more accurately describes the operational environment for tree water balances on these sites than any single meteorological variable.

However, a third slope pair, the Schwartz site, actually showed higher PET on the north slope where measured temperatures were consistently higher, reminding us that one-dimensional energy budget analyses are not always successful. Our analyses and MT-CLIM logic does not include advected energy in the horizontal dimension, the inclusion of which would require a microclimate model of much greater sophistication. The logic of MT-CLIM implies that surface PET differences should be directly proportional to shortwave energy absorption and the related increase in vapor pressure deficits. How common these exceptions are in mountainous terrain would make a useful study.

MT-CLIM validation

Figure 7 shows a comparison of observed and predicted (MT-CLIM) daily microclimate conditions, viz. air temperature, relative humidity and incoming shortwave radiation on north and south slopes at the Ninemile site. To achieve clarity of the lines on the graph 1 out of every 3 days is dropped from the data set. Results from linear regression analysis of observed and predicted seasonal average microclimate conditions for the three study site pairs are given in Table 2. For all equations comparing predicted versus observed air temperatures, the R^2 ranged from 0.88 to 0.92. Slopes of the regression equations ranged from

TABLE 2. Comparison of observed and predicted seasonal average microclimate conditions (air temperature, relative humidity, and incoming shortwave radiation) on three north–south slope study sites by linear regression analysis

	Field observed X	MT-CLIM predicted Y	SE	Slope	Intercept	R^2
		Ambrose (n = 204 days)				
Temperature						
South	11.32	10.46	0.45	0.854	0.78	0.88
North	10.63	8.92	0.44	0.83	0.07	0.89
Relative humidity						
South	57	52	13.0	0.85	3.90	0.72
North	63	61	12.0	0.79	10.6	0.67
Radiation						
South	442	431	8.62	0.75	100	0.72
North	406	392	7.98	0.73	92	0.72
		Ninemile (n = 146 days)				
Temperature						
South	13.58	13.54	0.48	0.89	1.37	0.88
North	11.89	11.96	0.48	0.87	1.58	0.89
Relative humidity						
South	58	54	15.0	0.77	9.25	0.68
North	67.5	60	15.0	0.89	−0.2	0.68
Radiation						
South	456	421	100	0.65	120	0.72
North	338	315	84.0	0.64	94	0.78
		Schwartz (n = 202 days)				
Temperature						
South	13.52	12.70	0.45	0.84	1.37	0.90
North	13.50	10.36	0.44	0.80	−0.5	0.92
Relative humidity						
South	58	50	1.36	0.82	2.26	0.63
North	57	59	1.34	0.79	14	0.65
Radiation						
South	418	423	8.54	0.71	124	0.60
North	364	387	7.8	0.715	127	0.62

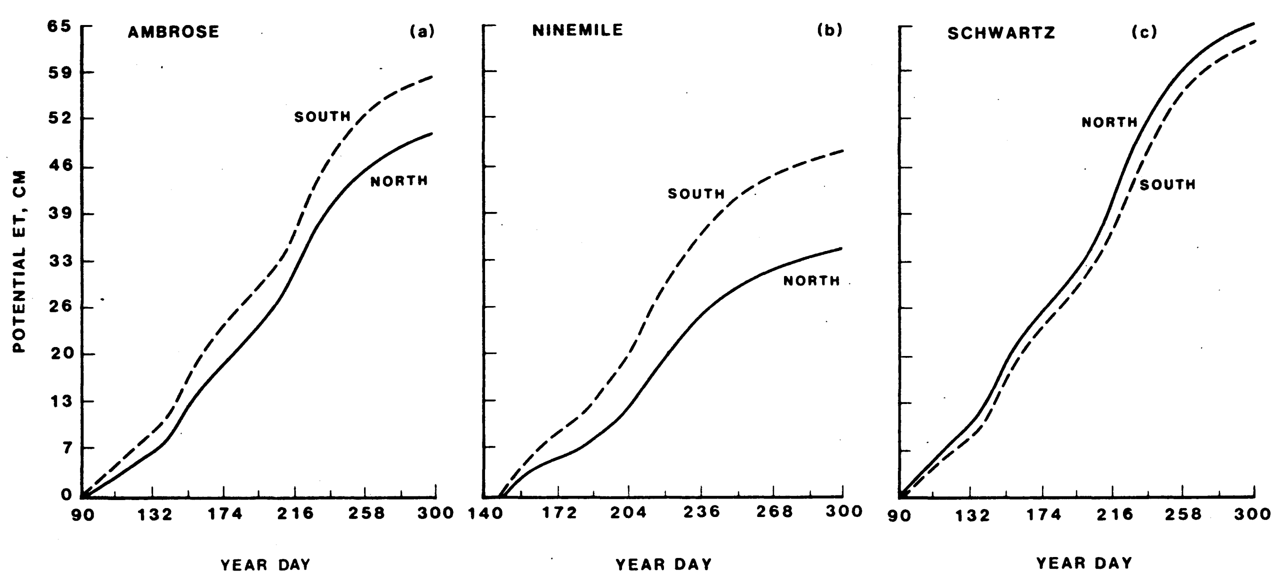

FIG. 6. Potential evapotranspiration, calculated using the Penman–Monteith equation, from surface parameters defined in the text and meteorological data measured on the three north–south slope study pairs in 1983.

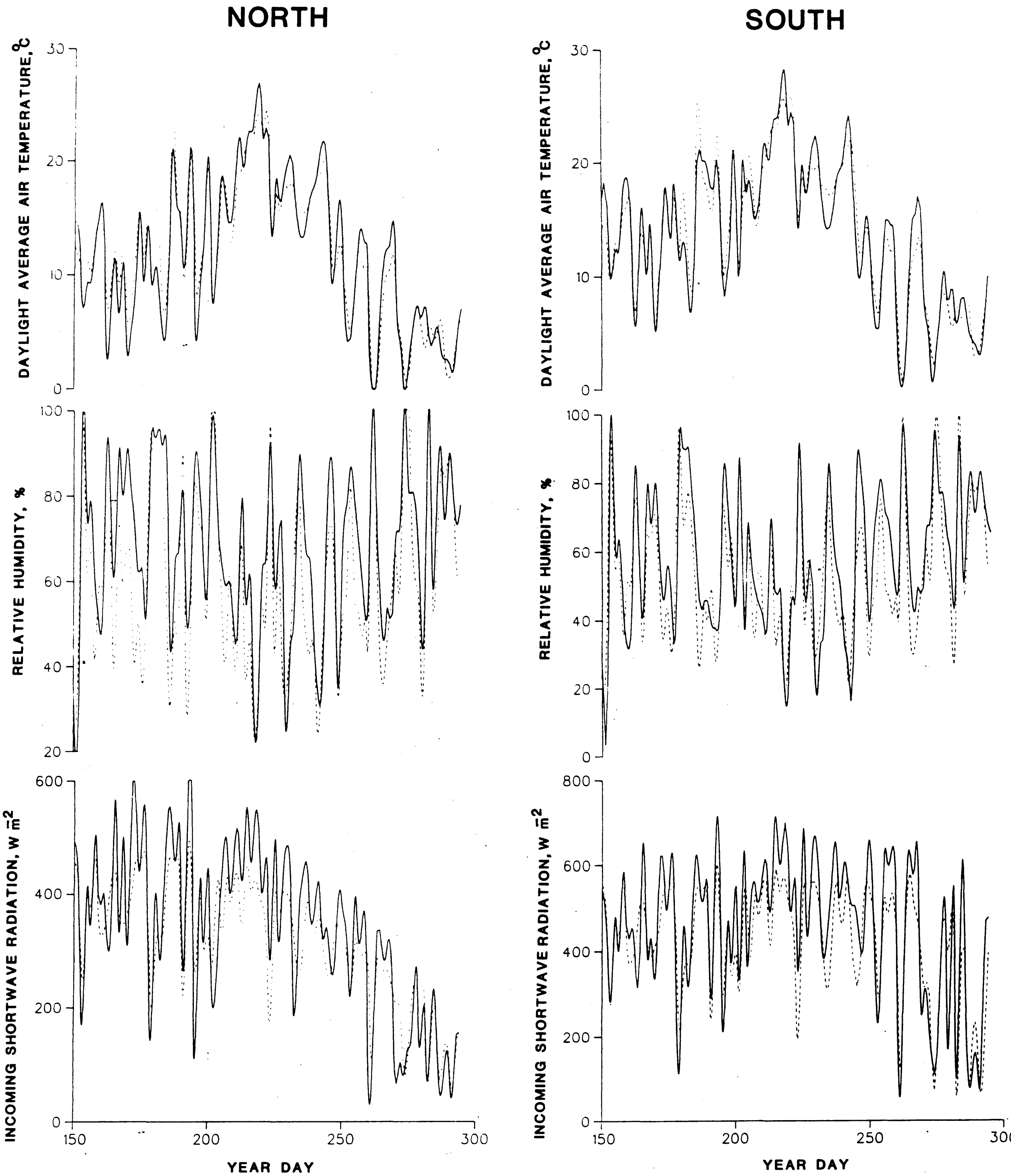

FIG. 7. Comparison of observed (—) and MT-CLIM estimated (---) daily microclimate conditions: daylight average air temperature, relative humidity, and incoming shortwave radiation on north and south slopes at Ninemile study site.

0.80 to 0.89 with Y-intercepts from −0.5°C to 1.58°C. Best prediction of observed seasonal average air temperature was −0.04° at Ninemile South and the worst, −3.14° at Schwartz North (Table 2). A small but consistent bias of overestimating low temperatures and underestimating higher temperatures is evident in these statistics and is caused by the lapse rate chosen. Various lapse rates were used and we chose the best compromise, because stronger lapse rates would cause greater error at high temperatures (>20°) but smaller lapse rates would cause greater error below 20°. However, the standard errors of the temperature estimates were always less than 0.48° for all six sites.

Predictions of humidity were similar because of the influence

TABLE 3. DAYTRANS/PSN calculations of seasonal ecosystem processes, comparing driving meteorological variables derived from field measurements and MT-CLIM estimates

	Evapotranspiration (cm)		Leaf Water Potential (−MPa)		Photosynthesis (mg CO_2/cm^2)	
	Field	MT-CLIM	Field	MT-CLIM	Field	MT-CLIM
Ninemile						
N	42	43	7.3	8.5	77	80
S	40	40	16	16	62	65
Ambrose						
N	59	56	10	7.3	109	107
S	61	58	13	11	106	102
Schwartz						
N	58	58	13	6.6	93	114
S	52	52	16	16	79	87

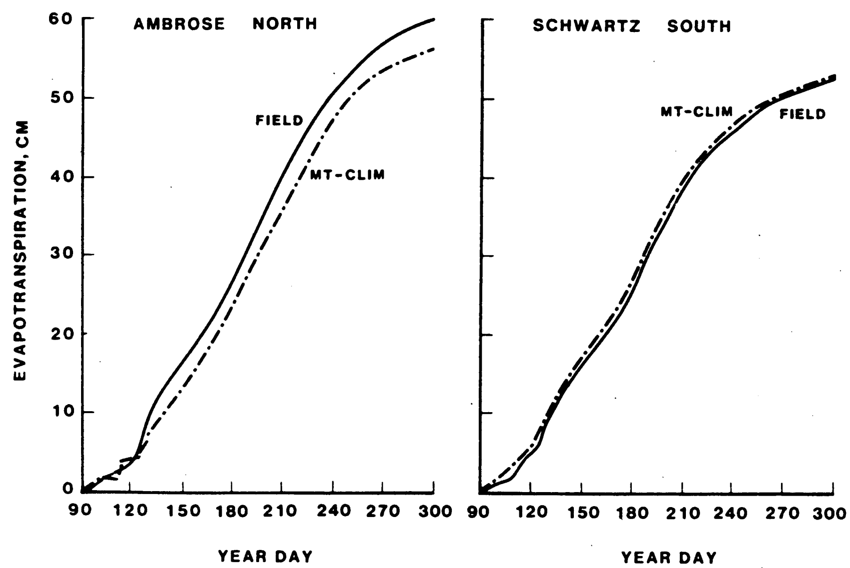

FIG. 8. Actual evapotranspiration calculated by DAYTRANS/PSN for the Ambrose north and Schwartz south sites for 1983, using measured snowpacks for initial conditions and comparing meteorological data measured on site against data estimated by MT-CLIM. These two sites were chosen to illustrate the best and the worst MT-CLIM prediction capability.

or air temperature on relative humidity, with all slopes between 0.77 and 0.89 and all intercepts above the origin. Overprediction at low values was the result of underpredicted air temperatures on warmer days when humidity is low. Conversely, overpredicted cool air temperatures caused underpredicted humidities on days of high relative humidity. Correlations were lower than for air temperature, with R^2 values between 0.63 and 0.72. We attribute the lower correlations to random errors associated with comparing results from different humidity sensors, which are much less dependable than temperature or radiation sensors. However, once again the standard errors never exceeded 15% RH.

Estimates of seasonal average site radiation were all less than 35 W m^{-2} from observed conditions, and the standard error of daily estimates averaged less than 100 W m^{-2} for the six sites. However, radiation was overpredicted on cloudy days and underpredicted on clear days. Better accuracy was achieved by Bristow and Campbell (1984), who were predicting daily radiation for the same site where temperature data were taken. We used base station temperatures to estimate atmospheric conditions in mountains removed both horizontally and vertically from the base location. A logical remedy would be to use estimated site temperatures to estimate radiation, but a circular logic prevents us from calculating final site temperatures without first calculating incoming radiation.

DAYTRANS/PSN simulations

To determine the adequacy of the MT-CLIM meteorological estimates, we ran the DAYTRANS/PSN model first with the site-measured data and then with the estimated meteorological data, and compared results (Table 3; Figs. 8, 9). We chose accumulated seasonal evapotranspiration, minimum predawn leaf water potential (as a measure of soil moisture depletion and tree water stress), and seasonal total photosynthesis as key ecosystem variables for comparison.

The calculation of ET using the predicted meteorological data never deviated by more than 5% from the calculations using measured conditions from each site (Table 3, Fig. 8). Seasonal PSN was calculated to within 5% of the values using the measured meteorological data sets at the Ambrose and Ninemile

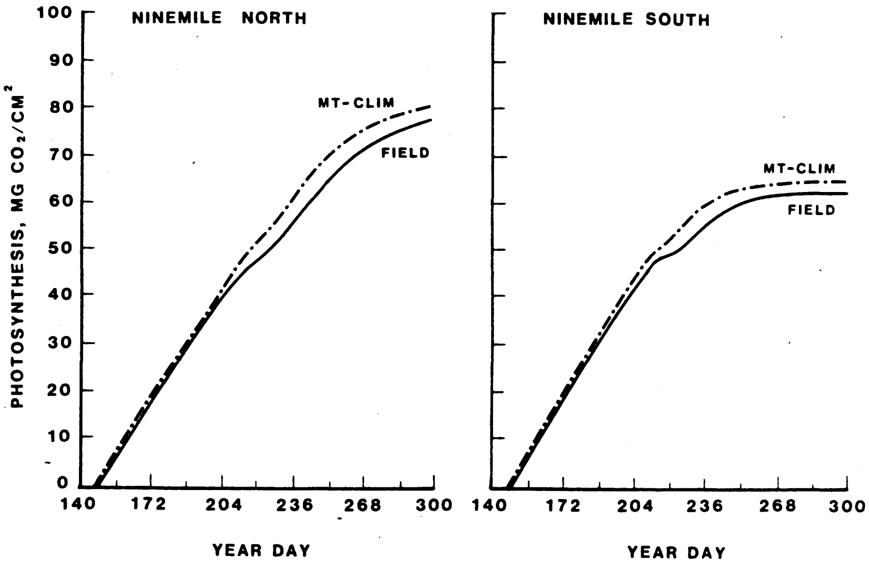

FIG. 9. Seasonal photosynthesis calculated by DAYTRANS/PSN for the two Ninemile sites for 1983, comparing meteorological data measured on site against data estimated by MT-CLIM.

sites (Table 3, Fig. 9). Photosynthesis at the Schwartz site was miscalculated by 10% on the south slope, and 22% on the north slope. Air temperature on the north slope had been underestimated by over 3°, and on the south the error in both temperature and humidity was rather large (0.82° and 8% RH), discrepancies definitely large enough to effect ecosystem processes to the magnitude calculated.

The trajectory of accumulating ET and PSN reflects seasonal changes in leaf gas exchange efficiency in this climate (Figs. 8, 9) (Running and Nemani 1985). In early spring, gas exchange is limited by cold air temperature, during May–July the water–temperature–radiation balance is optimum, and by late summer water stress, progressively colder temperatures, shorter day lengths and lower sun angles all contribute to slower gas exchange. In all cases the MT-CLIM driven DAYTRANS/PSN simulations correctly reproduced these seasonal changes in trajectory of ET and PSN accumulation (Figs. 8, 9).

Absolute validation of these ET and PSN estimates would be very difficult and expensive, yet indirect evidence shows that these calculations are reasonable. Thirty-year averages of precipitation compiled by the USDA Soil Conservation Service, Bozeman, MT (unpublished) extrapolated to the Schwartz and Ambrose sites estimate annual precipitation of 76 cm. DAYTRANS/PSN calculated ET ranging from 52 to 61 cm, or 68 to 80% of precipitation, a reasonable hydrologic partitioning for this semiarid region. Open pan evaporation estimates (always higher than ET) in the adjacent valleys average 80–90 cm annually.

The MT-CLIM driven estimates of seasonal PSN on the three slope pairs suggest the north slopes produce 5–31% higher PSN than their south slope equivalent (Table 3). If one assumes that seasonal PSN is related to long-term net forest productivity, these predictions appear to be reasonable. Tesch (1981) found a 40–60% north slope in western Montana to have 34.3% higher stand basal area of mature *Pseudotsuga menziesii* forest than the opposing south slope stand. On a site near Schwartz we have measured stand basal area of 8.00 m^2 ha^{-1} on a south-facing slope, while the opposite north-facing stand had a basal area of 17.0 m^2 ha^{-1}. Both contained mixed species stands of *P. menziesii*, *P. contorta*, and *Pinus ponderosa* 50–70 years old.

Conclusions

MT-CLIM appears to be generally capable of estimating site microclimatic conditions to an accuracy required for models of seasonal forest ET and photosynthesis. However, many problems remain. The logic of MT-CLIM does not treat atmospheric inversions, nocturnal cold air drainage, or any wind conditions, factors that may be important for other applications. We do not know what percentage of mountainous terrain is like the Schwartz site where temperature patterns are not proportional to incoming radiation but are influenced by advection. The vegetation at Schwartz provides no clue that the microclimate is abnormal; the south slope has a lower vegetation density and a much earlier spring snowmelt than the north slope, as is typical in this region. We consider daily conditions to be the shortest time period that the logic of MT-CLIM is appropriate.

Even if the logic in MT-CLIM were perfect, we are disappointed by the low density of primary weather stations that report cloud cover and humidity conditions, 8 in the entire state of Montana, or a density of 1 station per 100 000 km^2. The lack of true radiation data even from these few primary weather stations compounds problems. We plan next to explore augmenting MT-CLIM with data from the meteorological satellites for surface climate estimates. Satellite data provide complete spatial coverage, although at a scale of 1–4 km^2 depending on the sensor used (Yates et al. 1983). Surface temperatures and net shortwave radiation can be estimated roughly equally in accuracy to MT-CLIM under ideal conditions (McMillin and Govindariju 1983; Brakke and Kanemasu 1981). Direct satellite imagery might be able to discriminate temperature anomalies such as those as Schwartz correctly, which MT-CLIM could not. However, cloud cover impairs satellite data accuracy. Also, the larger scale of satellite estimates may necessitate interpolation of data from 1 to 25 km^2 averages to more localized sites.

We see tremendous utility for topographically detailed meteorological data expressed over large spatial scales. Questions of global climate change (Manabe and Weatherald 1980) and global vegetation dynamics (Justice et al. 1985) may be better analyzed with meteorological data aggregated from smaller areas. Regional estimates of crop productivity (Band et al. 1981), hydrologic balances and ET (Gardner 1983), or snowmelt and watershed discharge can be calculated more accurately if the spatial variation of meteorological conditions can be quantified. At local scales, topographic variability of photosynthesis and transpiration are capabilities that are being pursued (Hasler 1982; Segal et al. 1985).

However, it is difficult to validate estimates of variables over large areas. Validation of MT-CLIM for specific study sites as done in this paper is rather routine. But validation of the surface temperature and radiation of an entire watershed could not easily be done with normal surface instrumentation. Likewise, validation of processes like ET and PSN of large areas is impossible; integrating variables like vegetation leaf area index and primary productivity, or watershed discharge are necessary (Gholz 1982).

In forestry, research has progressed recently on the calculation of potential forest productivity or "biophysical site quality" (Lee and Sypolt 1974; Tajchman 1984; Giles et al. 1985; Running 1984*a*). All these approaches to forest site quality analysis are driven by site microclimate derived in various ways. We feel that future advances will require the extrapolation of surface microclimates that MT-CLIM and satellite coverage provide, coupled with simulation models of important ecosystem processes of ET and PSN such as available in DATRANS/PSN.

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