Estimating the Spatial Variability of Weather in Mountain Environments

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Models of crop and soil systems are useful tools for understanding the complexity of the soil-plant-atmosphere continuum. Their application, however, is limited by the availability of weather data that drives the processes described in such models. In this study, we describe a process-based interpolation model being developed for estimating maximum and minimum temperatures, precipitation, and solar radiation in mountain environments. The model is parameterized with data obtained from three weather stations set along an altitudinal gradient of 3020 to 3590 m above sea level in the La Encañada watershed near Cajamarca, Peru. Using an independent data set from a fourth station within the same watershed, we show that model estimates for daily maximum and minimum temperatures agreed well with observed data. The accuracy of model estimates for precipitation and solar radiation is still being evaluated.

Plant growth and soil-related processes are strongly influenced by weather. To simulate these processes accurately, models of crop and soil systems require weather data, which typically include daily values for maximum and minimum temperatures, rainfall, and solar radiation. Each of these variables affects, to some degree, processes such as photosynthesis, evapotranspiration, and the rate of plant growth and development, as well as soil-related processes that determine water and nutrient availability.

One of the principal limitations to these models is the lack of weather data. This is especially true in tropical mountain environments where few stations are set up to record weather data. To overcome this limitation, and to move towards the useful application of models in the analysis of production systems and natural resource management in mountain environments, we have begun to look at methods for estimating weather data inputs and their spatial variability. Estimates of the spatial variability of weather, along with its temporal variability, are needed to project spatial variation in model outputs such as yield and soil loss by erosion. Projections of spatial variation can be done in simulation studies through the use of a geographical information system (GIS) that combines spatial information on the weather with spatial information on other factors, such as crop, soil type, slope, aspect, and elevation.

Methods for estimating weather data at sites where observations are not available include extrapolation from one or two nearby points with observations, or interpolation between points with observations. A model for extrapolating weather data from a base station to adjacent mountainous

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sites has been developed and evaluated in the Rocky Mountains of the western USA (Glassy and Running, 1994). This model, however, is based on vertical (elevation-related) corrections to the base station variables, which may not give correct results for conditions in tropical mountain areas like the Andes. Interpolation schemes have also been examined in mountainous areas of the USA and Europe (Thornton et al., 1997; 2000), but these have been done with a larger number of stations placed across a denser network than one finds in the Andes or other tropical mountain areas.

The paucity of weather data in the Andes led us in 1995 to begin a study to obtain weather data along an altitudinal gradient that would be useful for evaluating different weather-estimation schemes. The study area is within a benchmark site established by the Consorcio para el Desarrollo Sostenible de la Ecorregión Andina (CONDESAN), located in the La Encañada watershed near Cajamarca in northern Peru. Sufficient data have now been collected to begin the evaluation of different estimation schemes, including the development of a model for spatial interpolation of extreme temperatures and solar radiation (Baigorria and Bowen, 2001). In this paper, we provide a description of weather variability recorded in the La Encañada study, as well as a preliminary analysis of procedures for estimating daily maximum and minimum temperatures.

Materials and Methods

Since 1995, three weather stations have been recording daily values for maximum and minimum temperatures and precipitation along an altitudinal gradient in the La Encañada watershed: (1) Manzanas (3020 m above sea level), (2) Usnio (3260 m), and (3) La Toma (3590 m). The greatest distance between stations is about 7 km, which is the distance between the Manzanas and La Toma stations. The Usnio station has been recording daily values since 1983, when it was set up by ADEFOR, a local nongovernmental organization. The Manzanas and La Toma stations were set up to record daily temperatures and precipitation at the beginning of 1995. At the end of 1998, we replaced the temperature-recording charts and rainfall gauges at all three sites with automatic recording stations equipped with a data logger and sensors (Davis Instruments, Davis, CA, USA) for measuring daily maximum and minimum temperatures, rainfall, global solar radiation, relative humidity, wind speed, and wind direction.

By the end of 2000, we had 18 years of daily records for extreme temperatures and precipitation at the Usnio station, including two years (1999-2000) of daily solar radiation data. For the other two stations, Manzanas and La Toma, there were six years of recorded weather data, including two years of daily solar radiation data.

The weather data collected in La Encañada are being used to develop an interpolation model for estimating maximum and minimum temperatures and solar radiation in complex terrain. Although only the general concepts of the model are described here, more details on a prototype of the model are available in Baigorria and Bowen (2001). Basically, the model, as it has been constructed for La Encañada, is built upon a GIS that integrates information from the three weather stations with a digital elevation model (DEM) containing information on latitude, elevation, slope, and slope aspect. The outputs from the model are presented in raster format with a cell size controlled by the DEM (30 by 30 m), provided by De la Cruz et al. (1999).

The model framework for interpolating temperature extremes and solar radiation across the landscape is based, not on statistical interpolation of measured values, but rather on fundamental relationships between net flux of radiation at the earth's surface, temperature, land-surface characteristics, and topography. Temperature extremes are estimated as a function of net radiation and solar radiation as a function of temperature and atmospheric conditions. Interpolation is used to parameterize the model using measured data from the three stations. After parameterization, the model then calculates temperature extremes and solar radiation for each grid cell, taking into account the elevation, slope, and aspect, as well as the effective horizon. The effective horizon defines how a landform opposite the given slope affects the number of hours that the sun can be seen from the slope.

To evaluate the accuracy of the weather-interpolation model with independent data, we installed portable automatic weather stations at five additional sites within the watershed. These stations, which were installed during December 1999, record daily temperature extremes and precipitation but not solar radiation. They are distributed at elevations varying from 3250 to 3500 m above sea level. Because all sites provided similar results, model comparisons for temperature estimations are shown for only one of the independent data sites, Calvario (3250 m; 7.085°S, 78.343°W).

Results

A predominant characteristic of climate in the La Encañada watershed is illustrated by the monthly means shown in Table 1. That is, temperature falls and rainfall increases with increasing elevation. For maximum temperatures, the annual average decreases from 16°C at Manzanas (3020 m) to 14°C at Usnio (3260 m) to 11°C at La Toma (3590 m). Absolute trends are smaller for minimum temperatures: the annual average decreases from 6°C at both Manzanas and Usnio to 3°C at La Toma. In Figure 1, a comparison of daily temperature extremes recorded during 1999 also shows more pronounced differences for maximum temperature among sites.

Although the annual distribution of rainfall varies somewhat, in most months, rainfall tends to increase with elevation (Table 1). The relationship with elevation is better reflected in the average annual rainfall, which shows Manzanas receiving a total

Table 1. Monthly means for daily maximum and minimum temperatures (TMAX, TMIN), rainfall (RAIN), and global solar radiation (SRAD) recorded at stations in La Encañada placed along an altitudinal gradient of 3020 m (Manzanas), 3260 m (Usnio) and 3590 m (La Toma) above sea level.[1]

Variable	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
TMAX (°C)												
La Toma	11	10	10	10	10	11	11	12	12	12	12	11
Usnio	14	15	14	14	14	14	14	13	15	15	15	14
Manzanas	17	16	16	16	15	15	16	17	16	18	18	17
TMIN (°C)												
La Toma	3	4	3	3	2	3	2	3	3	4	3	3
Usnio	6	7	6	6	6	6	5	5	6	7	6	6
Manzanas	7	7	7	7	5	4	4	5	6	7	6	8
RAIN (mm)												
La Toma	92	139	99	74	46	56	20	13	57	52	73	133
Usnio	92	107	110	70	43	21	9	11	40	65	72	75
Manzanas	55	140	105	73	36	17	3	20	41	50	69	43
SRAD (MJ m^2/d)												
La Toma	19	15	18	18	16	18	19	20	19	22	20	20
Usnio	20	16	18	17	15	18	19	22	19	22	16	18
Manzanas	16	17	19	16	16	17	19	21	17	21	22	20

[1] Manzanas (7.118°S, 78.310°W); Usnio (7.089°S, 78.316°W); La Toma (7.062°S, 78.282°W).

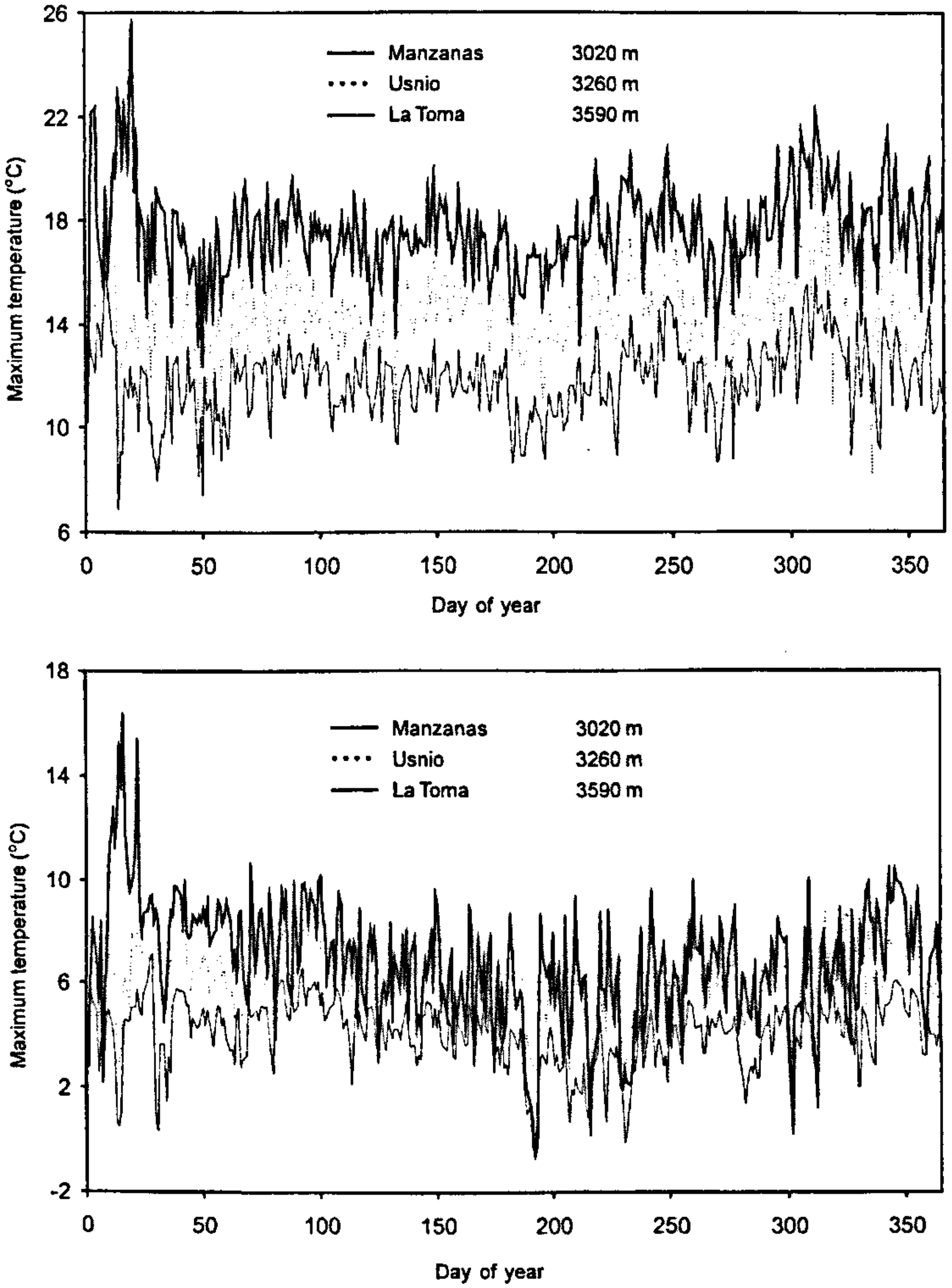

Figure 1. Daily maximum and minimum temperatures recorded during 1999 at three stations located along an altitudinal gradient in La Encañada, Peru.

of 652 mm, Usnio 715 mm, and La Toma 854 mm. For the watershed in general, rainfall is minimal during June, July and August. Crops grown during these months need supplemental irrigation or they will suffer from extreme water deficits.

The monthly means in Table 1 also show how at each site temperature varies little over the year, with the mean for all months being within 3°C of each other. That is, there is little temperature difference between the warmest and the coldest months. This fairly constant annual cycle is in contrast to the much larger diurnal range of temperature (the difference between daily maximum and minimum temperatures) shown in Figure 1 for temperatures recorded during 1999. In this case, the diurnal range appears to be two to three times greater than the annual range of 3°C. This is a common characteristic of climate in equatorial mountain regions (Sarmiento, 1986).

When considering methods for estimating weather data in mountain environments, we thought it appropriate to first look at the accuracy of simple procedures, such as the use of a temperature lapse rate, which is the decrease in air temperature with increase in elevation (de Scally, 1997). To obtain the La Encañada lapse rates for maximum and minimum temperature, we regressed annual means on elevation, as shown in Figure 2. The slope in the given equations represents the decrease in temperature for each meter increase in elevation above a given point. Thus, for each 100-m increase, the maximum temperature would be expected to decrease 0.93°C, whereas the minimum temperature would decrease by 0.53°C. These lapse rates are within the range of values presented for a diverse set of studies done worldwide by de Scally (1997).

Using these lapse rates and temperatures recorded at the Manzanas station during the year 2000, we then calculated daily values for maximum (TMAX) and minimum (TMIN) temperatures for a point at an elevation of 3250 m (230 m above the Manzanas station). The calculations were done simply by subtracting the difference in temperatures based on the estimated lapse rates and elevation (TMIN = 1.22°C; TMAX = 2.14°C) from daily values recorded at the Manzanas station. The point being estimated was equivalent in elevation to the Calvario station where weather data were collected on site during 2000; hence, these data served as a check on the accuracy of the estimates. A comparison of the minimum temperatures calculated from the lapse rate versus those measured in Calvario is shown in the top graph of Figure 3. The estimates of daily minimum temperature calculated based solely on lapse rate tended to be much less than the actual measured values. Although there was a significant linear relationship between calculated and measured values, the regression line was far removed from the one-to-one line.

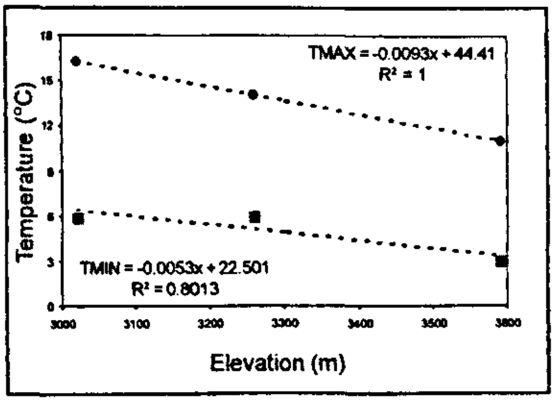

Figure 2. Linear regressions relating changes in maximum (TMAX) and minimum (TMIN) temperatures to changes in elevation (slope equals temperature lapse rate).

When the interpolation (simulation) model described earlier was used to calculate minimum temperatures, there was much better agreement between simulated and measured values (bottom graph, Figure 3). By taking into account other information provided by the DEM, specifically, slope, aspect, and effective horizon for the Calvario site, the interpolation model

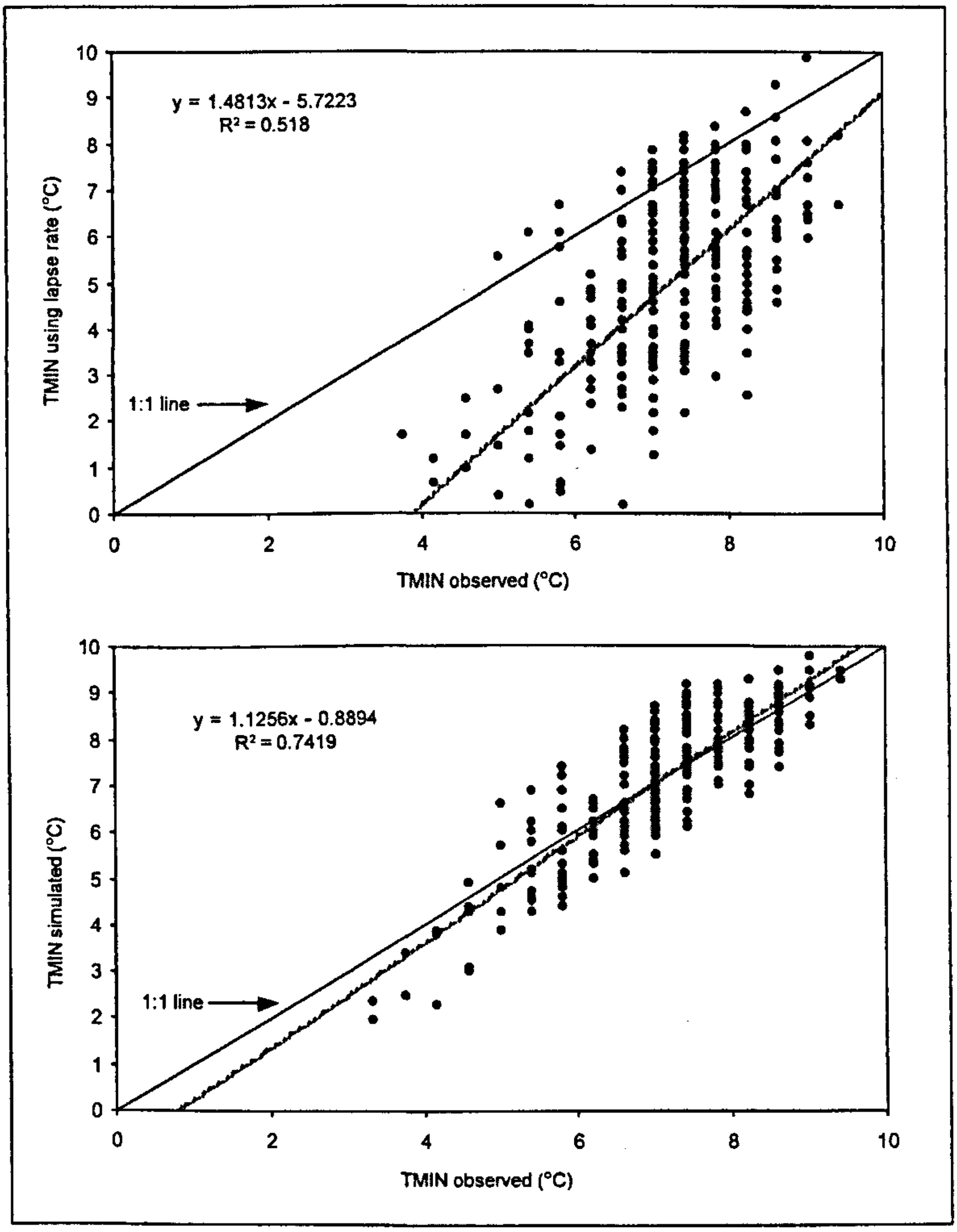

Figure 3. Relationship between minimum temperature (TMIN) observed at the Calvario station (3250 m) and that estimated using only the temperature lapse rate (top figure) or a simulation model that incorporates the effect of topographic parameters obtained from a digital elevation model (bottom figure). The broken line is the regression line and the solid line is the 1:1 line.

proved to be more accurate for estimating daily minimum temperatures.

For estimating daily maximum temperatures, differences between the lapse rate and interpolation model were less dramatic. In fact, the lapse-rate method provided slightly better results, although both methods provided good approximations to the one-to-one line, with similar scatter. The closeness of fit by the two methods is not shown here, but it can be illustrated by linear regression: whereas the equation was $y = 0.8954x + 2.94$ ($R^2 = 0.8619$) when only elevation and the temperature lapse rate were used, it was $y = 0.7693x + 3.25$ ($R^2 = 0.8261$) using the interpolation model linked to a DEM.

Discussion

A preliminary analysis of the interpolation model being developed for La Encañada indicates that it can be successfully applied to estimating the spatial variability of daily maximum and minimum temperatures within the watershed. Further analysis should focus on evaluating daily estimates for rainfall and solar radiation. The interpolation model described here has recently been expanded to include spatial estimates of rainfall based on topography and wind circulation (Baigorria et al., 2000).

A critical question for future work is how accurate such an interpolation model might be for other watersheds where only one or two weather stations exist, or where a few weather stations are spread across a larger region. In an attempt to address these questions, we have formed a partnership with the Peruvian Institute for Agrometeorology and Hydrology (SENAMHI) that includes an evaluation of the interpolation model using weather-station data from throughout Cajamarca Province.

Because few watersheds in the Andes have even one weather station, another approach we are investigating is the use of remote-sensing techniques to estimate weather data. For example, Diak et al. (2000) have validated a fairly simple process for obtaining real-time estimates of downwelling longwave radiation and incident solar radiation using data from geostationary operational environmental satellites (GOES). Dubayah and Loechel (1997) also used GOES data to estimate solar radiation and demonstrated that such estimates could also be made for complex terrain when GOES data are linked to a DEM. In the long run, satellite-based estimates may provide the most accurate and cost-effective approximations of weather data for mountain environments.

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