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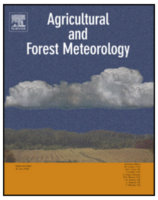

Physical controls on frost events in the central Andes of Peru using in situ observations and energy flux models

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ABSTRACT

Radiative frosts are a major hazard to agriculture in the tropical Andes of Peru, but there are very few studies of their physical controls. In this study we focus on identifying and approximately estimating the effect that physical variables have on both the downward surface longwave flux ($LW_{\downarrow}$) and the minimum temperature (T_{min}). Through a combination of case studies and statistical analysis of in situ data in the IGP Huancayo Observatory, we found that low cloud cover (CC), surface specific humidity (q), and soil moisture are key factors controlling the day-to-day variability of T_{min}, which is more pronounced in the dry/cool season. We found that all frost days had $q < 7$ g/kg in the dry season and $q < 5$ g/kg in the wet season, although it should be emphasized that q covaries with CC and soil moisture.

We successfully validated a numerical soil heat diffusion model with data from a field campaign in July 2010 and we used it, together with a radiative transfer model, to estimate the sensitivities of T_{min} and $LW_{\downarrow}$ to atmospheric and soil variables. With these results we estimated the partial contributions of these variables to the overall day-to-day variability in T_{min} and $LW_{\downarrow}$. We found that low cloud cover is the dominant factor, although specific humidity has a comparable role in the wet season. Lack of information on the cloud liquid water path is an important source of uncertainty. Enhanced soil moisture has a strong mitigating effect on frosts, although strong variability of soil moisture in the wet season could contribute substantially to the development of frosts.

1. Introduction

The Mantaro valley in the Peruvian Andes is arguably the main agricultural region in the Peruvian Andes and is the main provider of produce of Lima, the Peruvian capital. However, the agriculture is extensive, largely dependent on rainfall, and is particularly vulnerable to frosts, which can destroy the crops and are, therefore, considered the most damaging among extreme hydrometeorological events (Trasmonte et al., 2008; Trasmonte, 2009; Núñez et al., 2012). As reported by Garcilaso de la Vega (1609) in his “Comentarios Reales”, the Inca farmers predicted frosts when they observed cloudless skies at night and produced smoke as a way to mitigate the frost damage to the crops. These prediction and mitigation practices persist in rural communities in the Mantaro valley (Martínez et al., 2012), where the absence of late afternoon cloudiness has been verified to increase the probability of freezing temperatures by more than four times relative to cloudy skies (Saavedra, 2012).

The strong relation between cloudiness and minimum temperature indicates that the net radiative loss in the nocturnal surface energy balance is a key process for the occurrence of frosts in the Andes (Lhomme et al., 2007; Sanabria, 2009) and different methods have been tested to mitigate the impacts on the crops (Morlon, 1991; Lhomme and Vacher, 2002). Sicart et al. (2010) indicate that clouds increase downward longwave by up to 55% near the Zongo glacier in Bolivia. Furthermore, low clouds are expected to emit more downward longwave radiation (e.g. Geiger et al., 2003; Dai et al., 1999). Using world-wide station data, Dai et al. (1999) concluded that the land diurnal temperature range (DTR), i.e. the difference between the maximum and minimum temperature, can be reduced in 25–50% by the presence of clouds and that their spatial distribution determines that of DTR. They found a strong correlation between minimum temperature and longwave radiation, and at the same time with specific humidity, but with cloud cover the correlation was weak. On the other hand, Huang et al. (2006) used models to estimate that a cloud radiative forcing of 8.5 W m^{-2} is associated with an increase of 0.68 °C in nocturnal temperature. Studies developed in the Andes of Peru are scant. Villegas (1991) indicate that frost in Mantaro basin, in the Andes

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of Peru, is associated with clear skies and dry air. The occurrence of frost in this region is mainly between April and August, and the lowest temperatures during June and July (Instituto Geofísico del Perú, 2005).

Sanabria (2009) made use of two models (Lhomme and Guilioni, 2004; Cellier, 1993) built taking into account physical processes to model minimum temperatures. Sanabria (2009) used longwave radiation and empirical methods (Swinbank, 1963; Brutsaert, 1975), but based on their results, they recommended that measurements be made with pyrgeometers. Sicart et al. (2010) implemented a parameterization of this longwave radiation in tropical mountains using surface air temperature and vapor pressure, as well as solar radiation, to estimate the cloud effects. Although clouds are arguably the primary control on longwave radiation, the air humidity and temperature also play a role in the clear-sky emission and are key parameters used in empirical models (e.g. Lhomme et al., 2007; Sicart et al., 2010). Another physical variable that affects the minimum temperature is the soil thermal conductivity, which allows thermal exchange between the surface and the deeper layers, damping the temperature changes at the surface, and increases with the soil moisture, which implies that precipitation in previous days can prevent the occurrence of a frost event (e.g. Geiger et al., 2003).

To better understand and quantify the roles of different atmospheric variables that control the minimum temperature at a site in the Mantaro valley in the central Andes of Peru, in this study we used a combination of in situ observations with numerical 1D models. We first provide a description and climatic characterization of the region of study. Then, we present an empirical analysis of the relationship between the minimum temperatures and variables such as specific humidity, cloud cover and precipitation using long-term meteorological data. After this, we use a soil heat diffusion model and an atmospheric radiative transfer model to model the minimum temperatures at the surface and $LW_{\downarrow}$, respectively, validated with data from a field experiment. Experiments with the models are then used to assess the sensitivity of the minimum temperature and $LW_{\downarrow}$ to changes in other atmospheric variables.

2. Study area and data

All the measurements in this study were made in the Huancayo Observatory of the Geophysical Institute of Peru (IGP Observatory, 12.04°S, 75.32°W, 3350 m.a.s.l.), which is surrounded by non-irrigated agricultural land in the Mantaro valley, in the central Andes of Peru, located 12 km from the city of Huancayo and 7 km from the Mantaro river (Fig. 1), between the western Andes and the Huaytapallana Cordillera to the east, between the Pacific ocean and the Amazon. In this research, we used three kinds of data: synoptic meteorological data from the Huayao station (WMO Id 84630), data from a collocated automatic weather station and data from a field experiment in the same site. The soil consists of clay covered by short grass (2–3 cm high), partly dry due to lack of irrigation during the dry season, with a leaf area index on the order of 0.8.

Synoptic meteorological data (1973–2006) include daily minimum (T_{min}) and maximum (T_{max}) temperature, and precipitation PP (at 07 local time or LT), as well as air temperature, relative humidity, air pressure and cloud cover observed at 07, 13 and 19 LT. These variables are measured at 2 m height above the soil surface. Air temperature, relative humidity and air pressure were used to calculate specific humidity. In the subsequent analysis, the cloud cover (CC) and specific humidity (q) are considered as the mean of the 19 LT and 07 LT (next day) measurements to give an estimate of the nocturnal values. We computed the daily climatology for this data using harmonic analysis, using the first six annual harmonics, for the different measurement times. In order to quantify the variability, we calculated the interquartile range (IQR), that measures the difference between the 75 and 25 percentile and is a measure of the spread of the distribution. Additionally, the 2, 10, 25, 50, 75, 90, and 98 percentiles for T_{min}, T_{max} and q are calculated. In the case of CC and PP, we computed the monthly frequency of five categories for precipitation (0 or dry, 0–2, 2–5, 5–10, and 10–42 mm/day) and five categories for cloud cover (0 or cloudless, 0.5–2, 2.5–4, 4.5–6 and 6.5–8 oktas).

The field experiment took place in July 15–18, 2010, corresponding to the dry, cold season. We measured $LW_{\downarrow}$ with a Kipp & Zonen CGR3 pyrgeometer mounted on a 6 m tower to prevent obstacles in its hemispheric field of view. The measurements were instantaneous at approximately hourly intervals, as the pyrgeometer could not be connected to a datalogger at that time. We also used data from a collocated automatic weather station in this period, which included 2 m air temperature and relative humidity, air pressure, and wind speed measured at height of 10 m, recorded every 10 min. The sensors were a Vaisala thermo-hygrometer HMP35C (accuracy: ±0.2 °C, ±3%RH), Vaisala barometer PTB101B (±0.5 hPa) and Young wind monitor 05103 (±0.3 m/s) respectively.

We measured temperature in the soil using seven RadioShack 63-1032 indoor/outdoor digital thermometers. With the outdoor (external) sensor, the temperatures at 50, 30, 20, 10, 5, 2 cm below the soil surface and at 0 cm were measured; while the indoor sensors measured at 10, 20, 40, 60, 80, 100, and 140 cm above the surface. The temperature at 0 cm was measured with the digital thermometer placed on top of the soil surface unsheltered and

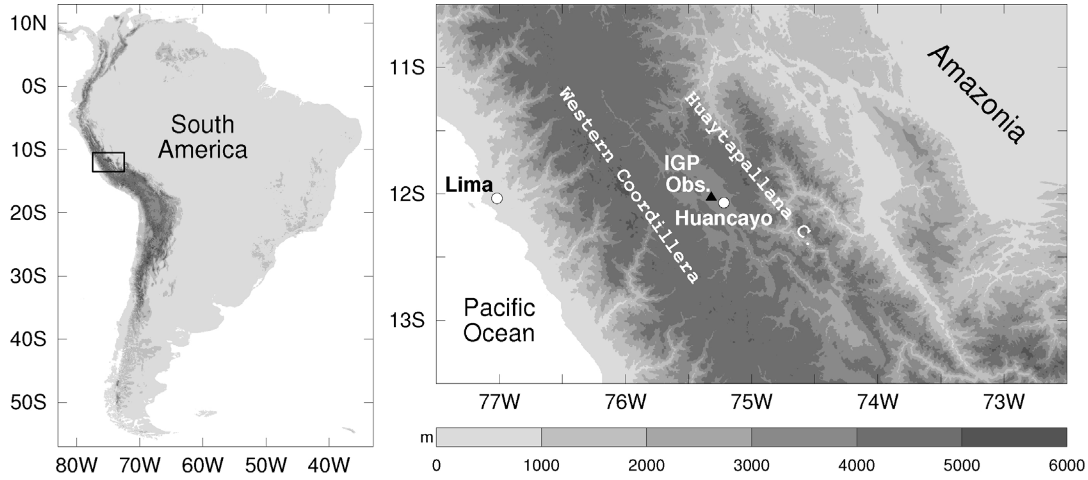

Fig. 1. IGP Observatory and topography around this location. At the East are located Huancayo city and Huaytapallana cordillera.