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Estimating downward long-wave radiation on the Andean Altiplano

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Abstract

The Andean Altiplano is a vast plateau lying at an average altitude of 4000 m above sea level, between Bolivia and Peru, and prone to radiative frost during the cropping season. Since the occurrence of radiative frost is generated by a deficit in long-wave radiation, accurate estimation of downward long-wave radiation is essential in models of frost prediction. However, most simple formulas tend to significantly overestimate this radiation in clear-sky conditions. From measurements made during two cropping seasons on two different sites on the Bolivian Altiplano, it is shown that the downward long-wave radiation can be more accurately estimated by means of an adjusted form of Brutsaert's [Brutsaert, W., 1975. On a derivable formula for long-wave radiation from clear skies. Water Resour. Res. 11, 742–744] equation, with a modified leading coefficient (1.18 instead of 1.24) multiplied by a cloudiness correction. The lower value of the leading coefficient apparently results from steeper vertical gradients of temperature and humidity in this high-altitude region. The cloud correction takes the form of a linear function of the ratio (s) between the observed magnitude of solar radiation and its clear-sky estimate, expressed as $F(s) = -0.34s + 1.37$. The formula was first calibrated on one measurement site (Condoriri) and then tested on the other site (Irpani). For daytime hours, the comparison between estimated and measured values is rather satisfactory. During nighttime hours the formula yields reasonably good estimates when the value of ratio s (not available at night) is replaced by its mean value calculated the previous day between 14 h and 16 h 30 min. Crawford and Duchon's [Crawford, T.M., Duchon, C.E., 1999. An improved parameterization for estimating effective atmospheric emissivity for use in calculating daytime downwelling long-wave radiation. J. Appl. Meteorol. 38, 474–480] cloud correction, based on the same ratio s, proves also to work fairly well under these particular conditions.

Keywords: Long-wave radiation; Andean Altiplano; Clear-sky; Cloud correction

1. Introduction

Lying between 3700 m and 4100 m above sea level, the Andean Altiplano of Bolivia and Peru is a region where radiative frosts can frequently occur during the growing season from October to April, resulting in significant losses in crop production (Le Tacon et al., 1992). Native populations, however, have been able to develop specific agricultural techniques aimed at mitigating frosts, such as the terraces and the "raised fields" (Morlon, 1991; Lhomme and Vacher, 2002) or the selection of crops and varieties resistant to low temperatures. In this context, providing reliable nocturnal temperature forecasts allows the use of active or passive methods of protection to avoid crop damage in case of frost occurrence. Various approaches have been designed to predict the minimum temperature reached during nocturnal cooling from weather data registered the day before, generally at sunset. They can be purely empirical, obtained from statistical relationships, or mechanistic, based upon physical principles

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(Georg, 1978). In the mechanistic models of frost prediction (Lhomme and Guilioni, 2004), an accurate estimate of downward long-wave radiation is essential, due to the fact that frost occurrence is generated by a deficit in long-wave radiation. The most important atmospheric gas contributing to thermal radiation is water vapor, but liquid water and ice absorb and emit long-wave radiation more effectively than water in the vapor phase. It is the reason why the cloud cover plays an important role to prevent the radiation deficit. Carbon dioxide, ozone and other trace gases also contribute to this radiation, but in a less significant way.

There exist numerous formulations to estimate the thermal radiation of the atmosphere from simple meteorological variables, such as air temperature and air humidity. Most of them operate in clear-sky conditions: Brunt (1932), Swinbank (1963), Brutsaert (1975), Staley and Jurica (1972), Satterlund (1979), Idso (1981), Berdahl and Fromberg (1982), Culf and Gash (1993), Prata (1996), Dilley and O'Brien (1998), Perez-Garcia (2004). Radiation schemes issued from numerical weather prediction models are also used to estimate thermal radiation (Niemela et al., 2001). In cloudy-sky conditions, estimating atmospheric thermal radiation is rather difficult and fewer formulas exist: Sugita and Brutsaert (1993), Alados-Arboledas et al. (1995), Crawford and Duchon (1999), Sridhar and Elliott (2002). Most of the existing formulas being empirical in nature, they should be handled with care, because they are likely to be specific to the atmospheric conditions under which they were developed.

Unfortunately, as will be shown below, the existing formulations rarely provide accurate estimates of atmospheric thermal radiation in the particular environment of the Andean Altiplano, a region where the atmospheric mass is reduced due to its high altitude and where the variation in air humidity can be very large. The objective of this study, therefore, is to derive a simple and practical formulation adapted to this particular environment and accounting for cloudiness. The paper is divided into three main sections. The first one deals with the theoretical basis used to develop the formulations. The second one describes the sites and the measurements. The last one details the resulting formulas and evaluates their performance.

2. Theory

2.1. Clear-sky formulation

In a plane-stratified atmosphere under clear-sky conditions the downward long-wave radiation at the surface is given by the following equation (Goody, 1964; Brutsaert, 1975), where subscript 0 denotes clear-sky conditions

$$\mathrm{LW}_{\mathrm{d},0} = \int_{a=0}^{a=\infty} \sigma T^4(a) \frac{\partial \varepsilon_{\mathrm{s}}(a)}{\partial a} \mathrm{d}a \tag{1}$$

σ (=5.67 × 10^{-8} W m^{-2} K^{-4}) is the Stefan-Boltzmann constant; $T(a)$ is the temperature, a function of altitude z; ε_s is the slab emissivity; the quantity $a = a(z)$ is the amount of water vapor in the air column from the surface up to level z, scaled for the pressure effect (P) and given by

$$\mathrm{d}a = \rho_{\mathrm{v}} \left(\frac{P}{P_{\mathrm{a}}} \right)^{1/2} \mathrm{d}z \tag{2}$$

where ρ_v is the water vapor density and P_a is the pressure at the surface (sea level). To compute Eq. (1) a parameterization of the slab emissivity together with the atmospheric profiles of temperature, humidity and pressure are required. Given the relative complexity of the calculation and the fact that the data required are rarely available, simplified and empirical expressions of $\mathrm{LW}_{\mathrm{d},0}$ are generally used. They take the general form

$$\mathrm{LW}_{\mathrm{d},0} = \varepsilon_0(T_{\mathrm{a}}, e_{\mathrm{a}}) \sigma T_{\mathrm{a}}^4 \tag{3}$$

where T_a is the air temperature measured at screen level and expressed in Kelvin; ε_0 is the effective emissivity of a cloudless atmosphere, generally expressed as a function of air temperature and vapor pressure (e_a) at screen level. A series of formulations for the effective emissivity of the atmosphere in clear-sky conditions (ε_0) are described in Appendix A: Brunt (1932), Swinbank (1963), Brutsaert (1975), Idso (1981), Berdahl and Fromberg (1982), Prata (1996), Dilley and O'Brien (1998). Brutsaert's formula, reworked by Prata (1996), is the only one with a theoretical background. As demonstrated in Appendix B, it is obtained directly from Eqs. (1) and (2), assuming exponential atmospheric profiles for pressure, temperature and humidity, and it reads

$$\varepsilon_0(T_{\mathrm{a}}, e_{\mathrm{a}}) = c_0 \left(\frac{e_{\mathrm{a}}}{T_{\mathrm{a}}} \right)^{1/7} \tag{4}$$

Eq. (4) will be used as a basis for our own derivation. The leading coefficient c_0 depends mainly on the attenuation coefficients involved in the exponential profiles (Eqs. (B2)–(B4)): at sea level for a nearly standard atmosphere it has a theoretical value of 1.24, with e_a expressed in hPa and T_a in Kelvin. Using measured profiles of temperature and water vapor density, Culf