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Measurement uncertainty in rainfall kinetic energy and intensity relationships for soil erosion studies: An evaluation using PARSIVEL disdrometers in the Southern Appalachian Mountains

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ABSTRACT

The increased use of observations of rainfall microphysics from disdrometers to produce more accurate rainfall kinetic energy estimates requires closer analysis of measurement uncertainty, and in particular how the type of sensor influences rainfall kinetic energy estimates in different hydrometeorological regimes. This study evaluates the performance of Parsivel[1] (P1) and Parsivel[2] (P2) in measuring rainfall DSDs (drop size distributions) in terms of rain depth (*P*), rain rate (*I*), and kinetic energy (*KE*) at three locations in the Southern Appalachian Mountains for warm season rainfall. For the same storm system, there is large spatial variability of rainfall DSDs between ridges and valleys, and between exposed upwind ridges and the inner region. Parsivel[1] measures underestimate the number of small drops, while all rainfall variables are overestimated for DSDs with a large number of drops in the midsize range (1–2 mm in diameter) for both P1 and P2. Overall, results show differences of 40% in *KE* estimates when P1 is used compared with the more recent P2. The uncertainty analysis clearly illustrates the dependence on hydrometeorological regime and the instrument proper. Relationships between rainfall *KE* and intensity (*I*) need to account for the instrumental influence towards better characterization of the rainfall erosion potential locally; and regional scale studies must include spatially distributed observations to capture the dominant hydrometeorological regimes, especially in regions of complex topography where the spatial variability of rainfall is very high.

1. Introduction

Soil erosion is one of the main causes of land degradation worldwide, especially for agricultural soil. Erosion depletes soil of critical nutrients, and significantly affects the most important ecological soil functions: food production, infiltration capacity, carbon and nitrogen storage, and the sustainability of biological habitats (Blum et al., 2006). Anthropogenic activities, such as urbanization, agriculture, and in general clearing and logging of forested areas expose and mobilize soils leading to accelerated erosion, loss of productivity and landscape change (Pimentel and Kounang, 1998; Pimentel, 2006). Robust quantification of erosion rates at the spatial scales of the dominant processes is critical for developing sustainable conservation practices and land-use planning (Pimentel et al., 1999; Bilotta et al., 2012). The Universal Soil Loss Equation (USLE or RUSLE: Wischmeier and Smith, 1958; Renard et al., 1997), an empirical relationship accounting for rainfall erosivity, erodibility, topography, land use and land cover, is the most commonly used quantitative tool to assess erosion potential and risk conditions. Because of its empirical basis, there is a great uncertainty associated with the application of the USLE to climatic regions very different from those where calibration was conducted, and long-term and up-to-date data are necessary to assess uncertainties due to climate non-stationarity.

Recent research efforts have focused on the characterization of rainfall microphysics and rainfall–soil interaction at local and regional scales (Petan et al., 2010). Raindrop impact, the key mechanism for disaggregating and mobilizing soil particles, depends on the kinetic energy of raindrops. Therefore, accurate measures of the size (mass) and velocity of raindrops are essential to determine rainfall erosivity. This is possible using instruments such as disdrometers that record raindrop size spectra, or drop size distribution (DSD). Raindrop mass is derived from the DSD diameter, while fall velocity can be measured or estimated from empirical laws relating the terminal fall velocity (V_T) and the raindrop diameter (D) (e.g., equations from Atlas et al., 1973; Beard, 1976; Atlas and Ulbrich, 1977; or reviews by Uplinger, 1981; Testik and Barros, 2007).

DSDs recorded by disdrometers are widely used in meteorological studies to describe rainfall intensity–reflectivity relationships that provide key to the estimation of precipitation from satellite based sensors (Iguchi et al., 2000; Krajewski et al., 2006; Kozu et al., 2009). The performance of disdrometers and associated measurement uncertainty have been evaluated against a plethora of rainfall sensors in terms of rain depth, rain rate, reflectivity, DSDs and velocity spectra, and wind influence especially motivated by recent satellite missions

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such as TRMM, the Tropical Rainfall Measurement Mission (Tokay and Bashor, 2010; Jaffrain and Berne, 2011; Thurai et al. 2011; Fiedrich et al., 2013; Tokay et al., 2013). In soil erosion research, pioneer use of disdrometers was undertaken by Bollinne et al. (1984) in Belgium, and Rosewell (1986) in Australia using Joss–Waldvogel disdrometers, followed by Salles et al. (1999) in Belgium and France, among others. More recently, affordable laser precipitation monitors such as Parsivel or Thies Klima have allowed the increased use of these instruments in erosion studies alongside classical splash erosion measurements (Fernández-Raga et al., 2010, Angulo-Martínez et al., 2012), and to estimate rainfall erosion potential based on kinetic energy–intensity relations (Cerro et al, 1998; Sempere-Torres et al., 1998; Petan et al., 2010). Nevertheless, critical elements of uncertainty not addressed in previous studies include the neglect of spatial variability beyond field scale, dependence on hydrometeorological regimes that is the physical basis of uncertainty, and sensor measurement uncertainty.

The present study aims at evaluating and quantifying the environmental and instrumental uncertainty associated with two versions of the optical spectro-pluviometer, Parsivel^1 and Parsivel^2 (OTT, 2008), in kinetic energy estimates measured under natural conditions in the Southern Appalachians, North Carolina, USA. In order to understand instrumental difference alone, both sensors were evaluated under laboratory controlled conditions. Data were collected in preparation for IPHEx2014 (Integrated Precipitation and Hydrology Experiment, Barros et al. 2014), a Global Precipitation Mission ground validation field campaign (GPM-GV), taking place during 2014 in the Southern Appalachians and the Southeast Region of the USA. Here, we report how the instrument error affects the relationship between rainfall kinetic energy and intensity as a function of the hydrometeorological regime towards a framework to estimate rainfall kinetic energy from intensity records independently of sensor type. Although the results shown here were obtained for two disdrometers from the same manufacturer, the focus is on the physical basis of the errors, that is error type, which is general, and thus the methodology can be applied to any sensor.

2. Methods

2.1. Experimental setup

The Southern Appalachian Mountains are characterized by complex relief but moderate orography with the maximum elevation about 2000 m.a.s.l. (Prat and Barros, 2010a). The region experiences a humid continental climate with strong orographic effects, and thus high spatial and temporal variability of rainfall often causing widespread flooding and landslides (Wooten et al., 2008; Tao and Barros, 2013, 2014). In the warm season, from spring through early fall, major weather systems include westerly mesoscale convective systems and fronts, southerly and easterly tropical depressions, and localized convective activity, and thus storm precipitation is characterized by higher intensity and shorter duration (≤24 h) compared to the cold season, when intensities are low but duration can last several days.

Prat and Barros (2010a) showed that there are significant differences in rainfall microphysics in the region, depending on the nature of the storm system and location where DSD data were collected. They showed that the right-hand side of observed valley DSDs is "heavier" than that of DSDs in adjacent ridges for the same event, suggesting enhanced drop coalescence between ridge and valley locations. Wilson and Barros (2014) observed that the diurnal cycle of light rainfall is related to the diurnal cycle of fog occurrence, "*with mid-day peaks concurrent with valley fog, and evening peaks concurrent with radiation fog*". Their detailed analysis of rain gauges (RGs), radar profilers, and disdrometers showed intermittent periods of very intense rainfall in valleys and sheltered ridge locations concurrent with dense fog and/or cap clouds, which they explained by the seeder–feeder mechanism for raindrop coalescence between small fog drops and rainfall raindrops though modelling experiments.

During the 2012 warm season (May–July), rainfall microphysical characteristics were measured at three monitoring sites in the Southern Appalachians (USA): (1) Purchase Knob (PK), in one of the ridges at the Pigeon River basin, at Haywood County (1501 m.a.s.l.), and at two sites in the French Broad at Madison County: (2) Marshall Ridge (MR) (1186 m.a.s.l.), and (3) Asheville-Buncombe Technical Community College (ABTech) in the adjacent valley (599 mm.a.s.l.) (Fig. 1). Geolocation, period of measurement and instrumentation are provided in Table 1. For further details, see also Wilson and Barros (2014).

Three Parsivel disdrometers, one Parsivel^1 (P1) and two Parsivel^2 (P2-1, P2-2), were deployed at PK early in the monitoring period (Fig. 2). A science grade network of 33 tipping-bucket RGs (Hydrological Services model TB3/0.1 with a catchment size of 282.8 mm; 0.1 mm/tip; stainless steel mechanism) has been operating in the region since 2007 (Prat and Barros 2010a). Each RG is visited approximately every two–three months for regular maintenance, clock checks, and data collection. Because the data are used to evaluate remote sensing rainfall products, RGs are rigorously calibrated in the field at least twice per year over a wide range of rainfall rates. Over a five-year period, changes in rainfall estimates between calibrations remain <2% for >95% of the network (always at PK), and <5% overall. RG data were available at PK and MR during the monitoring period, allowing comparisons against disdrometer data in terms of rain depth and rate. After the monitoring period at PK (19/05/2012–08/06/2012), the disdrometers were moved to MR and ABTech, pairing one Parsivel^1 (P1) and one Parsivel^2 (P2-1) at MR, while the other Parsivel^2 (P2-2) was placed at ABTech with the objective of documenting ridge–valley variability during the period 22/06/2012–11/07/2012. These setups allow analysis of two types of uncertainty: i) the uncertainty associated with the environmental factors governing rainfall variability at different locations (hydrometeorological regime); and ii) the uncertainty associated with the sensor proper.

The disdrometers, Parsivel^1 and Parsivel^2 (OTT, 2008) are laser optical devices which measure the size and fall speed of hydrometeors. The size categories span 32 diameter classes with uneven intervals starting at 0.25 mm in diameter up to 25 mm. Likewise, the velocity field is also composed by 32 uneven categories from 0.05 to 20 m s^{-1}, with varying velocity intervals. Details of the instruments and the measurement technique, along with the assumptions used to determine the size and velocity of hydrometeors, can be found in Löffler-Mang and Joss (2000), Battaglia et al. (2010), Tapiador et al. (2010), Jaffrain and Berne (2011) and Tokay et al. (2013). The measurement principle behind the Parsivel disdrometers is the detection of the amplitude decrease of the laser signal as a falling particle intercepts the laser beam for a certain period of time, which is translated into estimates of the size and velocity of the falling particle (Löffler-Mang and Joss, 2000). However, since the laser thickness is 1 mm and many drops have larger diameters, there is significant added uncertainty in velocity estimates. A correction for coincident particles passing at the same time through the laser is applied automatically by post-processing software provided by the Parsivel manufacturer, and the corrected observations are stored in spectral form. The operational software provided with the disdrometers determines 1-min rainfall intensity by integrating the volumes of all individual particles. It is important to briefly reference here the antecedents behind the evolution of Parsivel disdrometers. The original company, PM Tech AG, Pfinztal, Germany, sold Parsivel to OTT Hydromet, Kempten, Germany. After 4 years of operation in 2004, OTT reduced the price by using a less accurate laser, while improving calibration (Tokay et al., 2013), and as a result the Parsivel^1 (P1) disdrometer became more affordable and was acquired by many researchers. Intercomparison tests against other disdrometers and RGs made evident an underestimation of the smaller drops, while overestimation of mid-size and larger drops was suggested (Battaglia, et al., 2010, Tokay et al., 2013). OTT reviewed the Parsivel sensor and launched a new sensor, the Parsivel^2 (P2), which is relatively more