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Evaporation of impact water droplets in interception processes: Historical precedence of the hypothesis and a brief literature overview

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SUMMARY

Intra-storm evaporation depths exceed post-storm evaporation depths in the interception of rainfall on plant canopies. An important fraction of the intra-storm evaporation may involve the small impact (or splash) droplets produced when raindrops, and perhaps gravity drops (drips released from plant parts), collide with wet plant surfaces. This idea has been presented as a new conception by Murakami [Murakami, S., 2006. A proposal for a new forest canopy interception mechanism: splash droplet evaporation. Journal of Hydrology 319, 72–82; Murakami, S., 2007a. Application of three canopy interception models to a young stand of Japanese cypress and interpretation in terms of interception mechanism. Journal of Hydrology 342, 305–319; Murakami, S., 2007b. A follow-up for the splash droplet evaporation hypothesis of canopy interception and remaining problems: why is humidity unsaturated during rainfall? In: Proceedings of the 20th Annual Conference. Japan Society of Hydrology and Water Resources (in Japanese). <http://www.jstage.jst.go.jp/article/jshwr/20/0/20_62/_article>] but was in fact advanced by Dunin [Dunin, F.X., O'Loughlin, E.M., Reyenga, W., 1988. Interception loss from eucalypt forest: lysimeter determination of hourly rates for long term evaluation. Hydrological Processes 2, 315–329] more than 20 years ago. In addition, Dunin et al. considered that canopy ventilation might be enhanced in intense rain. This note draws attention to the historical precedence of the work of Dunin et al. and also presents a short review of literature on impact droplet production, highlighting areas where data are still required for the full exploration of the role of droplet evaporation in canopy interception. Droplet production needs to be properly parameterised and included in models of interception processes and landsurface–atmosphere interactions.

Introduction

The interception of rainfall on vegetation involves both intra-storm and post-storm evaporation. Murakami (2006, 2007a,b) advanced what was claimed to be a new mechanism driving intra-storm evaporation, namely the rapid evaporation of small impact or splash droplets produced on or within the canopy. Murakami pointed out that the evaporation of small droplets may account for the tendency, reported in some studies of interception, for the rate at which water is lost within a plant canopy to increase with rainfall rate (e.g. Jackson, 2000; Link et al., 2004). This is envisaged to arise from the creation of more numerous small water droplets when larger, faster, or more abundant incident raindrops strike the plant canopy. Especially in the case of droplets <50 μm diameter, evaporation is sufficiently rapid that even in conditions of high relative humidity, the droplets would be consumed before reaching the ground and would therefore not contribute to measured throughfall (e.g. Xie et al., 2007).

The purpose of this note is twofold. The first goal is to draw attention to the prior publication of the splash droplet evaporation hypothesis by Dunin et al. (1988) more than 20 years ago. Indeed, Dunin et al. (1988) advanced a related hypothesis that has not been examined since. They proposed that intense rain promotes the ventilation of the plant canopy, and hence more rapid evaporation. For example, a circulation of air through the plant canopy additional to that related to any external wind field, could be the result of the downward drag exerted by the falling droplets, a mechanism known from to arise in the convective structure of thunderstorm cells (e.g. Kamburova and Ludlam, 1966). This might drive air into the canopy from above, and generate outflows around or beneath the canopy, so ventilating the space within the foliage and branches. In other words, Dunin et al. (1988) hypothesised that increased rates of water loss from the canopy during intense rain might be the result of at least two mechanisms, both of which would be positively correlated with rainfall rate.

The second goal of this note is to present a brief review drawing attention to some of the literature on splash and droplet production, including studies using plant specimens as splash targets, and briefly to highlight some findings of significance to the water

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droplet evaporation hypothesis. This literature was not cited by Dunin et al. (1988) or by Murakami (2006), yet it provides valuable evidence in support of the droplet evaporation hypothesis as well as guidance on areas where additional understanding is needed.

The importance of intra-storm evaporation in the interception of rainfall has long been known. For instance, Horton (1919) presented data showing linearly increasing interception losses for rainfall events exceeding 10 h duration. Nevertheless, it has not been fully resolved just how the intra-storm evaporative losses arise and what mechanisms account for the significant rates of wet-canopy evaporation that have been recorded, including nocturnal wet-canopy evaporation when there is no solar radiation. Sustained wet-canopy evaporation during rain requires explanation in view of the high relative humidity (low vapour pressure deficit) during rainfall events and the low net radiation often measured under overcast conditions. One suggestion that has been raised several times is the advection of energy from adjacent regions, rather than local net radiation being the primary energy source accounting for intra-storm evaporation (e.g. Stewart, 1977; Pearce et al., 1980). There is a tendency (not always found) for wet-canopy evaporation rates to increase with rainfall rate (e.g. Dunin et al., 1988 and papers cited by Murakami, 2007a), and there has been a dearth of hypotheses to account for this observation. In fact, it is possible to develop multiple working hypotheses to account for a dependency of interception on rainfall rate. These include the more rapid and complete wetting of the vegetation under more intense rain, including progressive wetting of the undersides of leaves and branches by splash processes (e.g. Guzman and Gomez, 1987). The result is a progressive increase in the area of wet surface from which evaporation can proceed. Thus, during an hour of rainfall of high intensity, evaporation from the wetted undersides of leaves would contribute to canopy evaporative loss for a longer time than would be the case in an hour of less intense rain (e.g. see Carlyle-Moses, 2004). However, hypotheses such as this are not explored further here. This note focusses solely on the water droplet evaporation hypothesis.

If the evaporation of small water droplets is a significant process in intra-storm evaporation from plant canopies, then as Murakami (2007a) has suggested, models not incorporating the effect will underestimate wet-canopy evaporation rates and, hence, interception amounts.

A note on terminology

The expression 'impact droplet' is used here following Moss (1989), who published pioneering analyses of small droplet production resulting from the interaction of raindrops with foliage, including some of the effects of changing the incident drop size, the effect of raindrops striking the edges of leaves, and other significant issues. The term 'impact drop' is preferred to 'splash drop', since as Moss (1989) showed, a large proportion of drop breakup events caused when raindrops strike plant structures are not simple splash on a broad wet surface such as the upper surface of a leaf or branch, but rather involve the somewhat different 'slicing' and related processes of drop interaction with leaf edges, or plant elements such as narrow petioles. Likewise, 'secondary drop' is not used, since this term already has the specific meaning of droplets generated in splash corona processes (e.g. Roisman et al., 2006).

The canopy interception experiments of Dunin and co-workers

Dunin et al. (1988) carried out interception loss studies in State Forest at Kioloa on the south coast of New South Wales, Australia. The forest was dominantly young spotted gum (*Eucalyptus maculata*) and stringybark (*Eucalyptus globoidea*), with tree heights of up to 10 m and LAI of about 3.0. They used both a 40 tonne lysimeter providing <0.05 mm equivalent water depth resolution and conventional throughfall collectors (4.6 m^2) and stemflow collection apparatus. Supplementary data included Bowen ratio observations made above the forest canopy, rainfall records and standard meteorological parameters (windspeed, net radiation, etc.).

The results of Dunin et al. (1988) showed a clear correlation between evaporation loss rate during rain and the rainfall rate. For example, on February 8, 1985, the peak wet-canopy evaporation rate was 0.8 mm/h, associated with a heavy rain rate of 6 mm/h (using the classification of rain rates by Tokay and Short, 1996), during pre-dawn darkness. In multiple rain events, the same coincidence of high rain rate intervals and periods of high wet-canopy evaporation rate was found. Moreover, interception losses were shown to arise primarily during rain, and aggregate event losses of up to 8.0 mm equivalent water depth over the canopy area were recorded despite the canopy storage capacity (and hence maximal post-rain evaporative loss) having been determined to be only 0.35–0.5 mm. Using data from three 12 month periods, the mean fraction of interception loss arising from intra-storm evaporation was 69.6% whilst post-rain drying of the canopy contributed 30.4% (Dunin et al., 1988, Table II). Thus, as some studies have shown, evaporation during rain may be the dominant contributor to interception, rather than post-rain drying of foliage.

The observation that interception loss rate rose in parallel with rainfall rate was highlighted by Dunin et al. (1988) as an observation demanding a physical explanation. They offered the speculation that the impact shattering of raindrops might be responsible, providing a mist of what Moss (1989) subsequently termed impact droplets, in the forest canopy. Additionally, they speculated that high rain rates might not only produce more impact droplets, but might enhance the evaporation of these droplets by increasing turbulent mixing in downdrafts, perhaps bringing in dry air from aloft. In other words, they envisaged a role for higher rain rates in increasing the ventilation of the canopy spaces as well as in creating small drops that would rapidly be consumed by evaporation. These hypotheses appear not to have been explored fully since their original exposition.

Using data from 69 rainfall events of duration $\geqslant 3$ h, Dunin et al. (1988) related wet-canopy evaporation rate E_w to rainfall rate R and mean wind speed U using multiple regression. The resulting equation was

$$E_w = 0.04 + 0.06U + 0.022R$$

for which r^2 was 0.46. Thus, the two independent variables accounted for about half of the statistical variability in wet-canopy evaporation rate. The bivariate correlation between rain rate and evaporation was 0.51, and between wind speed and rain rate, 0.38. Rainfall rates appear often to have been in the heavy category of Tokay and Short (1996) (i.e., $5 < R < 10$ mm/h) and it is thus interesting to consider how impact droplet production might arise in rain rates in the extreme category and beyond, such as the 400–600 mm/h events listed by LeMéhauté and Khangaonkar (1990) and the high rain rate events reported in the literature and tabulated by Dunkerley (2008). The following section of this paper presents a short review of some of the factors likely to be involved in the link between wet-canopy evaporation rate and rainfall rate via the evaporation of impact droplets.

Studies of the production of impact droplets

Murakami (2007a) referred to the lack of information on the size distribution of small water droplets within plant canopies. Whilst it is true that there is a dearth of field data of this kind, there