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Dominant factors influencing precipitation efficiency in a continental mid-latitude location

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ABSTRACT

The bulk precipitation efficiency (PE) of transient precipitation systems at a continental, mid-latitude location is established as a function of season and dominant cloud type (convective versus stratiform). These results quantify for the first time controls on PE that have long been assumed to be true. Moreover, previous studies have been unable to establish a link between the efficiency of precipitation systems and short-term changes in the warm cloud depth ($T > -10°$C). These results show that the depth of the warm cloud layer, over which the collision–coalescence process will dominate, is not a short-term control on PE, but a seasonal one.

1. Introduction

Studies of precipitation efficiency (PE), which is defined broadly as the ratio of total precipitation to the total amount of ingested moisture, have been conducted for more than 50 yr. This study is unique, as it applies a robust approach to PE calculation to many precipitation systems for a single location throughout the course of 1 yr in order to verify that PE values vary with seasons and rainfall systems (convection versus stratiform). These ideas have long been asserted without establishing any observational experiment to support them.

Different types of observational approaches have been proposed to define PE (e.g., Sellers, 1965; Newton, 1966). A growing recent body of work exists (e.g., Ferrier et al., 1996; Li et al., 2002) where numerical simulations of convective clouds have been examined, but that group lies outside the scope of this paper. The present work is not too different from that of Braham (1952), who used surface and sounding data obtained from the Thunderstorm Project to determine the water and energy budget of a thunderstorm. Although his study was not directly about an estimation of PE, it can be seen as the first step on how one can use a water budget to calculate PE. In principle, this approach is one that we follow, although we use the initial fields from an hourly mesoscale numerical model as a proxy for balloon observations. In this note, we establish the data selection and analysis methods, provide analysis of data from a period of 1 yr, and offer some conclusions.

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2. Method

2.1. Event selection

Columbia, Missouri (MO), is chosen as the focus area for this study, with data taken from the Missouri Climate Center's Sanborn Field station. This site constitutes a continental, mid-latitude location. Columbia's annual mean rainfall accumulation is slightly less than 1000 mm (39.4 in), which is based on an average from 1837 to 2003 [National Weather Service (NWS) 2005]. Most of the total rainfall comes in the spring and summer season with mean values of 294 mm (11.56 in.) and 297 mm (11.69 in.), respectively. This is followed by a fall season with a mean value of 244 mm (9.6 in.) and a winter season, with a mean value of 144 mm (5.66 in.). With such a seasonal rainfall distribution, it is worthwhile to study PE over this area to represent a typical continental mid-latitude region.

For the purpose of this study, certain criteria are set so that only the more significant precipitation events are sampled. Events of continuous rainfall of 4 h or more are employed, so that rainfall systems passing across this area would be sampled more effectively. In addition, the total rainfall must be at least 6.4 mm (0.25 in.) in each event, which is a sum of stable non-convective and convective (when present) precipitation. With those criteria, 31 events are identified in a period from 1 October 2003 to 30 September 2004, as shown in Table 1. Given our calculation method (discussed below), it is assumed that all of those selected precipitation systems were in a steady-state condition throughout the event period when they passed over Sanborn Field. Snow events are ignored for this particular study because the Sanborn Field observational station did not have a capability to

Table 1. Calculated PE of the respective events

Date	PE (%)	Cloud type
14 October 2003	40	Convective
17 October 2003	23	Convective
25 October 2003	29	Convective
17 November 2003	10	Convective
9 December 2003	5	Stratiform
22 December 2003	9	Stratiform
4 January 2004	14	Convective
16 January 2004	25	Stratiform
17 January 2004	8	Stratiform
2 February 2004	8	Stratiform
4 March 2004	12	Stratiform
5 March 2004	62	Stratiform
26 March 2004	26	Convective
28 March 2004	28	Stratiform
24 April 2004	16	Stratiform
29 April 2004	86	Convective
30 April 2004	22	Convective
19 May 2004	53	Convective
25 May 2004	150	Convective
9 June 2004	22	Stratiform
2 July 2004	45	Convective
12 July 2004	236	Convective
16 July 2004	26	Convective
24 July 2004	11	Convective
4 August 2004	−78	Convective
20 August 2004	121	Stratiform
23 August 2004	44	Convective
24 August 2004	45	Convective
15 September 2004	143	Convective
16 September 2004	24	Convective
18 September 2004	35	Convective

measure reliably the liquid equivalent of such events on an hourly timescale basis.

2.2. Calculating PE

The efficiency of a precipitation system is often described as the ratio of total precipitation to total available moisture. Total precipitation can be obtained directly from any surface weather station observation located within the study area, while the total available moisture has to be calculated. By assuming a steady-state system, one can convert time series data into space, and apply the expressions that follow.

In this study, a total water balance equation introduced in Palmén and Newton (1969) is used to determine the total available moisture for a single site, which is given as:

$$\underset{\mathbf{A}}{P} = \underset{\mathbf{B}}{E} \underbrace{- \frac{1}{g}\int_{p}^{p_o} \frac{\partial q}{\partial t}\mathrm{d}p - \frac{1}{g}\int_{p}^{p_o} \nabla\cdot q\mathrm{V}d\mathrm{p}}_{\mathbf{C}} \tag{1}$$

Term **A** is surface precipitation, term **B** is surface evaporation and term **C** is the moisture availed to a column through local processes (e.g., conversion to/from the liquid phase, entrainment via turbulent mixing) and moisture flux convergence. During a rainfall event, the relative humidity often approaches 100%. As the atmosphere becomes saturated, term **B** will become very small and is thus neglected in these calculations. Moreover, with such short periods of time involved, there is no significant difference in the calculation by ignoring term **B**. To calculate the total available moisture of term **C**, the surface pressure, p_o, will be taken as 1000 mb, which is a typical station pressure for Columbia (located approximately 265 m above sea level), while the upper level pressure, p, is taken as the standard 300 mb since the atmosphere is relatively dry above that level. Term **C** is divided into two components, which are the local change of specific humidity, $\frac{\partial q}{\partial t}$, and the horizontal moisture flux convergence, ($\nabla\cdot q\mathrm{V}$), by the horizontal wind (V), integrated between the 1000- and 300-mb pressure levels.

Over sufficiently long timescales, eq. (1) will demonstrate conformity to the concept of conservation of water mass. For this study, with each event lasting for only a few hours, one would not expect to see a balance between the left-hand side and the right-hand side of eq. (1). Thus, eq. (1) is solved as a ratio, taken with the total accumulated precipitation as the numerator and the time integrated moisture tendency as the demoninator, generating eq. (2):

$$X = \frac{P}{\left(-\frac{1}{g}\int_{p}^{p_o} \frac{\partial q}{\partial t}\mathrm{d}p - \frac{1}{g}\int_{p}^{p_o} \nabla\cdot q\mathrm{V}\right)} \tag{2}$$

This produces a value of X, where X theoretically should vary between 0 and 1. X subsequently is multiplied by 100 to give the PE value as a percentage.

2.3. Data

For this study, surface rainfall data measured at the Sanborn Field automated weather station is used for the precipitation contribution in eq. (2). Sanborn Field was used primarily for its close proximity (∼1 km) to a SuomiNet station (Ware et al., 2000) which employs the wet delay in global positioning system signals to retrieve a precipitable water (PW) vapor profile. We also make use of the initial fields from the rapid update cycle (RUC) model (hereafter RUC20), to obtain atmospheric variables at different pressure levels. The RUC20 (Benjamin et al., 2004) is a hydrostatic mesoscale meteorological numerical model, featuring 50 layers in the vertical and 20-km horizontal grid spacing. Grids from the RUC20 hourly initializations were used to establish term **C** in eq. (1). By assuming a steady-state condition on transient precipitation systems, we can then convert these hourly moisture difference profiles into a single profile of the system in space.

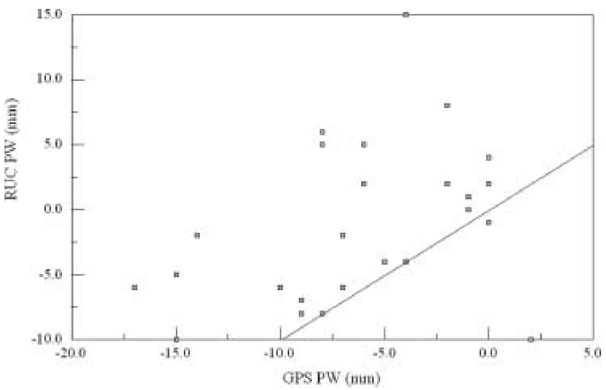

Fig. 1. Changes in precipitable water (PW; mm) over the course of sampled events obtained from the SuomiNet system (abscissa) and the RUC20 model (ordinate).

In order to determine the veracity of the moisture fields estimated by the RUC20 model, a comparison of the change between the beginning and end of a precipitation event in PW measurements from the SuomiNet observation system and the PW generated by the RUC20 was completed. The variation shown in Fig. 1 indicates that the PW estimated by the RUC20 model tended to be biased towards a wet condition. The RUC20 revealed less PW change compared to the GPS observation system. This result shows that the total available moisture estimated using the RUC20 model has a tendency to give a higher value, which later might generate lower PE values. The statistical test of PW change obtained from the GPS observation system and through the model gave a modest correlation coefficient ($r = 0.378$) with a 94% confidence level.

3. Results

3.1. PE values

Following the methods explained in detail in Section 2, PE values were calculated using eq. (2). These values range from a minimum of −78%, which took place on 4 August 2004, to a maximum of 236%, which occurred on 12 July 2004.

Physically, as mentioned in Section 2, PE values over the lifetime of a precipitation system *should* range between 0% and 100%. Upon deeper inspection, those cases studied herein that lie outside the stated range failed to meet our assumption of a steady-state precipitation system. Indeed, Marwitz (1972) stated that high efficiency (∼100% and more) is probably a reflection of the degree of accuracy of the available moisture and rainfall rate. Yet, a precipitating system tends to have an instantaneous PE greater than 100% when the value is estimated during the system's dissipating stage. It rains out while at the same time the water influx is approaching zero, which can produce a PE value up to ∞. This statement is best visualized with the conceptual diagram of Market et al. (2003), which is their Fig. 1. Newton (1963, 1966), Foote and Fankhauser (1973), Gamache and Houze (1983) and Ferrier et al. (1996) all have shown that PE values could be larger than 100% depending on the stage of development of the precipitation system. The four values in excess of 100% are thus retained in this analysis.

None of the earlier known research has discussed PE estimation that has a value of less than 0%. In this study, a value of −78% was encountered in the PE calculation. A closer inspection of the calculated values of moisture flux convergence suggests that the system was undergoing strong moisture advection away from the system (likely through the anvil), experiencing a net loss in moisture during the whole event. This process leads to a negative value when calculating the moisture flux convergence (in term **C** of eq. (1)). Since this system collapsed as it passed through the study area, it did not fulfill the assumption we stated earlier, that the system should be in a steady-state throughout the event period whenever it is within the study area. Thus, this event is ignored in the ensuing analyses; all others are retained (Table 1).

However, it is important to note that multiple screening approaches to the dataset in Table 1 yield similar statistical results. Specifically, the Mann–Whitney tests discussed below all allow us to reject the null hypothesis that there are no differences between the compared samples, always at a confidence interval in excess of 95%. This result is obtained whether comparing the full data set that includes negative values as well as those in excess of 100%, only positive values but still including those over 100%, or only those very well behaved values that range from 0% to 100%.

3.2. Seasonal variations

Four annual seasons were identified, with summer encompassing the months of June–August; fall is September–November; winter is December–February; spring is March–May. The variation of PE values indicate that they tended to be higher from the beginning of March until the end of August and decreased in the middle of September to the end of February. This means that the values increase when the spring season begins in March and become higher as the summer season commenced; values decrease at the end of summer and continue to decrease as the winter arrives. The calculations of the average values of PE, according to their respective season, indicate that the highest value is recorded in the period of summer with 69% efficiency, followed by spring, fall and winter with 51%, 43% and 12% efficiencies, respectively as in Table 2.

Meanwhile, by choosing the months from April to September as the warm season, and October to March as the cold season, a box plot by seasons in Fig. 2 shows that the 75th percentile of PE value for cold season system lays slightly above the 25th percentile of PE value for warm system. In addition, a Mann–Whitney statistical test between those two seasons gives approximately a 97% confidence level for the two-tail probability test.

Table 2. PE averages according to season

Month	Number of events	Season	Average PE (%)
December, January and February	6	Winter	12
March, April and May	9	Spring	51
June, July and August	8	Summer	69
September, October and November	7	Fall	43

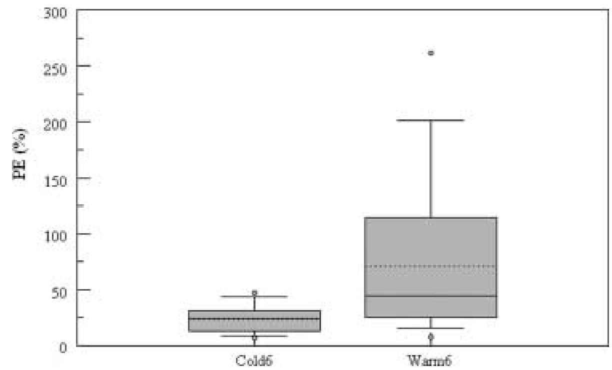

Fig. 2. Box plot of PE values for rain events in the 6 cold months (October–March; $N = 13$) versus the 6 warm months (April–September; $N = 17$), at Columbia, MO, from October 2003 to September 2004.

Both of these statistical reports strongly suggest that the PE value is higher during the warm season and lower in the cold season.

3.3. System variations (stratiform versus convective)

Rainfall systems can be divided into two broad types: convective and stratiform. For this study, hourly airport surface observation reports for Columbia, MO (~10 km southeast of Sanborn Field), were examined in an effort to differentiate between types of systems for all the events in Table 1. Additionally, images from regional National Weather Service WSR-88D radars were also used to support the conclusion. If thunderstorm activity was reported in any of the hourly observations during the event period, the system would be classified as convective; otherwise, it would be categorized as stratiform. Of 30 study events, 19 were identified as convective while the other 11 were stratiform as listed in Table 1. A summary of rainfall system type is shown in Table 3.

The average PE value for respective systems indicates that it was higher for convective systems than stratiform. The ability of updrafts and downdrafts to collect water droplets in convective cloud systems makes PE values higher (Ferrier et al., 1996). Besides that, clouds formed during the warmer season tend to have greater depth, which can promote higher moisture content of air and enhance the collision–coalescence process.

What little precipitation might fall places most of the stratiform systems outside the criteria set for this study: that is, to have

Table 3. Summary of rainfall system types

Rainfall system	N	Summer	Fall	Winter	Spring	Mean PE (%)
Convective	19	6	7	1	5	56
Stratiform	11	2	0	5	4	29

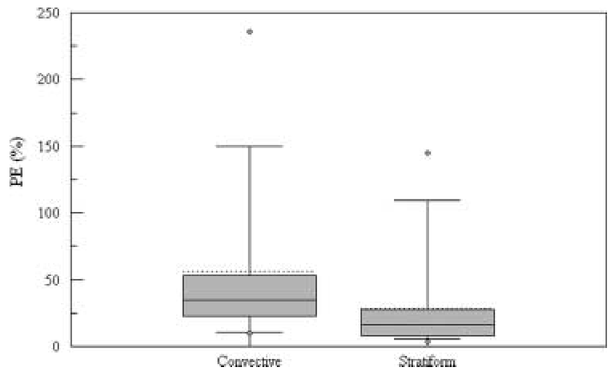

Fig. 3. Box plot of PE in convective ($N = 19$) versus stratiform ($N = 11$) precipitation systems.

more than 6.4 mm total rainfall during each event. Without the benefit of a warm environment and substantial moisture, most stratiform systems are likely to form during the cold season, with low PE values, which appears to support the results in Tables 2 and 3.

Meanwhile, a descriptive statistical report from the box plot by rainfall system types in Fig. 3 shows that the 75th percentile of PE value for stratiform system lays near the 25th percentile of PE values for convective systems. In addition, a Mann–Whitney test between those two data sets gives about 97% confidence level for the two-tail probability test. These statistical reports strongly suggest that the PE value is generally higher for a convective system than the stratiform one.

4. Conclusions

The goal of this study was to support the assertions that PE values vary with season and cloud type. To accomplish this goal, a PE calculation method was presented based on the water budget equation introduced by Palmén and Newton (1969) to estimate the PE value for each rainfall event during 1 yr of study. PE was calculated during each rainfall event, and a value of between 0% and 100% was expected. Even so, PE values ranging from −78% to 238% were calculated from 31 rainfall events that have been identified through 1 yr of observations. This large variation is due to the application of the steady-state assumption about all systems used for this study, in order to permit the time-to-space conversion that drives the efficiency estimate in eq. (2).

Even though the estimated PE values were of a wide range, the study did show that the average values varied with season and cloud system. PE is higher during warm season and lower during cold season, where the summer generates the highest value with 69% efficiency follow by 51% in spring, 43% in fall and 12% in the winter seasons. Analysis of the type of cloud system demonstrated that the average PE value was higher for convective clouds with 56% efficiency, and lower for the stratiform type, with 29% efficiency. With these results, we validate the claim by earlier studies that PE values vary with season and cloud type.

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