

An Atmospheric Water Balance over a Mountain Barrier

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(Manuscript received 25 February 1985, in final form 29 July 1985)

ABSTRACT

The flow of moisture through a "slab" of air, upwind and over the Park Range in northwest Colorado, was estimated from wintertime meteorological measurements. On average, 6–14% of the inflow moisture precipitated onto the barrier (86 to 94% flowed over the barrier). Because such a small amount of the moisture precipitates, snowfall augmentation activities on the upwind Park Range barrier should not significantly affect the moisture reaching the downwind Front Range barrier.

1. Introduction

A common characteristic of midlatitude mountain ranges is that more precipitation falls on the upwind slopes than falls either on the upwind or downwind plains as documented by Barry (1981). This characteristic is illustrated in Fig. 1. At least two factors are responsible: First, the ranges enhance precipitation from synoptic-scale systems; i.e., less precipitation would have fallen if the mountain range were not present. The enhanced precipitation is referred to as the orographic component of synoptic-scale precipitation. Second, the ranges trigger precipitation where none would have occurred otherwise. This phenomenon is called mountain-induced precipitation. According to Grant and Kahan (1974) the mountain-induced precipitation provides more than 90% of the annual runoff in most sections of the western United States.

Mountain-induced precipitation is characterized by little or no precipitation on the upwind plain, major precipitation on the windward slopes, dramatic evaporation of cloud and remnant precipitation on the leeward slopes with the attendant warming (due to latent heat released during cloud and precipitation formation) of the downwind air. With the formation of mountain-induced precipitation, moisture flows through the cloud system with a fraction condensing and precipitating.

The rate at which inflow moisture condenses within mountain-induced clouds has been estimated from upwind soundings by a number of investigators (e.g., Elliott and Hovind, 1964; Dirks, 1972; Marwitz, 1974). They estimated the precipitation efficiencies of these clouds by dividing the calculated condensation rates by measured precipitation rates. The resulting efficiencies ranged between 17 and 68% depending on the sta-

bility of the clouds (Elliott and Hovind, 1964). Knowledge of the precipitation efficiency is important to applications such as cloud seeding to augment mountain-induced precipitation and may ultimately lead to better precipitation forecasts.

Knowledge of the fraction of the inflow moisture which precipitates and the fraction which flows over the barrier is potentially useful. These values were not reported in the precipitation efficiency studies. The purpose of this paper is to report estimates of the fraction of the inflow moisture which precipitates and the fraction which flows "unused" over the Park Range in the northern Colorado Rockies. The values were deduced using a water-balance approach. On average, 6 to 14% of the moisture precipitates. Hence, most moisture flows unused over the range.

2. Approach

A box model was employed to estimate the water-balance. The moisture flow through the box model is illustrated in Fig. 2. The box is defined as a unit width, vertical slab of air, bounded on the upwind edge by a rawinsonde ascent from the surface to the tropopause, and on the downwind edge by a vertical plane between the mountain crest and the tropopause. Then, the water balance of the precipitating orographic cloud consists of three components: inflow vapor (M_1), precipitation (M_2), and outflow moisture (M_3). The box model permits defining the following relationship between the moisture components:

$$M_1 = M_2 + M_3, \quad (1)$$

i.e., inflow moisture equals precipitation (no evaporation is assumed) on the upwind slopes of the mountain barrier plus the amount of moisture flowing over the barrier.

This investigation used published wintertime atmospheric measurements from the Park Range region

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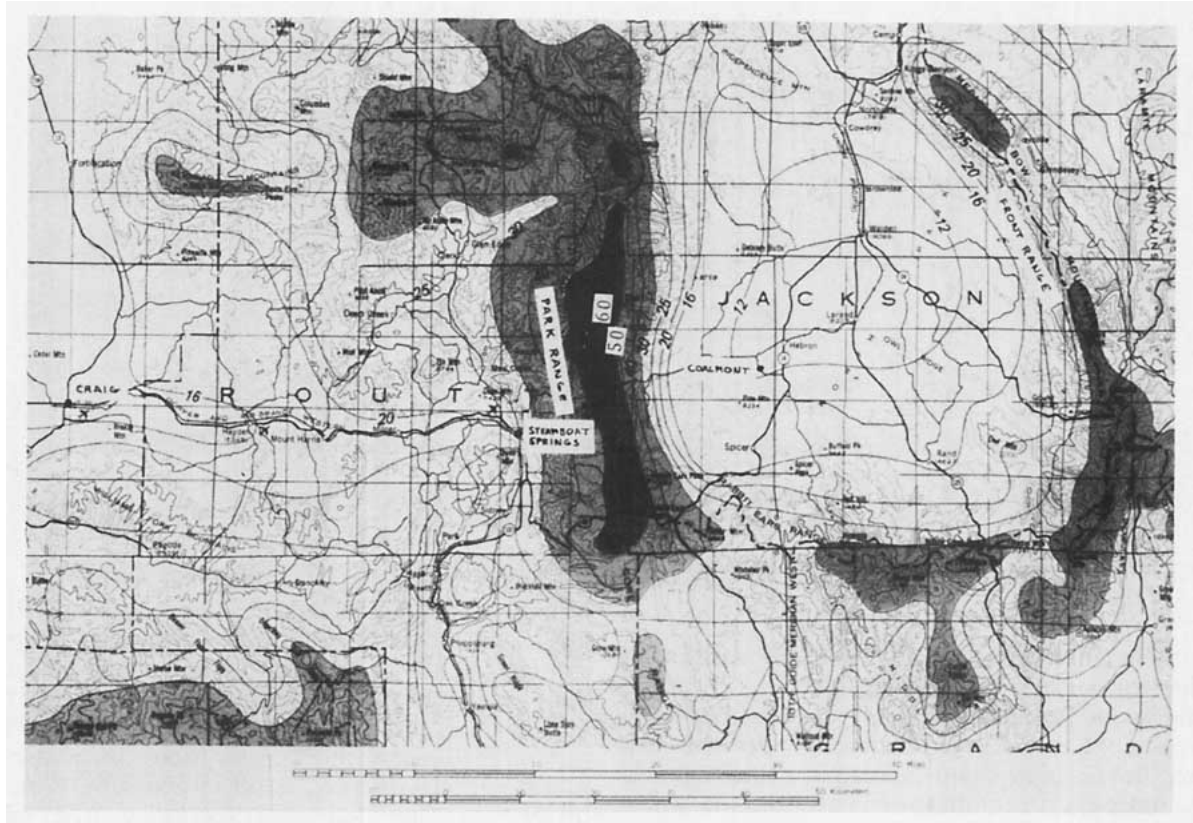


FIG. 1. Mean annual precipitation (in.) in the vicinity of Steamboat Springs, CO. The shaded regions represent ≥ 30 in. (76 mm) of precipitation. The location of the continental divide is illustrated by the vertical dashed line near the center of the map and the locations of the Park and Front Ranges are also given (from Doesken et al., 1984).

of northern Colorado to estimate the three moisture components. The long, north-south oriented range is ideal for water balance studies because the flow is forced to be primarily two-dimensional. The moisture components were estimated from the following measurements: M_1 : upwind rawinsonde temperature, moisture and wind from Lee (1984); M_2 : surface precipitation from Hindman et al. (1983) and Doesken et al. (1984); M_3 (liquid): mountaintop incloud liquid water from Hindman et al. (1983); M_3 (ice): surface precipitation; M_3 (vapor): estimated, using (1).

These measurements are from different winter storms. The storms were distributed among the winters of 1978/79–1981/82. Hence, the measurements provide estimates of the average winter moisture components. The average values were derived with upper and lower bounds. These bounds provide limits to the moisture components. As a result of the averaging process, the results of this investigation are good to within an order of magnitude.

3. Moisture components

a. Inflow vapor (M_1)

Lee (1984) has reported vertical soundings of temperature, pressure, moisture and winds from Craig, Colorado which is 73 km upwind of the Park Range.

These soundings were taken during periods when snow was falling upwind and on the Park Range. The soundings, taken at 3-h intervals, were analyzed to define the inflow moisture. The inflow moisture was defined by the following expression:

$$M_1 \text{ (g h}^{-1} \text{ cm}^{-1}\text{)} = 3600 \sum_{i=1}^n \bar{v}_i \bar{q}_i \bar{\rho}_i \Delta z_i, \quad (2)$$

where \bar{v}_i (cm s⁻¹) is the average air speed normal to the inflow edge of the box, \bar{q}_i (g kg⁻¹) is the average mixing ratio and $\bar{\rho}_i$ (kg cm⁻³) is the average air density. These average values apply to the height interval Δz_i (cm); $i = 1$ to n sums from the surface to the tropopause. Finally, 3600 has the units s h⁻¹.

Soundings from the two storms reported by Lee (1984) were analyzed (0000–2100 GMT 23 Feb 1979 and 0000–1800 GMT 11 Dec 1979—a total of 15 soundings). Values of M_1 were derived from (2) for each sounding and the M_1 values for each storm were averaged. The average M_1 values from the two storms were, respectively, $4.2 (\pm 1.2) \times 10^6$ and $1.8 (\pm 0.21) \times 10^6$ g h⁻¹ cm⁻¹. These values are significantly different because the uncertainties of the means do not overlap. Nevertheless, the values are well within the same order of magnitude. Combining all the soundings from the two periods produces a value of $3.2 (\pm 0.740) \times 10^6$ g h⁻¹ cm⁻¹.

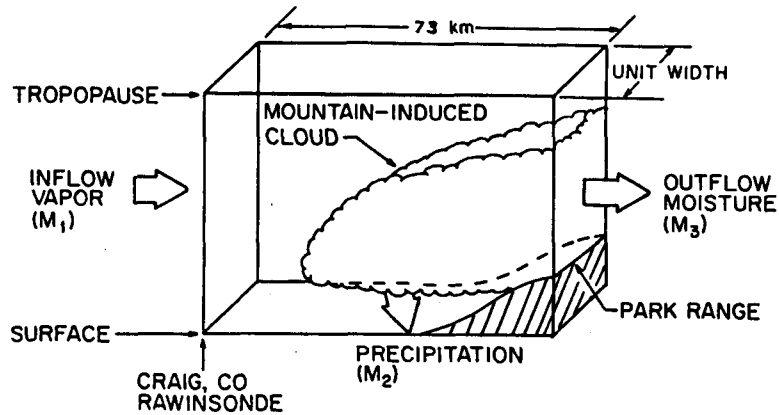


FIG. 2. Atmospheric box model and moisture components utilized in this study. The box is bounded by the Craig, CO sounding on the upwind side, the crest of the Park Range on the downwind side, the tropopause at the top and the earth's surface at the bottom. Figure 1 provides the details of the region.

b. Precipitation (M_2)

Precipitation measurements (24 h new snowfall and water equivalent) were routinely taken at 2743 m elevation at the Steamboat Ski Area located on the western slopes of the Park Range. The precipitation was measured from a snow-board exposed in a sheltered area. The water-equivalent measurements from the winters of 1981/82 and 1982/83 were used by Hindman et al. (1983) to define an average snowfall rate of $0.54 (\pm 0.11)$ mm h^{-1} . This value was distance-weighted using the magnitude and distribution of the precipitation values between Craig, Colorado and the Park Range crest shown in Fig. 1. The procedure for weighting the 0.54 mm h^{-1} value was as follows: The value corresponds to the 35 in. (889 mm) precipitation isopleth directly east of Steamboat Springs in Fig. 1. Precipitation rate values (P') were calculated as follows for each precipitation isopleth value (P'') in Fig. 1 between Craig and the crest:

$$P' = 0.54 (\text{mm } h^{-1}) P'' (\text{mm}) / 889 \text{ mm.} \quad (3)$$

Then, the P' values were weighted by the distance over which they were assumed valid and summed as follows to obtain the distance-weighted precipitation rate P^* :

$$P^* = \sum_{i=1}^n P' \Delta x_i / x, \quad (4)$$

where the x_i (cm) values are the length increments along the line between Craig and the crest and x (cm) is the distance between Craig and the crest (7.3×10^6 cm). The weighted-precipitation rate from (4) is $0.34 (\pm 0.08)$ mm h^{-1} .

The P^* value from (4) was used with the following expression to determine the moisture component due to precipitation (M_2):

$$M_2 (\text{g } h^{-1} \text{ cm}^{-1}) = 0.1 \chi P^* \rho_w, \quad (5)$$

where ρ_w is the density of water (g cm^{-3}). Substituting the χ and P^* values into (5) results in a M_2 value of $2.9 (\pm 0.50) \times 10^5 \text{ g } h^{-1} \text{ cm}^{-1}$. An assumption in deriving this value is that negligible evaporation of the precipitation occurs in the subcloud layer. This assumption is reasonable because cloud bases during storm periods are only ≈ 700 m above the Yampa River Valley floor. Marwitz (1974) reports a M_2 value of $1.2 \times 10^6 \text{ g } h^{-1} \text{ cm}^{-1}$ from his study in the southern Colorado Rockies, a value which is within an order of magnitude of the value determined here.

c. Outflow moisture (M_3)

The outflow moisture consists of three components: M_3 (liquid), M_3 (ice), and M_3 (vapor). The liquid component was defined from measurements by Hindman et al. (1983) as the average horizontal flow of liquid water R over the crest of the Park Range at the surface during storm periods; $R = 5.7 (\pm 0.82)$ mm h^{-1} . This value, assumed to be representative through the cloud depth, is probably an overestimate. (Measurements were not available to determine the vertical distribution of liquid water content between the barrier crest and the cloud tops; aircraft cannot penetrate much of this region.) Cloud top measurements from Lee (1984) were an average of 4 km AGL or were about 2730 m above the barrier crest ($Z' = 2730$ m). The value of M_3 , then, is defined by

$$M_3 (\text{liquid}) (\text{g } h^{-1} \text{ cm}^{-1}) = Z' R \rho_w. \quad (6)$$

Substituting the Z' and R values into (6) results in a M_3 (liquid) value of $1.4 (\pm 0.22) \times 10^5 \text{ g } h^{-1} \text{ cm}^{-1}$.

The M_3 (ice) value was approximated by deriving a precipitation "blow-over" rate at the crest. The rate was derived because measurements were not available of the vertical distribution of the ice water content between the barrier crest and the cloud tops. The "blow-over" rate was assumed to be equal to the distance-

weighted precipitation rate between the barrier crest and Coalmont which is 20 km downwind of the crest (see Fig. 1). Coalmont was chosen because it has nearly the same annual precipitation as Craig. The 0.54 mm h⁻¹ precipitation rate, which corresponded to the 35 in. precipitation isopleth directly east of Steamboat Springs in Fig. 1, was assumed to correspond to the 35 in. precipitation isopleth directly east of the barrier crest. Most of this precipitation is blown over the crest. An unknown and probably substantial amount of the blow-over evaporates; consequently, the blow-over rate determined here will be a conservative value. The weighted precipitation rate downwind of the crest was calculated following (4). The resulting precipitation rate (P^{**}) was found to be 0.37 (± 0.11) mm h⁻¹. So, the value of M_3 (ice) is given by (6) except R is replaced by P^{**} . Substituting the Z' and P^{**} (for R) values into (6) results in a M_3 (ice) value of $1.01 (\pm 0.31) \times 10^4$ g h⁻¹ cm⁻¹.

The value of M_3 (vapor) is approximated from (1), where $M_3 = M_3$ (liquid) + M_3 (ice) + M_3 [vapor]. Substituting the previously determined M_3 (liquid) and M_3 (ice) values into (1) results in an M_3 (vapor) value of $2.76 (\pm 0.690) \times 10^6$ g h⁻¹ cm⁻¹.

A summary of the moisture components and their values is given in Table 1.

4. Discussion

Using the mean values and their ranges from the table, we calculated the following values: the fraction of inflow moisture that precipitates: $M_2/M_1 = 0.0916$ with a range between 0.060 and 0.138 and the fraction of inflow moisture that flows over the barrier: $M_3/M_1 = 0.91$. It can be seen from the results that between 6 and 14% of the inflow moisture actually precipitates. Conversely, between 86 and 94% of the inflow moisture flows over the barrier.

These results indicate that, on average, a small amount of atmospheric moisture precipitates on the Park Range barrier; most of the moisture flows over the barrier. This result is for an entire atmospheric column. It may well be that somewhat more than 9% of the moisture in the lower levels of the column precipitates and somewhat less than 9% in the upper levels precipitates, averaging 9% for the entire column. If this

is so, then precipitation formation on downwind barriers may be reduced. However, synoptic-scale moisture convergence may offset the potential reduction.

Snowfall augmentation by cloud seeding upwind of mountain barriers has been reported to increase wintertime precipitation by about 10 to 15% by Grant and Kahan (1974). Thus, cloud seeding activities upwind of the Park Range at best will increase the amount of inflow moisture which precipitates by 1.3%. Conversely, the outflow moisture will be reduced by 1.3%. Consequently, cloud seeding activities on the upwind Park Range barrier should not "rob" moisture from the downwind Front Range barrier.

5. Conclusions

An order of magnitude water balance of wintertime orographic clouds was produced using a box model. The model accounted for inflow moisture, precipitation, and outflow moisture. The values for these moisture components were determined from atmospheric measurements made upwind and over the Park Range in northwestern Colorado. It was found that, on average, a small amount of atmospheric moisture precipitates on the mountain barrier (6 to 14%). Cloud seeding activities are estimated to increase these values 1.3%. Thus, cloud seeding activities on the upwind Park Range barrier should not rob moisture from the downwind Front Range barrier. To improve these estimates, measurements are required of the vertical distribution of the liquid water and ice water between the barrier crest and the cloud tops.

Acknowledgments. This paper represents a portion of the research sponsored by NSF Grant ATM-84-07543 and Air Force Contract F19628-84-C-0005. The paper was revised while the author was the NAVAIR-SYSCOM Visiting Professor in Meteorology at the U.S. Naval Academy, Annapolis, Maryland.

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TABLE 1. Moisture component values and their uncertainties.

Component	Value (g h ⁻¹ cm ⁻¹ × 10 ⁻⁶)
M_1 inflow vapor	3.20 (± 0.740)
M_2 precipitation	0.290 (± 0.050)
M_3 outflow moisture	2.91 (± 0.790)
M_3 (liquid)	0.140 (± 0.022)
M_3 (ice)	0.010 (± 0.003)
M_3 (vapor)*	2.76 (± 0.764)

* Determined from $M_1 = M_2 + [M_3$ (liquid) + M_3 (ice) + M_3 (vapor)].