The Water Balance of Orographic Clouds[1]

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ABSTRACT

A significant question bearing on the prediction of orographic precipitation and the seeding of orographic clouds is what fraction of the water condensed over an orographic barrier falls on the barrier as precipitation. This has been treated in a rather inadequate manner to date, largely because of lack of basic data.

Through the use of abundant storm-sounding data taken upwind of two Southern California orographic barriers and data from the corresponding mountain recording raingage networks, comparisons of computed condensation and observed precipitation have been made for a number of winter storms over a four-year period. The results indicate that approximately one quarter of the orographically produced condensate fell as precipitation on the watersheds.

A breakdown into air mass stability on the basis of the inflow rawinsonde data showed that, for similar orographic flow conditions, more precipitation was produced by unstable air masses than by stable air masses.

1. Introduction

The problem to be solved was the determination of what fraction of the condensate formed over an orographic barrier falls on or near that barrier. The fact that ceilings are higher on the lee side of a mountain range demands that this fraction be less than one, yet quite often theoretical orographic precipitation models are based upon the assumption that all of the water condensed by the orographic lifting falls on the barrier.

The implications with respect to cloud seeding are clear; only the condensate which would otherwise move over the barrier and evaporate downwind can be tapped by artificially increasing the efficiency of the conversion of cloud water to precipitation.

By analogy to the smaller scale precipitation mechanisms of the atmosphere, one might expect very small orographic barriers to convert a fraction of the condensate into precipitation in line with the 0.19 found by Braham (1952) for the thunderstorm. Medium-sized barriers might be comparable to giant squall-line type thunderstorms of the Midwest for which Newton[2] cites a fraction of 0.50.

Ideally, the water balance could be established by means of three sources of data:

1) Serial rawinsondes in the air mass just upwind of the barrier;
2) Serial rawinsondes in the air mass just downwind of the barrier; and
3) Precipitation data over the barrier.

Due to the network-type arrangement of sounding stations, inflow-outflow sounding pairs are non-existent. However, in California there are several stations lying on the upwind side of various orographic barriers that are well instrumented with respect to recording precipitation gages. The lack of item 2 can then be rectified by use of an appropriate barrier wind flow model and an adiabatic chart for lifting the inflow air mass over the crest.

A number of computations of orographic condensation have been made by Myers (1962) and others[3,4] for these California barriers, primarily in connection with the practical problem of assessing the maximum possible precipitation over such barriers. In this context, it is appropriate to deal with extraordinarily heavy storms where the conversion of condensate to precipitation may be complete. However, with the ordinary type of storm this is decidedly not the case, as will be shown.

2. Orographic flow model and computational procedures

The essence of flow models, to date, has been the limitation of the orographic updraft by a nodal surface at some height above the crest. The streamlines con-

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[2] Newton, Chester W., 1962; *Dynamics of severe convective storms.* Report No. 9, National Severe Storms Project, U. S. Weather Bureau, Kansas City, Mo., 44 pp.

[3] Knox, Joseph B., 1960: *Procedures for estimating maximum possible precipitation.* Bulletin No. 88, Calif. Dept. of Water Resources, 29 pp.

[4] Weaver, R. L., 1962: *Meteorology of hydrologically critical storms in California.* Hydrometeorological Report No. 37, U. S. Weather Bureau, 207 pp.

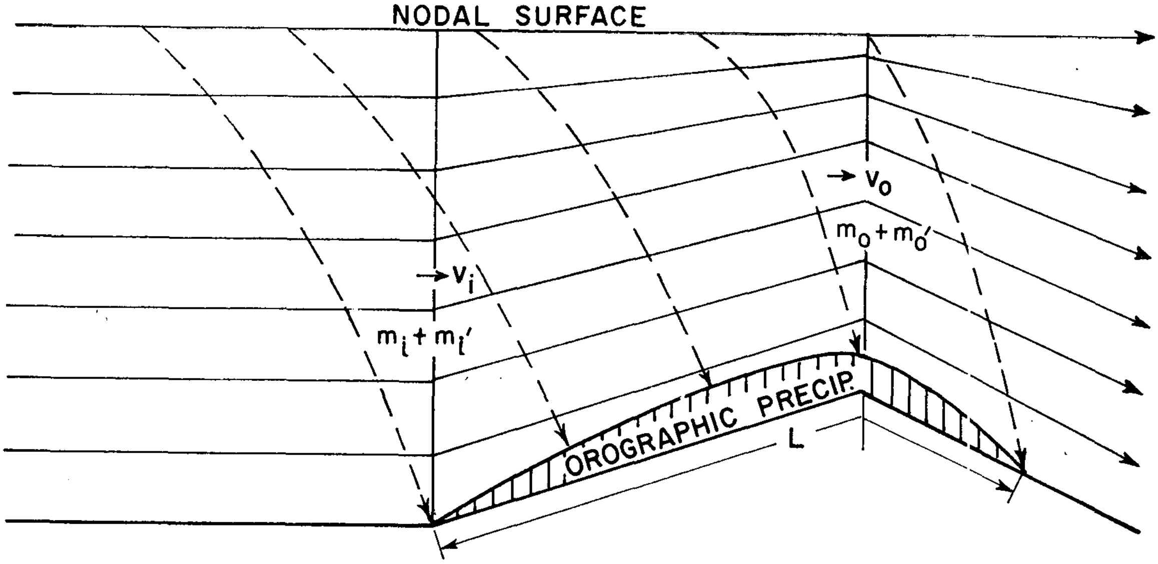

FIG. 1. Orographic precipitation model. V refers to the wind component perpendicular to the barrier and m to the water vapor content, with subscripts i and o referring to inflow and outflow, respectively. The solid lines represent streamlines; the dashed lines precipitation particle trajectories.

verge over the crest as shown in Fig. 1 and become level at the first nodal surface. At higher elevations, a series of reversals may occur. The condensation is, for the barriers investigated, most important below the first nodal surface whose height varies inversely with the stability and the vertical wind shear of the inflow air mass.

The theory will not be detailed here as it is adequately developed elsewhere by Myers (1962); however, it can be remarked that the pertinent equations are the Bernoulli, the hydrostatic, and the mass continuity. For a stable air mass, these alone, with appropriate boundary conditions including the inflow wind shear and stability, provide a family of solutions depending upon the value of the parameter, ratio of velocity at crest level to that at inflow ground level. Myers has employed the well-known hydraulics principle of minimum energy to determine which member of the family will represent the true flow.

The above flow model was used in this study but with additional refinements for the conditionally unstable air mass whose instability is realized over the barrier. In such a case, the theory indicates that the air over the crest would be warmer than that upwind, causing the isobaric surface to slope upward toward the crest. The resulting deceleration on the moving parcel would cause a vertical spreading of the streamlines with no nodal surface. However, in reality, there is always some limiting stable layer at or below the tropopause which coincides with the top of the positive area on an adiabatic diagram (following the parcel method). This lid has been used as the effective nodal surface in the conditionally unstable cases. Furthermore, for these situations, it has been assumed that the intense vertical mixing over the mountain crest will result in a uniform, no-shear outflow, whereas in the stable cases the vertical wind shear of the inflow has been carried to the outflow section.

The basic water balance can be expressed by the equation:

$$C_o=\int_o^L P_o dx+E=\int_n^c (m_i+m_i')V_i\frac{1}{g}dp - \int_n^c (m_o+m_o')V_o\frac{1}{g}dp. \quad (1)$$

The subscripts i and o refer to the inflow and outflow sections, respectively; C_o represents the orographic condensation to be determined; P_o is the precipitation rate along the distance L where all the precipitation which results from orographic lifting falls; E represents the losses due to evaporation; m and m' are the mixing ratios for water vapor and cloud-water, respectively, and V is the wind component normal to the barrier. The height of the nodal surface (in pressure units) is given by n and the base of the inflow by c.

The values of V_i and m_i are measured by the upwind rawinsonde while V_o and m_o are computed. The cloud-water content m', determined by measurement[5] to be a small fraction of the water vapor term m, has been neglected, as have the effects of convergence of the

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[5] Elliott, Robert D., Einar L. Hovind and John W. Flavin, Jr., 1962; Investigation of cloud-water budget of Pacific storms. Final Report NSF C-104. 54 pp.

precipitation particle trajectories and gage catch corrections. The integration has been carried out in 50-mb increments with the lifting condensation computed graphically over the same increments on the adiabatic chart.

The integrals were evaluated for the Santa Ynez range north of Santa Barbara and for the San Gabriel range northeast of Los Angeles, where three-hourly rawinsondes were available during storms from Point Arguello, west of Santa Barbara, and from Santa Monica in the Los Angeles basin. The readers are referred to the paper by Elliott and Shaffer (1962) for detailed geographical description of this region. The balloons released from Point Arguello normally travel northward over land of relatively low relief, while balloons from Santa Monica may traverse ridges of 500 to 1500 ft heights shortly after release.

The direction normal to the mountain was taken to be 180° in the Santa Ynez range and 220° in the San Gabriel range. Only cases with low level winds (3000 and 5000 ft wind, respectively) within 45° of these normal directions were used in this study in accordance with the results by Elliott and Shaffer, who showed statistical evidence of significant reduction of the orographic precipitation in these areas for wind directions outside the above limits.

Terrain cross sections and mean annual precipitation sections for the two ranges are shown in Figs. 2 and 3. The annual precipitation for the San Gabriel range (Fig. 2) shows a sharp rise at S from the coastal and basin amounts of about 13 and 18 inches to around 45 inches on the main crest, corresponding to the steep rise in the mountain range. The annual precipitation amount returns to its coastal value about 53 miles from the coast, which is taken as the boundary of the "spillover." Its location agrees with computations based upon reasonable fall velocities of the rimed snow and rain characteristic of this area. The distance L (see Fig. 1) was taken to be 27 miles and the total lift was assumed to occur between 1000 and 8000 ft, on the basis that the ground elevation is already close to 1000 ft at the foot of the San Gabriel range.

Fig. 3 shows how the mean annual precipitation distribution for the Santa Ynez range rises from the coastal values of around 17 inches to over 30 inches along the crest, falling off to 17 inches approximately $4\frac{1}{2}$ miles beyond the crest. This is assumed to be the limits of the "spillover," while the orographic effect is considered to start just north of Santa Barbara Airport. The distance L was taken to be 9.7 miles with a total lift from sea level to the 4000-ft level.

The two mountain ranges were divided into physical sectors with recording raingages well distributed within each. In the Santa Ynez range, three sectors with gage elevation ranging between 1000 and 4000 ft were used: one on the upwind flank, one on the crest and one in the Santa Ynez valley downwind of the crest. Since the San Gabriel range has an additional front range (see Fig. 2) four sectors with gage elevation ranging between 2500 and 6000 ft were used there: one on the front range, one in the intermountain valley, one on the upwind flank of the main range, and one in the area just beyond the main crest. The number of gages within each sector varied between one and three, and the records were weighted so as to give equal representation to each sector.

By way of smoothing the precipitation data, a three-hourly average centered on the hour in question was made so that in effect relationships between three-hourly totals were being employed. The rawinsonde data were considered representative of the local precipitation during the hour subsequent to the launching of the balloons. Appropriate time lags based upon the march of precipitation peaks from the non-orographic stations and the rawinsonde launch sites to the mountain networks were employed.

The total precipitation falling on an orographic barrier can, according to Elliott and Hovind (1964), be broken down into two basic components: 1) precipitation resulting from convergence mechanism on scales ranging from pre-trough storm convergence down through more localized frontal convergence to that associated with convection bands; 2) precipitation resulting from the effects of orographic lifting only. Weaver[6] employed a similar categorization in his studies of orographic precipitation in storms of extreme intensity.

The magnitude of the convergence component may be appreciably less in the higher mountains than over the coastal plains. Elliott and Shaffer showed that in very stable storms, where the orographic component is negligible, the precipitation rates in the San Gabriel range were only 45 per cent of those at Los Angeles International Airport. This difference is attributable to the added growth of precipitation particles, through collision and coalescence, while falling through the increased depth of cloud-water over the coastal plains. However, for the substantially lower Santa Ynez range, Elliott and Shaffer found this effect to be negligible with the convergence component best represented by 100 per cent of the precipitation rates at Santa Barbara Airport, Goleta. In this study, therefore, these ratios have been used to represent the convergence components in the respective areas. Applying the appropriate time shift between the coast and the mountains, as discussed earlier, these convergence components have been subtracted from the mountain precipitation rates to obtain a measure of the orographic effect.

Finally, it should be noted that this analysis has been confined to the heavier frontal precipitation south of cyclonic centers and excludes precipitation associated with cold lows aloft as treated by Williams and Peck (1962).

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[6] Weaver, *op. cit.*

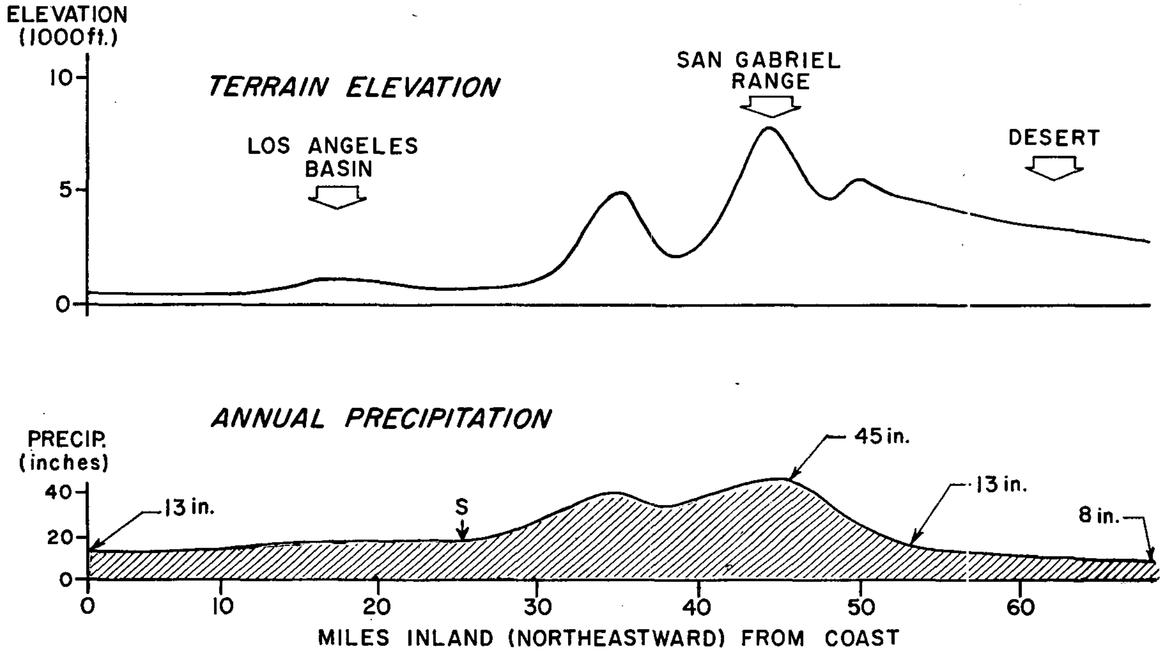

FIG. 2. Composite cross section of terrain elevation and annual precipitation for the coastal plain, the San Gabriel Range, and the desert.

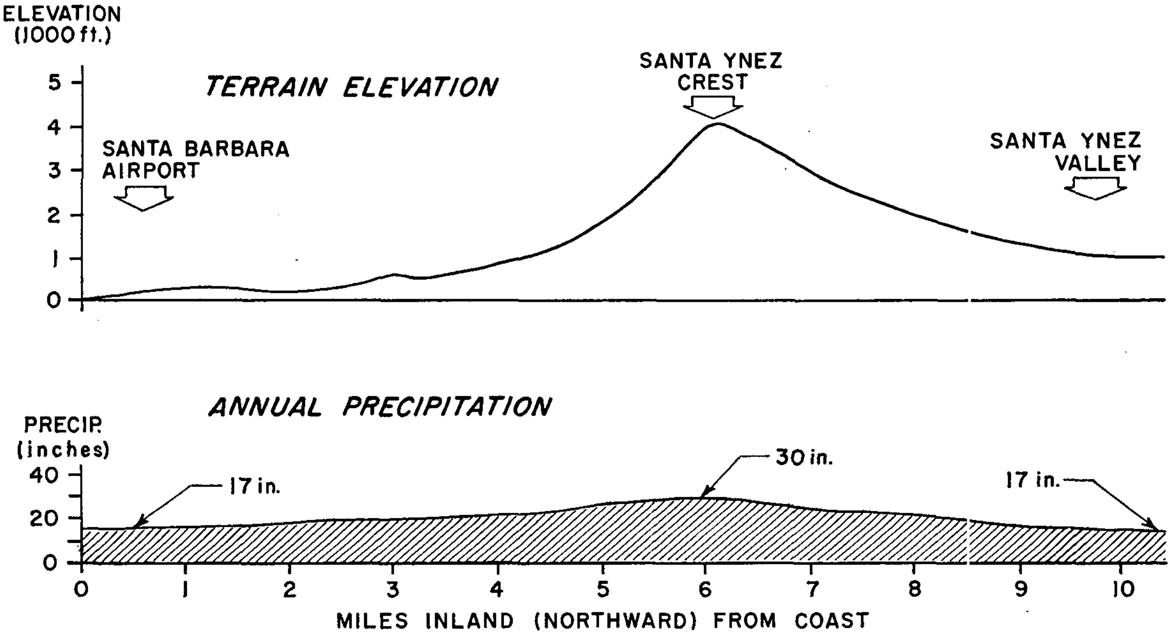

FIG. 3. Composite cross section of terrain elevation and annual precipitation for the coastal plain, the Santa Ynez Range, and the Santa Ynez Valley.

TABLE 1. Summary of comparisons between computed orographic condensation (C_o) and orographic precipitation (P_o).

Mountain range	Type	No. of cases	Ratio: (P_o/C_o)
San Gabriel	Stable	31	0.256
San Gabriel	Unstable	8	0.274
Santa Ynez	Stable	21	0.174
Santa Ynez	Unstable	22	0.261

3. Discussion of results

Table 1 summarizes the pertinent statistics resulting from this analysis. Notice the relatively few unstable cases in the San Gabriel range, due in part to the fact that the special three-hourly rawinsondes from Santa Monica were taken in conjunction with the water budget study in the Santa Barbara Channel area and were therefore often terminated before the main front reached the San Gabriel mountains. Consequently, since most of the unstable regions occur near the front, many of these were lost.

The ratio of orographic precipitation to condensation averaged 0.260 by case in the San Gabriel and 0.218 in the Santa Ynez. Thus, the orographic mean flow is seen to cause approximately one-quarter of the condensed water to fall out over watersheds of this size. The difference in results from the two ranges suggests that the larger barrier is more "efficient" in removing the water it condenses, and this relation becomes even more apparent when compared to the two-third ratio found by Myers (1962) for the 60-mile wide Sierra Nevada range in the intense storm of December 1955.

The results in Table 1 also show that the ratio of orographic precipitation to condensation was higher in the unstable than in the stable cases. An analysis of covariance in each area showed this difference to be highly significant in the case of the Santa Ynez range, but significant only at the 8 per cent level in the San Gabriels. However, this does not necessarily indicate a greater efficiency with convection which, of course, is stronger in the unstable cases. In fact, the purely convective precipitation process can be expected to be less efficient in converting the condensate to precipitation because of mixing of moist convection columns with the drier exterior air. Instead, the difference is considered indicative of greater orographic precipitation rates by reason of added convective overturning in the unstable air mass.

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