Rainfall at Hilo, Hawaii¹

By Tsutomu Takahashi

*Cloud Physics Observatory, Department of Meteorology, University of Hawaii
Hilo, Hawaii 96720*

(Manuscript received 4 September 1976, in revised form 17 December 1976)

Abstract

Rainfall at Hilo, Hawaii was studied by the character of inversion height and strength, which has a strong relation with movement of the upper cyclone. The electric field, satellite pictures, and general meteorological parameters such as upper wind, temperature and humidity profiles obtained by radiosonde were referred to for the rain classification. August rain was studied in detail as typical of trade-wind rain, and for another month, rain with ice phase was studied to compare with the rainfall pattern from warm rain.

The types of rain are subdivided into: a) morning and evening rain, caused by land and sea breezes when the inversion is low; b) intense, all-day rain, occurring when the inversion is high; c) weak but continuous rain, occurring when there are double inversions. There is no rain when the inversion height is less than 1.7 km.

Winter time cool rain is also studied. It is characterized by long-lasting, heavy rain-falls accompanied by high electrical activity and usually by lightning. This contrasts with warm rain, heavy but short-lasting falls with weak, negative electricity. It seems that although the presence of ice crystals does not contribute to high rainfall intensity from deep cloud, it is important for the generation of high electrical activity and for maintaining heavy rain.

1. Introduction

Many papers have been published about rain in Hawaii from the view of high rainfall amount and great climatic differentiation in such a small area (Leopold, 1948, and others). Yeh *et al.* (1951) classified Hawaiian rainfall into eight synoptic groups. Their classification showed that summer rain is mainly affected by a high pressure cell (trade wind system) and winter rain is mostly produced by the polar front. Yeh *et al.* (1951) obtained a good relation between winter rain and location of the jet stream.

Recently Makosky (1970) related summer rain to the frequency of vortices and obtained some relation to high rainfall in Hawaii.

In Hawaii, very moist air in the lower layers and the rapid transition from moist to dry air within a few hundred meters at around 2 km characterizes the trade wind humidity profile. This transition layer is relatively persistent even though the inversion height changes rapidly day

by day and the inversion may often disappear.

Since rain development is a strong function of cloud thickness and since cloud height is mainly determined by the inversion height and strength, I attempted to classify rainfall at Hilo in terms of the character of the inversion. August rain at Hilo (Hilo faces the trade wind, so that orographic shielding is insignificant) was chosen as typical of summer rain. Another month of summer rain (June, July and September) was also referred to for testing the validity of conclusion made by using August rain.

In this paper, the variation of the inversion height and strength is first discussed in relation to the upper wind profile and then rainfall in Hilo is classified in terms of the character of the inversion. After continuous rain is compared with a recent cloud model, discussion extends to the role of ice crystals in precipitation and the intensification of electricity.

2. Rain classification and time cross section

Continuous recordings of rainfall and electric potential gradients in August, 1975 are shown

¹ Contribution No. 76-5 of the Department of Meteorology, University of Hawaii.

Fig. 1 Rainfall intensity (heavy lines—strain gauge type) and electric potential gradient (thin lines—field mill type) with time in August, 1975, at Hilo, Hawaii. Reader can refer to Takahashi (1975) for more description of warm rain electricity.

in Fig. 1.

It rained almost every day except for two days (7th and 25th); rain eased off during the afternoons except for the 1st. Classifications could include morning and evening rain (5th, 8th, and 26th), daytime rain (1st, 3rd, 14th, 15th, 16th, 17th, and 20th), night time rain (9th, 10th, 21st, 23rd, and 27th), light but long-lasting rain (11th,

18th, and 19th).

Short duration rainfall is mostly characteristic while the electric potential gradient changes to negative during the rain. Upper wind, temperature and humidity profiles obtained at the Hilo Airport Weather Station are shown in Figs. 2, 3, and 4.

Two large upper cyclones moving toward the

Fig. 2 Upper winds observed by radiosonde at the Airport Weather Station, Hilo, Hawaii.

Fig. 3 Upper relative humidities observed by radiosonde at Hilo (thick solid lines—relative humidity, thin solid lines—temperature).

Fig. 4 Upper temperatures observed by radiosonde at Hilo, Hawaii. Slanted axis is chosen for temperature. Origin of each temperature scale at the ground is 25°C and divisions are at 10°C intervals. When the line is vertical, temperature lapse rate is 6°C km⁻¹.

west hit Hilo on the 3rd and on the 19th (Figs. 5a and b). Weak upper cyclone is also seen on the 13th. All the circulation extended down to 4 km. Because of the coarse weather stations in the tropics, small disturbance in the lower troposphere does not appear in the synoptic chart (Fig. 5c). However, time cross section of wind profile at the Hilo station shows the existence of many lower cells accompanied by the upper cyclone. The upper cool cyclonic cells were preceded and followed by small cells at middle troposphere (3–5 km); on the 1st, 11th, 18th, 24th, and 30th.

Fig. 5. Streamlines. a: 250 mb; b: 500 mb; c: 850 mb.

At each lower cell passage, winds in the cloud layer changed appreciably and the inversion was modified (2nd, from 8th to 10th, 20th, 29th, and 30th). On the 15th, a cyclonic vortex was located south of the island (satellite picture) and the easterlies were observed from the surface to 10 km.

When the lower tropospheric easterlies of the subtropical anticyclone were accelerated by these cells, inversions became stronger and shallower (from the 4th to the 7th). Similar events occurred from the 21st to the 24th; however, the northerly and southerly component of wind weakened the inversion. At the lower boundary of the cells,

northerlies or southerlies prevailed and inversion was destroyed.

A localized small cell west of the upper cyclonic cell at the 4 km transported unstable air from the south and made double inversions (18th). Similar weak double inversions are seen on the 1st and 11th. There was no inversion when a vortex lay south of Hawaii.

Moisture in the upper levels was carried by the southerlies east of the upper cyclone (4th and 20th). When there are double inversion, a cloud system is found beneath each.

Rain in Hilo will be classified in terms of inversion height (Fig. 6). A shallow inversion

Fig. 6 Classification of rainfall patterns at Hilo, Hawaii.

around 2 km corresponds to early morning rain (5th) and evening rain (26th). When the inversion was higher, light rain also fell in the late morning (24th). Daytime heavy rain occurred when the trade wind cloud deepened under the influence

Photo 1a. Satellite picture, 8^h48^m local time (Aug. 17, 1975), by ESSA. Dissipating vortex at 15°N-150°W which travelled from near Panama, originally. New active vortex is seen at 20°N-125°W.

Photo 1b. Satellite picture, 11^h18^m local time (Aug. 17, 1975). Near the Island of Hawaii, trade wind clouds are developing at high levels by the effect of the dissipating vortex.

Fig. 7 Diurnal variation of rainfall with different inversion heights during June, July, August and September, 1975. The thin shaded line shows the rainfall frequency when inversion is lower than 2 km; the dotted line, rainfall frequency when inversion is between 2.0 km and 2.5 km; and the thick line, rainfall frequency when inversion is between 2.5 km and 3 km.

of the cyclonic vortex (17th, photo 1a and 1b). Northerlies and southerlies at cloud level corresponded to less rain, especially during the daytime (28th and 9th), and even when the inversion was weak. Double inversion correspond to light but continuous rain (18th).

The diurnal variation of rainfall with different inversion heights during summer 1975 is shown in Fig. 7. When the inversion (where temperature increases with height) is lower than 2 km, rain is frequent during morning and evening. On the other hand, when inversion height is higher than 2.5 km, time of rain is widely distributed with less rain during the daytime.

Fig. 8 Annual rainfall for the Big Island of Hawaii. U.S. Weather Bureau. Flight path also shown.

Fig. 9 Potential temperature (thick line) and water vapor pressure (thin line) in morning. Flight path is shown in Fig. 8. Sounding was done by small spiral climbing by Cessna at positions shown by arrows. Sounding times were shown below each arrow. "B" stands for the location of cloud band. Inversion layer is shaded.

In the early morning, cloud builds over the ocean near and parallel to the windward shore of Hawaii under the influence of land breeze. The structure of temperature and water vapor was studied with an airborne fine thermistor installed in a double cylinder to minimize the radiation effect, and a Lyman- α humidimeter. Six flights were made (Fig. 8). Figure 9 shows temperature and water vapor profiles measured during the morning of Nov. 13, 1975 when the trade wind inversion was low.

Dry and cold air in the shallow land breeze accumulated over the ocean in the lower level to a distance of 15 km from the shore. Four cloud

2 a

2 b

Photo 2a. Morning clouds taken from Cessna on Nov. 13. Cloud band is building over the ocean parallel with the coast.

Photo 2b. Afternoon clouds taken from Cessna on Oct. 29. Thick haze is seen between coast and cloud band.

bands were observed on this day, formed by lifting of trade wind air over this cold dome. These cloud bands gave drizzle. They moved successively landward and dissipated shortly after crossing the coast. There was no other cloud over land. The sloping isentropes suggest that air at 1.5 km near the shore is slightly lifted. Photo 2a shows the development of a cloud band over the ocean near the coast. The inversion was horizontal (1.7 km) out to the limit of the flight.

On the other hand, on the afternoon of October 29, 1975, dry air was observed near the coast at a height of 1 km between the shore and 15 km off shore (Fig. 10). A group of shallow clouds which was observed between 15 km and 55 km from shore dissipated near the coast (photo 2b).

Fig. 10 Potential temperature (thick line) and water vapor pressure profiles (thin line) in afternoon. Increase of inversion height near the shore will be caused by the downward flow of dry air from inversion layer.

Because of land heating, outflow of air away from the mountain will increase during the afternoon. This outflow might be compensated for not only by the air under the inversion but also by dry air introduced from the inversion layer.

The morning rain is due to development of cloud bands by lifting at the cold dome formed by the land breeze. Less rain during the day might be due to the existence of subsiding dry air near the shore. In the late afternoon, as the land is cooled this dry air region disappears. Then clouds over the ocean will reach the coast without dissipation and will produce rain over the land. When the inversion is high and clouds are deep, clouds with rain will move over the coast without strong modification, even in daytime.

Wind direction also affects rainfall in Hilo. Hilo is the lee side when southerlies blow. Then clouds are carried in a semicircle toward north from South Point and form cloud line over the ocean far from Hilo. With northerlies, clouds experience strong wind shear because of the blocking of wind by Mauna Kea and the possibility of rain is reduced. At these times, even if there is no inversion, less rain is observed in Hilo, especially during the daytime. When there is a double inversion, drizzle will be seeded from altocumulus to lower cumulus. The precipitation process will be more efficient and the cumulus will rain out without strong vertical development.

The one-dimensional cloud model (Takahashi, 1976) was used to simulate the effect on rainfall of drizzle seeding in the cloud. When there is no drizzle sprayed into the cloud, the conversion speed from cloud droplet to raindrops is slow (Fig. 11a) and only very light rain is calculated

Fig. 11a Mixing ratio profile calculated in one-dimensional cloud model (re-produced from Takahashi, 1976). Dotted lines (cloud droplets), dashed lines (drizzle) and solid lines (rain-drops). Dot-dashed line is rainfall intensity at the ground.

Fig. 11b Spraying drizzle (size distribution is the same as Fig. 11a at $T=50$ min. and at this location) of $0.17 \text{ g} \cdot \text{kg}^{-1}$ at $T=50$ min. in the middle of cloud within 200 m depth. Significance of lines are the same as Fig. 11a.

at the ground (cloud nuclei concentration is assumed as 400 per cm^3). When drizzle ($0.17 \text{ gm} \cdot \text{kg}^{-1}$) is sprayed at $T=50$ min. to the central 200 m of the cloud layer, drizzle consumes the cloud droplets and is rapidly converted to rain (Fig. 11b). Rainfall intensity increases an order of magnitude and moderate rain is calculated at the ground.

3. Maximum rainfall intensity and inversion height

Maximum rainfall intensity observed in Hilo during the summer of 1975 was analyzed by reference to inversion height (Fig. 12). The large variation of data observed is partly due to the variation of concentration of cloud nuclei from day to day. The main reason might be the large rainfall gradients within showers. A main shower will not hit the station and in that case the maxi-

Fig. 12 Maximum rainfall intensity versus inversion height during June, July, August and September, 1975.

um rainfall intensity would be underestimated. If this is so, only maximum rainfall intensity at each inversion height would be meaningful.

It rains when the inversion is higher than 1.8 km and higher rainfall intensity is observed with higher inversion. When the inversion height is 2.5 km, maximum rainfall intensity is 100 mm per hour.

4. Patterns of cool rain and warm rain

Typical patterns of rainfall and electric potential gradient of warm rain (Aug. 14, 1975) and cool rain (Dec. 3, 1975) are shown in Fig. 13. Intense warm cloud rainfall lasts only a few minutes and is accompanied by negative potential gradient. The maximum negative potential gradient is around 1 kv per meter even if the rainfall rate is as great as $100 \text{ mm} \cdot \text{h}^{-1}$.

On the other hand, when snow is falling on Mauna Kea (14,000 ft.) and Mauna Loa (13,600

Fig. 13 Electric potential gradient (top) and rainfall intensity (bottom) from warm cloud (right side, August 14, 1975) and from thunderstorm (left side, December 3, 1975).

Fig. 14 Maximum rainfall intensity during shower and duration of shower heavier than 20 mm per hour. Solid circle: cool rain (October, 1973–January, 1976) and open circle: warm rain (August, 1975). Although the derivation of spatial rain distribution from rainfall at fixed station depends on the speed of the cloud cell, the tendency is for a wider, high rainfall distribution from cool rain than those from warm rain. “Cool rain” was defined as the case when high positive potential gradient appears. The shower having maximum rainfall intensity in the electric disturbance was only selected.

ft.), intense rain lasts longer and high positive potential gradient also appears. Negative potential gradient also increases and there is lightning in Hilo. Duration of the high rainfall when the rate is greater than $20 \text{ mm} \cdot \text{h}^{-1}$ is shown in Fig. 14 for both warm rain cases (Aug., 1975) and cool rain cases (1973–1975). In the latter, both rate and duration are greater than in the former.

5. Discussion and Conclusion

In this paper, rain in Hilo has been classified in terms of the character of inversion which in turn is determined by cyclonic cells in the middle and upper troposphere. Surface wind direction and local wind effects are also important.

The role of ice crystals in precipitation and intensification of electricity demands investigation since the main charge separation process will be involved with the ice phase.

Cloud formation is affected also by the Hawaiian island chain. When cloud moves from northeast, new cloud bands are formed two hundred km upwind from the islands and parallel to the chain (Photo 3). Because of the strong

Photo 3. Satellite picture, $11^{\text{h}}18^{\text{m}}$ local time (Aug. 30, 1975). Cloud at 200 km upwind from the chain of island is affected by islands. Karman vortex is seen downwind.

inversion, northeast winds skirt Hawaii. The study of the mechanism of formation and propagation of cloud bands near Hawaii may lead to an explanation of the formation of long cloud lines over the open tropical ocean.

Acknowledgements

The author would like to give his sincere appreciation to the Civil Air Patrol (Captain W. Kahaolopua and pilot J. Buckley) for their many hours of help with the airplane observations.

The author is indebted to Prof. C. Ramage for his very helpful suggestions and encouragement. Prof. C. Sadler and Prof. T. Schroeder gave much valuable information to the author. Mr. A. Austrung helped to prepare the diagram of upper soundings. The work was sponsored by the National Science Foundation under Contract (ATM 76-22194) and ONR (N00014-77-C-0031). Satellite pictures were provided by Honolulu Satellite Center.

References

- Leopold, L. B., 1948: Diurnal weather patterns on Oahu and Lanai, Territory of Hawaii. *Pacific Sci.*, **2**, 81–95.
- Makosky, F., 1970: Tropical vortices and other variables associated with Hawaiian summer rainfall. Thesis, Department of Meteorology, University of Hawaii.
- Takahashi, T., 1975: Electric charge life cycle in warm clouds. *J. Atmos. Sci.*, **32**, 123–142.

- , 1976: Warm rain, giant nuclei and chemical balance—a numerical model. *J. Atmos. Sci.*, **33**, 269–286.
- Yeh, T. C., C. C. Wallen and J. E. Carson, 1951: A study of rainfall over Oahu. *Meteorological Monographs*, **1**, (3), 34–46.
- , J. E. Carson and J. J. Marciano, 1951: On the relation between the circumpolar westerly current and rainfall over the Hawaiian Islands. *Meteorological Monographs*, **1**, (3), 47–55.

ハ ワ イ 島 の 雨

高 橋 劭

ハワイ大学・雲物理研究所

ハワイ島の雨を逆転層の高さ、強度に関係させて分類することをこころみた。貿易風の強い8月の場合がこの論文ではくわしく解析された。雨は逆転層が低い時に見られる早朝と夕方のシャワー（海・陸風に左右される）、逆転層の高い時に見られる日中の強い雨、逆転層が2層あるときの地雨に大別された、又この逆転層が上層の cyclonic cell の動きと密接な関係があることもわかった。

Front system の影響をうけるハワイの冬の雨との比較で空中電場に強い差が見られた。氷晶の存在がその原因であらう。