Trade Cumulus Cloud Groups: Some Observations Suggesting a Mechanism of Their Origin[1]

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Abstract

On a recent field trip to the western Caribbean, temperature gradients in the surface layers of the trade-wind oceans were found and related to the presence of cumulus cloud groups. The cloud groups generally formed over and slightly downwind of warm spots which were several kilometers in extent along the wind and 0.1—0.3° C in amplitude. Clouds were not found in the absence of warm spots although warm spots were occasionally encountered without clouds.

Air circulations, similar to but weaker than those produced by heated land masses, are hypothesized to exist over oceanic warm spots and their magnitude is estimated from previous work on heated islands. Observed differences in low-level moisture structure between clear and cloudy areas may be interpreted in terms of such circulations and their evolution with time. Some suggestions are made concerning the life cycles of trade cumuli.

I. Introduction

Oceanic trade cumulus commonly appear in irregular groups about 10—50 km across separated by somewhat wider clear spaces. Cloud grouping and structure do not seem to vary from day to night. Early observations showed that individual trade cumuli do not have "roots" in thermals extending up from the sea surface, nor are they observed in regular patterns suggesting polygonal convection cells. In fact, these two possibilities of their origin are excluded because the air layer below cloud is actually slightly stable at all elevations above the first few meters.

Time-lapse motion pictures suggest that trade-wind clouds almost always form in groups, and that the groups themselves go through a life cycle, beginning their existence as a large number of small cloudlets, a considerable fraction of which may later attain the precipitation stage together. Isolated swelling cumulus or shower clouds are exceptional. In view of the probable importance of large precipitating cloud areas in the initiation of tropical storms and of the interaction of cloud elements with one another to form larger clouds, we have become concerned with the original formation of these groups. We wish to ask what processes are at work below cloud to permit large numbers of moist air parcels simultaneously to reach the condensation level in particular localities.

The base of trade-wind clouds averages about 650 meters, with extreme variations ranging between 300 and 1,000 m. The lowest four-fifths of this subcloud layer is well mixed, with a temperature lapse rate about 0.9 adiabatic and a very slow vertical decay of mixing ratio (about 10^{-8} cm^{-1} or less). The upper 100—200 m is usually more stable, with a mean potential temperature increase of 1° C and an order of magnitude increase in moisture

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lapse rate. The stable layer is more pronounced in the clear regions than in those topped by clouds, where it is often absent altogether. On the average in clear areas the top of the mixed layer is at about 85 % of the height of the lifting condensation level of the air composing it, while in cloudy areas the mixed region reaches to 95—100 % of the L.C.L. or 75 m higher. These figures suggest that the origin of trade cumulus groups is to be sought in factors producing weak convergences on the 10—50 km horizontal scale in the subcloud layer. Small variations in one or more sea surface properties such as roughness, radiative character, temperature, or evaporation might suffice to set up such circulations; in particular it seemed desirable to determine whether or not slight differences in sea surface temperature (below the sensitivity of standard oceanographic instruments) might not be common and perhaps associated with cloud groups.

The latter suggestion arose from theoretical and observational studies of air flow over small heated islands, both in the tropics and in middle latitudes. In the sunny hours, islands in the trades are vigorous sources of cumulus, and in fact the cloud towers have often been used by pilots and mariners to locate an island when too far away to discern the land mass itself. The theory of flow over a heat source (STERN and MALKUS, 1953) shows why these islands are such excellent producers of cumulus. Corresponding to each heated island may be derived an "equivalent mountain", its height depending directly upon the land temperature excess and inversely upon the stability of the undisturbed air, with a shape corresponding closely to that of the island temperature profile. This "mountain" builds up and decays diurnally. For islands in the trade stream, every degree (Centigrade) temperature excess adds about 500 m to the mountain's magnitude. The mountain itself, rather than being a solid obstacle, consists of a deeper turbulent mixed layer which has been thickened due to the added heat flux and the convergent circulation, so that the low-level streamlines crossing it are deformed upward corresponding to its amplitude and shape.

Thus over the oceans themselves, very slight surface temperature patchiness might be responsible for the initial formation of cloud groups. Since the top of the mixed layer falls short of the condensation level by 50—100 meters or less, island-sized warm spots exceeding the temperature of their surroundings by just a few tenths of a degree could give rise to "equivalent hills" high enough to permit the air in the subcloud layer to reach the height of its average condensation level, so that the moister eddies near its top attain saturation and appear as small cloudlets. The surrounding areas would be clear spaces in which compensatory subsidence occurs, similar to the clear subsidence rings observed around the islands (MALKUS, 1955). Randomly distributed low hills of 10—50 km scale, giving rise to clouds clustered over and slightly downwind of them, would present a picture of cloud patterns similar to those photographed and mapped by the Wyman-Woodcock expedition to the trades (Fig. 1). It remained to determine whether adequate temperature gradients are present in the surface layers of the tropical oceans.

Recently an airborne instrument has been developed at the Woods Hole Oceanographic Institution which detects slight sea surface temperature differences. In April 1956, a short field trip to the western Caribbean was made, flying this instrument in the Institution's PBY airplane. The observations were made in such a manner that it was possible to relate sea surface thermal structure to cloud formations. In the few flights made to date, a remarkably clear relation between these patterns was observed. The first part of this paper describes the methods and results of the field work. Then some deductions are made concerning the convective air motions associated with surface thermal gradients of the sizes and magnitudes observed. These are used to interpret previously obtained data on the structure of clear and cloudy areas and to discuss the life cycles of trade cumulus clouds and cloud groups.

II. Observations of surface temperature anomalies and their relation to cloud groups

The airborne radiation thermometer is a device which measures the long wave-length radiation from the surface over which it is being flown. The detector looks through an optical system alternately at the surface and at a reference black body and compares the temperature of the two. The black body is main-

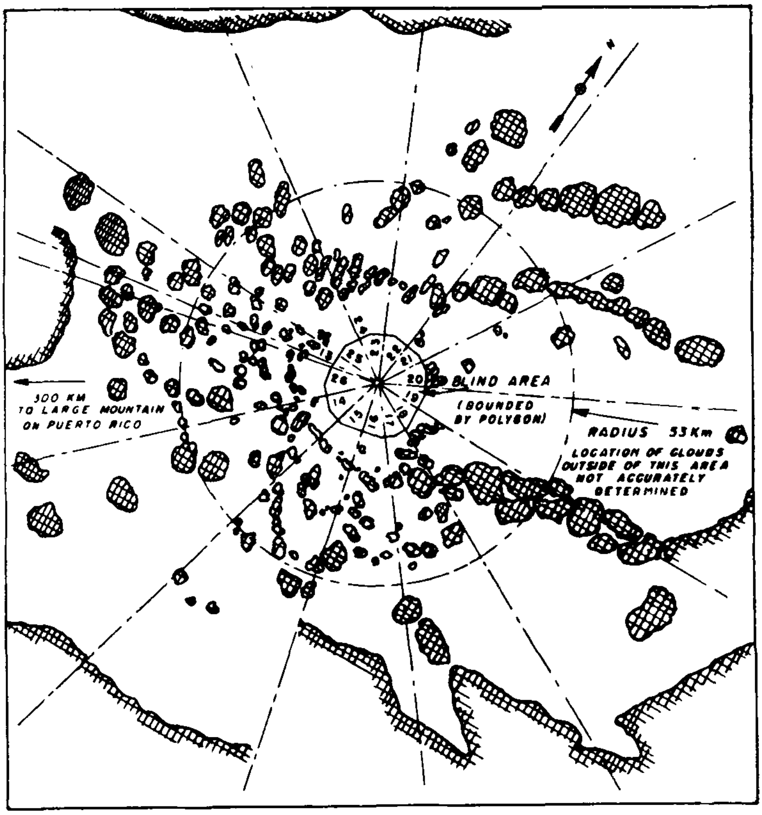

Fig. 1. Map made from cloud photographs showing a typical distribution of oceanic trade cumuli. Calculated from high altitude photographs Nos. 13—26 made by the Wyman-Woodcock Caribbean expedition. The radius of the dashed circle is 53 km; location of its center at 20°00′ N, 64°25′ W. The wind was east-southeast decreasing slightly with elevation. Note the rather irregular spacing of clear and cloudy areas. Only the medium and large clouds within the 53-km circle have been accurately located. The shaded areas are distant cloud banks.

tained at a temperature about five degrees higher than ambient in the aircraft. The instrument is calibrated so that the recorded signal is linearly proportional to the difference between the temperature of the surface and the constant temperature of the black body; at maximum sensitivity it resolves gradients of hundredths of a degree occurring over horizontal distances down to 50—100 m (when carried at the speed of the PBY). On the recent field trip, it was flown at 1,000 ft across the coastline of Jamaica (18° N, 77°30′ W) and neighboring small islands, and up- and downwind over the surrounding oceans. A small source of error arises from water vapor variations in the air column between the instrument and sea level; however, the column would have to possess sudden humidity gradients greater than five times the observed maxima to make this error larger than a few hundredths of a degree. It may be shown further that this error slightly minimizes the oceanic gradients detected. The best corroboration of the records presented here, however, lies in similar measurements obtained in the same area on the same days by the Research Vessel ATLANTIS, which was equipped with sensitive recording thermometers mounted near the surface and at several depths down to 80 ft.

On the aircraft flights, the locations of cloud formations were marked on the surface temperature records by hand punching a key from the blister as each cloud passed overhead and by a motion picture camera aimed vertically upward. Examination of the results shows that sea surface temperature differences from about 0.1—0.3° C were common on days with active cumulus convection. On days of light winds the gradients were often extremely sharp, a "step" up or down occupying less than 50 m in the horizontal, while with strong winds the edges appeared more diffuse, the same temperature change taking about 1 km. Both "warm spots" and "cold spots" were found, the sizes of which could often be determined from the records. Over the open sea these ranged from 4—20 km in extent along the direction of the wind. Larger scales probably also occurred, since frequently the aircraft crossed a gradient up or down without crossing any noticeable one in the opposite sense before the run had to be ended. Insufficient cross-wind flying was done to determine scales in that direction.

The association of thermal and cloud patterns was surprisingly good and may be summarized as follows: For four flights near Jamaica (10—60 miles offshore)

1) Clouds when present were always associated with warm spots (not cold spots) although they frequently were best developed at the downwind boundary of a warm spot where the temperature gradient was steepest.

2) Cloud groups were generally displaced slightly downwind relative to warm spots, as would be the case over a hill or island.

3) Groups of clouds were generally associated with warm spots, individual clouds being of a much smaller scale. Some individual clouds could be detected on the temperature records since their shadows occasionally produced cloud-sized cool spots as much as a few hundredths of a degree in amplitude.

4) Warm spots were sometimes found without any clouds. In the majority of those cases over the open sea, however, the temperature anomalies did not exceed about one-half the amplitude of those with which clouds were associated on a given day. Warm spots without clouds were also occasionally encountered within the subsidence zone surrounding Jamaica.

5) Oceanic cloud groups were not found in the absence of temperature anomalies.

The temperature records were quite reproducible: on return flights across the "step" zone the same gradients in the opposite sense were invariably found although on one occasion successive crossings made it appear that both the step and associated cloud group were

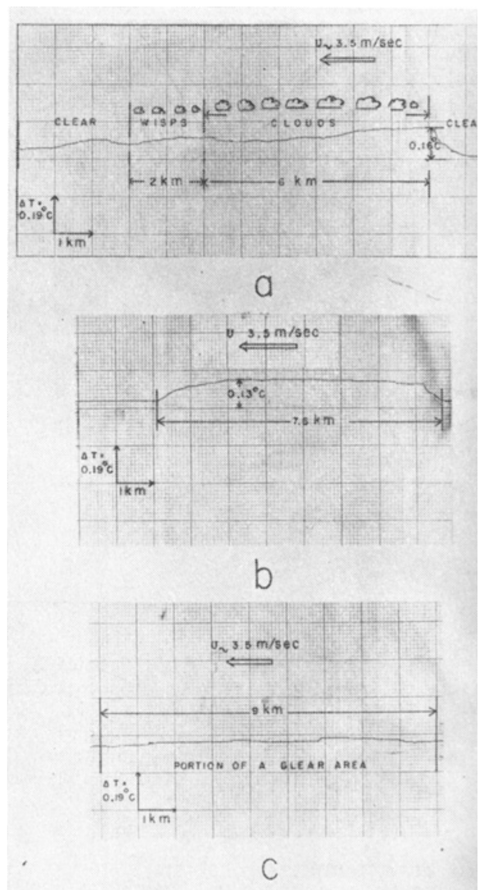

Fig. 2. Sea surface temperature records from radiation thermometer on day of light wind ($U \sim 3.5$ m/sec) and fair trade cumulus. All flights made into wind. Temperature increases upward.

a. Warm spot with cumulus. Clouds drawn somewhat larger than actual widths. Only beginning and end of group marked accurately.
b. Warm spot without cumulus. Found within subsidence ring off island of Jamaica (about 15 miles north). This warm spot has typical temperature profile for light wind day, steeper on upwind edge and more gradual on lee edge.
c. Typical record from clear zone on same day. On this occasion the clear zones were much wider than the cloudy ones and the warm spots were few and far between. No temperature anomalies greater than about 0.04° C were found in clear zones except near the island (see b.).

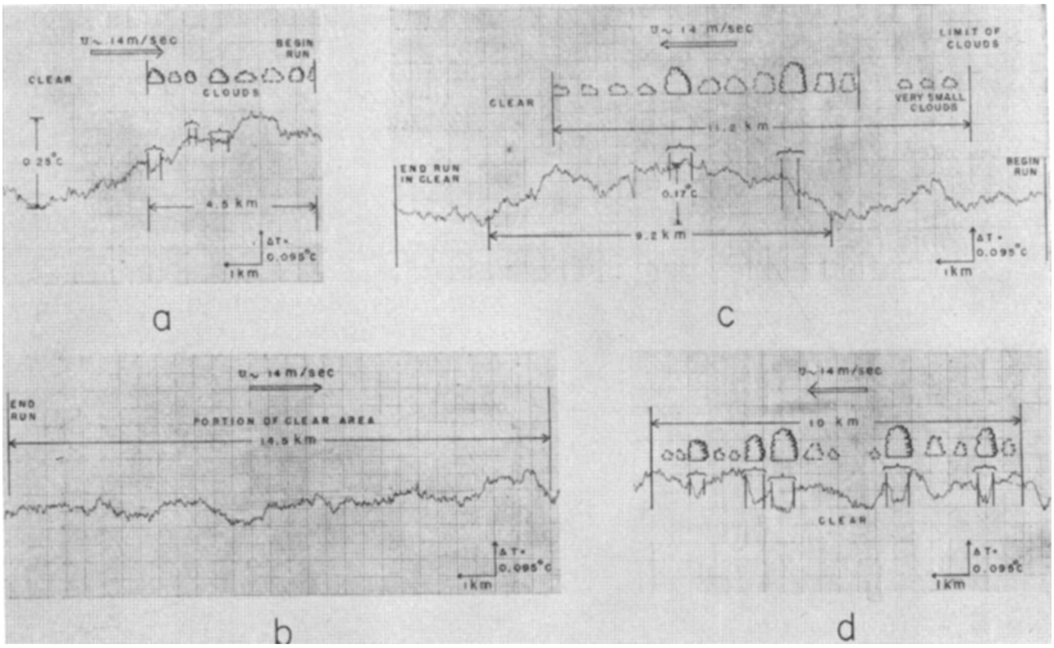

Fig. 3. Sea surface temperature records from radiation thermometer on day of strong wind ($U \sim 14$ m/sec) Some of the increased small-scale fluctuations on these records are real (some small dips are cloud shadows; a few are marked) and some are undoubtedly instrumental. The instrument was operated on this occasion in a manner bound to give more noise than on the occasions of Fig. 1 and 4. Temperatures increase upward.

a. Warm spot 0.25° C in amplitude associated with clouds. Run was made upwind and begins at right edge of figure (within cloudy area) and continued past its downwind edge far into clear area to left. Some of the cloud shadows were marked on the record and are denoted by small brackets with solid-line clouds above. The remaining (dotted) clouds are located approximately.

b. Typical clear area record for the same day. Direct continuation of upwind run begun in Fig. 3 a. Some of the small-scale noise may be instrumental in origin.

c. Upwind run completely traversing 9-km warm spot 0.17° C in amplitude. This warm spot was located on repeated traverses up- and downwind across it and showed little change in amplitude in the time studied. The solid-line clouds were coded accurately on the record as was the beginning and end of the cloud group. The remaining (dotted) clouds are located approximately.

d. Portion of a downwind run made within a warm spot at least 20 km across. Reproduced to show cloud shadows which had the most pronounced effect on the temperature record of any observed over water, due probably to clouds of greater vertical thickness and blacker appearance from below. The bracketed shadows with solid-line clouds drawn above were coded accurately on the record. The remaining (dotted) clouds are sketched approximately.

gradually dying out. No good idea of the duration of the warm spots could be obtained from the flights, although time-lapse photographs from the Jamaica beach (which were directed to following the life histories of cloud groups as a whole) suggest that often they persisted in nearly the same locality for at least 3—4 hours.

The ATLANTIS records confirmed the aircraft temperature data, and on certain rather calm days showed even sharper steps than the gradients reported above; on occasions a 0.1—0.2° C temperature rise or fall occupied only about 10—20 ft in the horizontal. Steps of the same amplitude were recorded on all the lower-level thermometers, with only very slight changes in shape with increasing depth. It appears that this temperature patchiness of the sea surface layers is not a peculiarity of the waters around Jamaica, for the Atlantis obtained similar anomalies on the homeward voyage to Charleston, South Carolina.

Several typical records from the airborne instrument are reproduced in Figures 2—4.

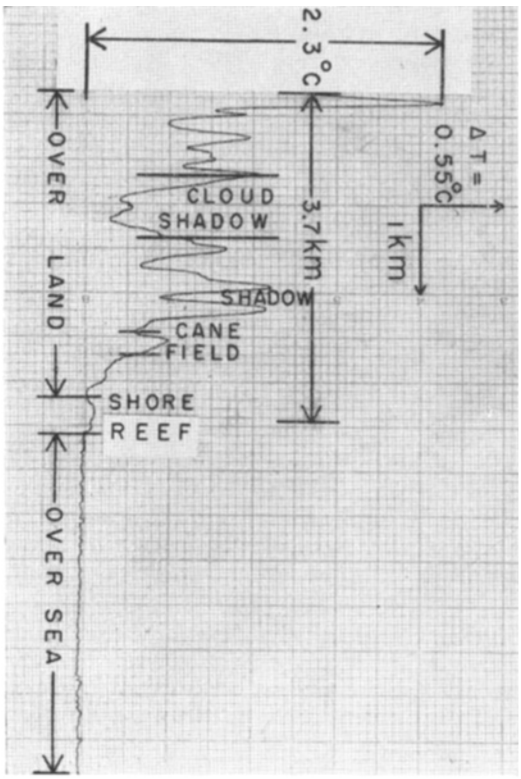

Fig. 4. Island run made at 10.00 a.m. local time on the same strong wind day as the records of Fig. 3. Run made from land to sea across Jamaica north coastline, which lies east-west or nearly parallel to the wind. All fluctuations shown over land are real. Some could be associated with terrain features and several marked dips occurred under cloud shadows; two of these were coded on the record. Instrument is operated on much lower sensitivity than preceding records so that maximum land temperature excess was 2.3° C.

One trace obtained from flying across the Jamaica coastline on a sunny day is shown for comparison. Even though the island record was not made at the maximum of diurnal heating (when the island thermal excess might be expected to be about 25 % greater), the land warming may at first appear small. To understand this it should be pointed out that the radiation instrument operates in the infra-red wave length range 8—13 microns, in order to minimize absorption by the water vapor intervening between the surface and the detector.

While a water surface is a nearly perfect black body in this part of the spectrum, a beach and soil surface undoubtedly has significant albedo. Thus what was measured here might be called the "equivalent black body temperature" of the island. The actual ground temperature, if measured, probably would have been much higher. However, the island temperature rise of Figure 4 is quite in keeping with the land thermal profiles deduced elsewhere as consistent with observed convective and sea-breeze circulations (see MALKUS and STERN, 1953; MALKUS, 1955). This agreement between "equivalent black body temperature" of the land surface and the temperature excess necessary to drive convective motions is probably more than coincidence—if the emission of infra-red radiation is one of the major processes controlling the heat flux from the boundary to the lowest air. Thus we may hypothesize that the radiation thermometer gives approximately the "effective" (for convective motions) boundary temperature of a land as well as a water surface. The contrast between the observed sea and land thermal profiles of Figures 2—4 is striking, the land showing enormously larger fluctuations, due both to differences in soil character and to cloud shadows.

III. Air circulations produced by differential heating

A mechanism for the initiation of cumulus groups over sea surface warm spots was suggested by the "equivalent mountain" analogy which, in fact, provided the incentive for the observations reported above. The "equivalent mountain" effect is associated with a horizontally convergent circulation across the warmed region and concomitant weak updrafts above it, superimposed upon the mean wind flow. If we may continue applying the island model of differential heating to the tradewind oceans, the approximate magnitude and structure of similar convergent circulations over the warm spots is readily deduced. This permits derivation of a quantitative relation between the observed temperature excess and the expected differences in air structure across a warm spot. While this picture undoubtedly oversimplifies the complex interactions between ocean and atmosphere, circulations of the deduced strength and scale account for several features of the subcloud air which were inexplicable in terms of turbulent fluxes alone, and in so doing provide a plausible connection between the evolution of cloud groups and processes occurring below cloud.

The maximum height of the "equivalent mountain" corresponding to a heated island has been shown to be

$$M = \frac{\tau}{\Gamma - \gamma} \qquad (1)$$

where M is in cm; τ is the effective island temperature excess in °C; Γ is the adiabatic lapse rate, and γ is the lapse rate of the undisturbed air upwind. This maximum is reached at a distance sufficiently inshore from the upwind beach to allow for the establishment by turbulence of a well-mixed ground layer. Thus the equivalent mountain slope may be more gradual than that of the temperature profile and in mid-latitudes on days of poor mixing the maximum height may not be attained in passage across the island. In the trades, the lower air is nearly adiabatic to begin with and the amplitude prescribed by the temperature profile is normally reached within 3—5 km downwind of the island boundary. The greatest "mountain" elevation and streamline deformation are thus commonly encountered at the lee shore where τ is largest. Since the average lapse rate of the trade-region moist layer (surface to inversion height at 2—3 km) varies little from about 0.8 adiabatic, the height of the equivalent mountain in kilometers is usually close to one-half the temperature excess in degrees.

The main features of the heat-produced circulation may now be deduced if we know the height at which the "sea breeze" reverses direction, because this is also the height of maximum vertical velocity: that is to say, it is the height at which the streamline deformation reaches the full amplitude prescribed by equation (1). This height has been derived as

$$h = \frac{\pi}{2} \frac{U}{\sqrt{gs}} \qquad (2)$$

where h is in cm; U is the undisturbed wind in cm/sec; s is the upwind static stability, $\Gamma - \gamma / \bar{T}$, where $\bar{T}$ is the mean absolute temperature of the air layer and g is the acceleration of gravity. Since in the trades gs varies little from about 7×10^{-5} sec^{-2}, this relation may be written approximately

$$h \text{ (km)} \cong 0.2\, U \text{ m/sec} \qquad (3)$$

Thus for a normal wind speed of 5 m/sec the height of the sea-breeze reversal is about 1 km, being proportionally higher or lower for a stronger or weaker trade.

It is now possible to estimate the average vertical motion at level h, since the air must ascend the height of the equivalent mountain in the time it requires to cross the island, namely U/d where d is the island width. Thus

$$\bar{w} = \frac{\tau}{\Gamma - \gamma} \frac{U}{d} \qquad (4)$$

Clearly this is only the average upward motion, for the vertical ascent rate depends on the slope of the equivalent mountain and thus on the features of the temperature profile; it no doubt varies across the island. Larger islands will show weaker mean ascent rates than smaller ones since τ does not rise linearly with island width. The prediction of equation (4) was borne out in comparing the vertical motions over Anegada (2 by 10 km) with those over Puerto Rico (50 by 160 km).

Thus up to maximum $\bar{w}$, its average rate of increase with height is $\bar{w}/h$ and if the island is larger in its cross-stream than down-stream extent, the average horizontal wind difference across it is approximately

$$\frac{\overline{\Delta u}}{\tau} \cong \frac{U}{(\Gamma - \gamma)\, h} \qquad (5)$$

and when h is substituted from (2)

$$\frac{\overline{\Delta u}}{\tau} \cong \frac{2}{\pi \bar{T}} \sqrt{\frac{g}{s}} \qquad (6)$$

or

$$\frac{\overline{\Delta u} \text{ (m/sec)}}{\tau} \cong 2.5 \qquad (7)$$

for normal trade-region stabilities. Equation (7) gives the wind difference across an island averaged from the surface up to the height where it vanishes. Observations indicate that the tropical sea breeze is about constant up to 300 m or so, from which it decreases roughly linearly to zero at h. Thus we deduce that the low-level wind difference across a heated region should be approximately 3.6 m/sec per °C mean effective surface temperature excess or that the sea-breeze component at each boundary should be about 1.8 m/sec per degree. Therefore for islands and oceanic warm spots in the trades, the "sea-breeze" strength and equivalent mountain height should depend primarily on the effective temperature excess. The height of sea-breeze reversal (maximum updraft) should vary directly as the wind speed.

These relations have been tested satisfactorily for three islands in the Atlantic trade-wind region, two large (about 50 by 150 km) and one small (about 2 by 10 km). The methods, observations used, and results are reported elsewhere (MALKUS, 1955; 1956). If they may now be applied to the oceanic warm spots, the expected circulations are inferred as follows: For a typical warm region 0.2° C in amplitude and 10 km horizontal extent in the direction of the wind, the equivalent mountain is 100 m high; Δu at the surface is 0.7 m/sec, and if the trade is blowing at 6.7 m/sec (15 miles per hour) the height of "sea-breeze" reversal is 1,350 m. The air would take about 25 minutes to cross the warm spot and the upward motions at 650 m (average level of cloud base) will be 4.3 cm/sec so that the streamline starting at that height at the upwind edge will have risen 65 m by the downwind boundary. The wind profiles expected at the two edges of the warm region are shown in Figure 5. These have been obtained by adding the heat-produced motions to an average oceanic trade-wind profile.

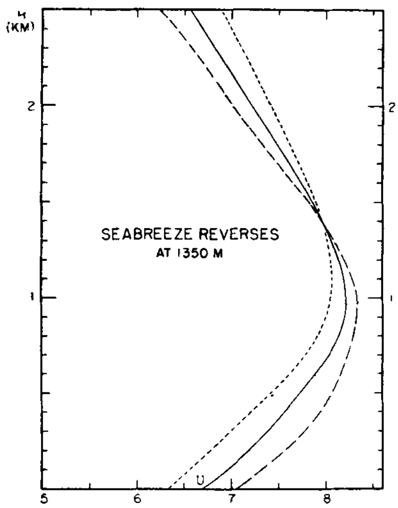

Fig. 5. Calculated wind anomalies associated with typical warm spot. An average oceanic trade-wind distribution with height is given by the solid curve *U*. The long dashed curve shows the modified profile expected at the upwind edge of a 0.2° C warm spot 10 km across, and the short dashed curve is the expected profile at the downwind edge. The surface value of the "sea breeze", its elevation of reversal, and its height distribution are obtained as outlined in text and equations. These profiles are believed to prevail after the warm spot has been in existence long enough for a quasi-steady circulation to develop.

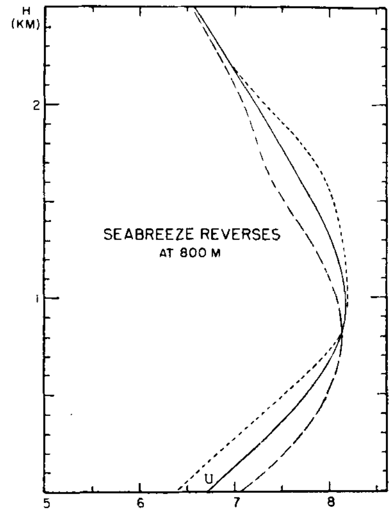

Fig. 6. Calculated wind anomalies associated with an oceanic warm spot in an intermediate stage of development. The solid curve *U* is the same as the solid curve of Fig. 5. In this case the expected profiles at the upwind (long dashed curve) and downwind short dashed curve) edges of the warm spot have been obtained assuming that the sea breeze changes sign at 800 m, instead of 1,350 m as in Fig. 5. The surface wind anomalies are the same in the two figures.

This situation is envisaged after the warm spot has been in existence long enough for the establishment of a quasi-steady flow pattern. The time dependence of the motion field should not be ignored. Island observations suggest that although the offshore subsidence ring is formed and the sea breeze sets in at the coast within an hour after the land becomes warmer than the water, the growth in size of the cell is slower, the maximum depth and inshore penetration requiring several hours. Thus it is probable that the main feature of the aging of the circulation is its deepening with time up to the maximum-depth configuration of Figure 5. A likely intermediate flow condition might be the one of Figure 6 in which the surface $\triangle u$ is the same but the "sea breeze" reverses at 800 m. The corresponding $\overline{w}$ at cloud-base level is 3.3 cm/sec. The effects of such circulations and their changes with time upon the air flowing through them is considered in the next section.

IV. Effects upon the air structure

During the Wyman-Woodcock expedition to the trades in 1946, numerous vertical soundings of air temperature and humidity were made over the open ocean. On many of the observing days, soundings were taken both in clear and cloudy areas. These have been segregated and the features of the lower air compared. Marked differences in moisture structure below cloud-base level were apparent. The top of the mixed layer averaged 550 m, or less than 100 m below cloud base. In this layer, the air in cloudy regions contained 2 % more moisture than that in the clear, with a 0.3—0.4 gm/kgm higher mixing ratio at the top. This means that the moisture lapse rate in the cloudy-zone mixed layer was on the average 22 % less than in the clear-zone mixed layer. In the 100-m "stable" layer just below cloud base, the differences were even more striking. The moisture lapse rate in cloudy zones fell short of that in clear zones by 33 %, and at cloud-base level (but generally away from clouds) the mixing ratio in cloudy zones exceeded that in clear zones by an average of about 1 gm/kgm. On three occasions in cloudy areas, the upward moisture lapse rate was actually zero or negative in this last 100 m below cloud base and the mixing ratio at cloud-base level exceeded that in nearby clear zones by 1.5—2.0 gm/kgm. The mean surface wind varied little throughout the observation period.

Turbulent fluxes do not account for these distributions. Furthermore, the effects upon turbulent transports of the small surface temperature excesses are unlikely to alter the air structure appreciably above the lowest 100 m or so in the time the air spends crossing the warm spot. Evaporation from the sea surface is increased by 4 % at most. On the other hand, weak circulations caused by the heating can account for the differences. The effectiveness of these scales of motion in transporting water vapor is illustrated when we calculate that the moisture flux produced by a 4 cm/sec vertical velocity exceeds locally the observed evaporation rate and turbulent flux by an order of magnitude. This does not imply that the net integrated upward flux due to these motions exceeds the turbulent transports, as will be seen later, but it does suggest local variations depending upon position relative to the flow pattern.

A typical trade-wind air stream flowing across a warm spot and through its circulation is now considered. The air starts at the upwind edge with the moisture structure typical of a clear area and the laws of mass and water vapor conservation are applied assuming that the air passes through the region in a time small compared to that needed for the motion field to change. Fluxes into and out of the mixed and stable layers are balanced successively using the circulations shown in Figures 5 and 6. The tacit assumption has been made that the evaporation and the upward turbulent flux through cloud-base level are about equal to each other and vary little with position. The results may be discussed using Figure 7. If we consider the mixed layer and apply first the circulation of Figure 6 and then the more mature flow of Figure 5, we get the results in Figures 7 a and 7 b respectively. Although the motion field differs slightly between a and b the resulting differences in moisture structure are negligible. If the air crosses the upwind boundary of the warm spot with the water vapor distribution typical of a clear area, then it may cross the downwind boundary with a distribution typical of a cloudy area. The depicted average mixing ratio increase of about 2 % is required by the superposition of the motion field upon an air stream which dries out with height in the manner of the trades: To satisfy continuity in a steady, horizontally convergent flow, the air column with the smaller wind must be more moist than the column with the stronger wind, in direct proportion that the mixing ratio at the top boundary is less than the average value at the inflow end. It is not a unique solution from these diagrams, which deal with the mixed layer as a single box, that the greatest

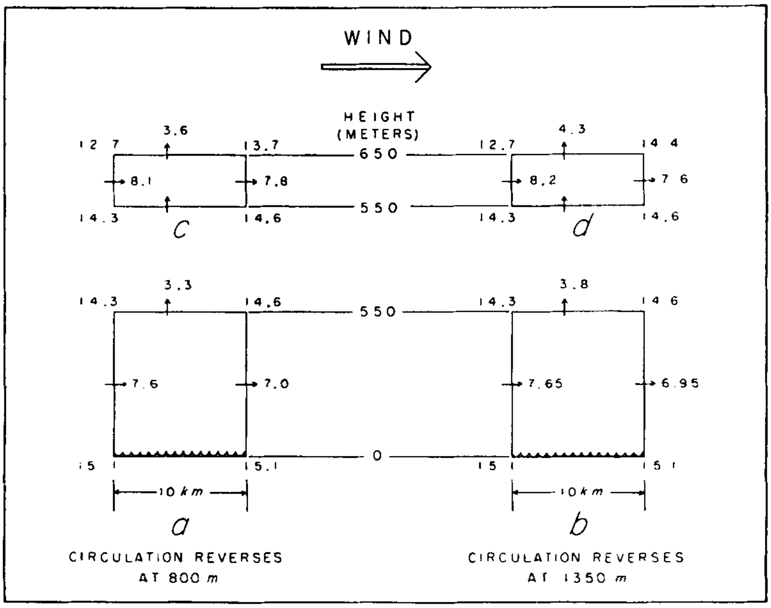

Fig. 7. Diagrams showing mixing ratio and velocity structures obeying mass and moisture conservation laws when typical trade-wind air flows across a 10-km warm spot. The horizontal arrows are wind speeds in m/sec; vertical arrows are mean vertical motions in cm/sec; and the numbers at the corner of each box are mixing ratios in gm/kgm. All figures are rounded off. Boxes a and c use the velocities of the shallower circulation of Fig. 6; boxes b and d use those of the deeper circulation of Fig. 5. In a and b the 550-m deep mixed layer is dealt with as a section 10 km across and unit width into the page. The air and water vapor entering per sec at the upwind (left-hand) side must equal the outflow per sec through the top and downwind (right-hand) side. In c and d the next higher stable layer is treated as a similar section 100 m deep. In each case the inflow air has the moisture distribution of a clear area. The moisture distribution at the outflow end is adjusted to satisfy continuity.

vapor accumulation occurs at the top. This must be so, however, if the moisture lapse rate increases upward as it does in the trade. The greatest moisture addition has thus been made at 550 m, which gives a diminution of mixing ratio lapse rate of 38 % between the extreme ends of the warm spot. This is consistent with the average difference of 22 % between clear and cloudy areas and gives a downwind-end sounding identical to many actually made in cloudy zones.

The required downstream accumulation of moisture becomes greater in the next higher layer through which the vertical decay of mixing ratio is much stronger. Applying the circulation of Figure 6 ("sea breeze" changing sign at 800 m) to the 100-m thick stable layer, we get the results of Figure 7 c. The upwind (left-hand) air column has the moisture structure of a clear area. Continuity is satisfied when the air leaving (right-hand column) has the structure of a cloudy area, with a 1 gm/kgm greater mixing ratio at cloud-base height and a moisture lapse rate smaller by 50 %. The deeper circulation of Figure 5 has a more striking effect, which is shown in Figure 7 d. The mixing ratio at cloud base must now be 1.7 gm/kgm greater at the downwind edge of the warm spot and the moisture lapse rate there practically disappears. This corresponds closely to the observed cases of vanishing or negative mixing ratio gradient just below cloud base. These distributions cannot be produced by turbulent fluxes alone, which on the contrary would shortly destroy such accumulations were not other scales of motion operating to maintain them. The observations and calculations presented here suggest a plausible origin of circulations of approximately the required amplitude and size.

Although the upward flux of water vapor is large above these warm regions due to the gradual ascent of air, mass continuity requires that it be large in the opposite sense in the surrounding regions of subsidence. Whether or not flows of the sort hypothesized lead to any net upward transport of moisture through cloud-base level depends upon the correlation between vertical motions and mixing ratio, which is unknown. If the correlation were perfect and if the clear areas were twice as wide as the cloudy ones, these circulations could produce a net upward flux through cloud-base level of about 1.3×10^{-6} gm cm^{-2} sec^{-1}. This is 33 % of the evaporation rate or about 43 % of the total moisture flux at that height. While this maximum figure is undoubtedly too large, there is evidence that motions of this scale contribute to the net upward pumping of moisture in the lower trade. If small-scale turbulence alone were to be responsible, it has been found that overly large eddy exchange coefficients are required (see BUNKER, HAURWITZ, MALKUS, STOMMEL, 1949, p. 70).

V. The life cycles of trade-wind clouds and cloud groups

If the velocity profiles of Figures 6 and 5 represent successive time stages in the development of the flow over an oceanic warm spot, it appears likely that the air below cloud will accumulate moisture as the circulation ages, particularly at the downwind edge. For a typical trade-wind sounding, an increase of mixing ratio of 1 gm/kgm would lower the condensation level by about 260 m or 850 ft. Between Figures 7 c and 7 d, the mean mixing ratio of the 100-m layer just below cloud base has risen by 0.35 gm/kgm. Therefore, as a typical circulation reached maximum growth, we might expect cloud base to descend by about 90 m or 300 ft. Some corroborative observational evidence has been gathered by Woodcock[1] near Hawaii. On successive flights below cloud in a fixed locality, he frequently found the cumulus bases lowering from 100—500 ft in one or two hours.

Some of the factors controlling the lifetimes of individual clouds within a group may also be understood in terms of these temperature anomalies and associated circulations. For the observed horizontal dimensions of the warm spots, the time required for normal trade-wind air to pass across them ranges from about five minutes to two hours. This coincides with the range of lifetimes of individual tropical cumuli. While the warm spot circulation remains relatively steady, it can be envisaged that individual clouds will form at some interval after the air crosses the temperature up-step and will dissipate shortly after passing the down-step, many kilometers further downwind. During passage across the warm spot, each cumulus may put up several towers, depending upon the time available. This picture has received support from a series of time-lapse films of some small oceanic clouds north of Jamaica. The group as a whole remained in nearly the same location for more than four hours, despite a 5—6 m/sec wind. The lifetime of a single cumulus measured about 30 minutes, or just the time required to cross the group. Each cloud first appeared at the upwind edge of the population, travelled across the region at approximately the wind speed, and perished as it became the last cloud on the downwind edge. This behavior of the group could not be accounted for in terms of the wind shear, which was strongly negative. Each cloud leaned upwind, put up new towers ahead (downwind) of itself, and evaporated on its rear (upwind) edge, consistent with the predicted asymmetry of a single cumulus in a windfield decreasing upward. None of these small clouds produced showers, which upon occurrence could give rise to different mechanisms of cloud propagation and production.

VI. Concluding remarks

Further observations with the airborne radiation thermometer are planned in other parts of the Atlantic trade and at other seasons. It is hoped to learn whether or not sea surface temperature patchiness of the sort described here is a common phenomenon and how generally it is related to cloud formations. More detailed measurements of the lowest air temperature, moisture, wind and turbulent structure directly over the warm regions are desired to shed light on the mechanisms of interaction between sea and air and to check the predictions concerning the circulations presented here.

[1] Reported in conversation with the writer.

It is hoped that such meteorological observations may be combined with measurements from a surface vessel in an attempt to elucidate the oceanographic factors controlling the origin, scale, and duration of these thermal anomalies, about which little or nothing is known at the present time.

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