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ON THE STRUCTURE OF THE TRADE WIND MOIST LAYER

BY

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INTRODUCTION

THE TRADE-WIND REGION AND ITS ROLE IN GLOBAL METEOROLOGY

The trade-wind zone extends from about 10 to 25 degrees latitude on either side of the thermal equator. Steady easterlies, with an equatorward component, dominate the surface of the globe in both hemispheres, from the subtropical ridge line all the way to the equatorial trough.

In the vertical, trade-wind air is characterized by its layered structure, illustrated schematically in Figure 1. A lower moist convective layer commonly extends to a height of about 2 kilometers, topped by a much drier layer aloft. The transition zone, a few hundred meters in thickness, is called the "trade-wind inversion". A region of rapid drying and usually of stabilization in temperature lapse rate, its mean level is determined by the balance of the opposing effects of subsidence and convection. It gradually weakens and rises in height downstream as convection spreads moisture upward against the diminishing brake of subsidence, which decreases as the air leaves the influence of the subtropical high-pressure cell.

The trade-wind moist layer forms an early link in the chain of the atmospheric energy supply. This begins with the tropical oceans. Largely in latent form of water vapor, the energy first enters the lowest air at the roughened sea boundary in a manner which ultimately must be controlled by molecular processes. It is then spread vertically and shipped equatorward, with increasingly large scales of motion playing a role in its transport.

First the vapor is stirred upward through a well-mixed surface layer by thermal-turbulent eddies 50–150 meters in diameter. At about 650 meters or 2,000 feet, the water vapor condensation level is reached and some of the wetter eddies condense to form clusters of small cloudlets. Small clouds aggregate into larger trade cumuli (typical photograph in Figure 2) which, fighting against entrainment or dilution by mixing, distribute water vapor through a several kilometer deep moist layer, but only a few are able to shoot towers into the dry air above the inversion.

As the trade-wind air flows westward and equatorward, myriads of these cumuli, growing in bunches day and night, build up the moist layer and load the lower air with latent heat. By overshooting towers, they gradually raise and weaken the inversion, which becomes less and less frequently observed in the downstream portions of the trades. There the previously steady current, stable to perturbations in its inversion-dominated poleward half, becomes unstable and breaks down into wave-like and vortical disturbances which in the equatorial trough zone are the rule and not the exception. In these, the cumuli grow to enormous cumulonimbus, funnelling surface air up to the tropopause. The consequent release of the accumulated latent heat balances local radiation loss and, on the average, leaves enough over to be exported aloft to middle latitudes, overcoming the deficits and maintaining the circulations there. The amount of latent heat available for release in the equatorial trough and thus for supply aloft to the westerlies across the subtropical ridge depends initially upon the accumulation by the lower trade, which in turn depends upon the efficacy of small-scale turbulent and convective process at the air-sea boundary.

The average structure of the inversion-dominated portion of the trade has received serious study in the past ten years (17). Treated as a quasi-steady circulation, the major features of its dynamics and energy budget have been outlined (10, 18). It has been shown to be a self-maintaining, energy exporting circulation branch, about 75–80% of the export being in the form of the latent heat mentioned above and the remainder in sensible heat form. The latter, largely derived from internal conversion of latent to sensible heat by convective precipitation, is small but vital; it produces the downstream pressure drop maintaining the flow against friction and providing the slight excess for downstream divergence.

A crude theoretical study of fluctuations in the outer trade was made in (10) in the latter context. The proportionality in a two-dimensional current (as this portion of the system seems to be) between subsidence and downstream divergence suggested a stable "feedback" between the convective scale of motion and the overall flow. Since subsidence is a major brake on convection, if convective warming became greater than normal, enhanced subsidence would begin to suppress it, and if convection died out, reduced

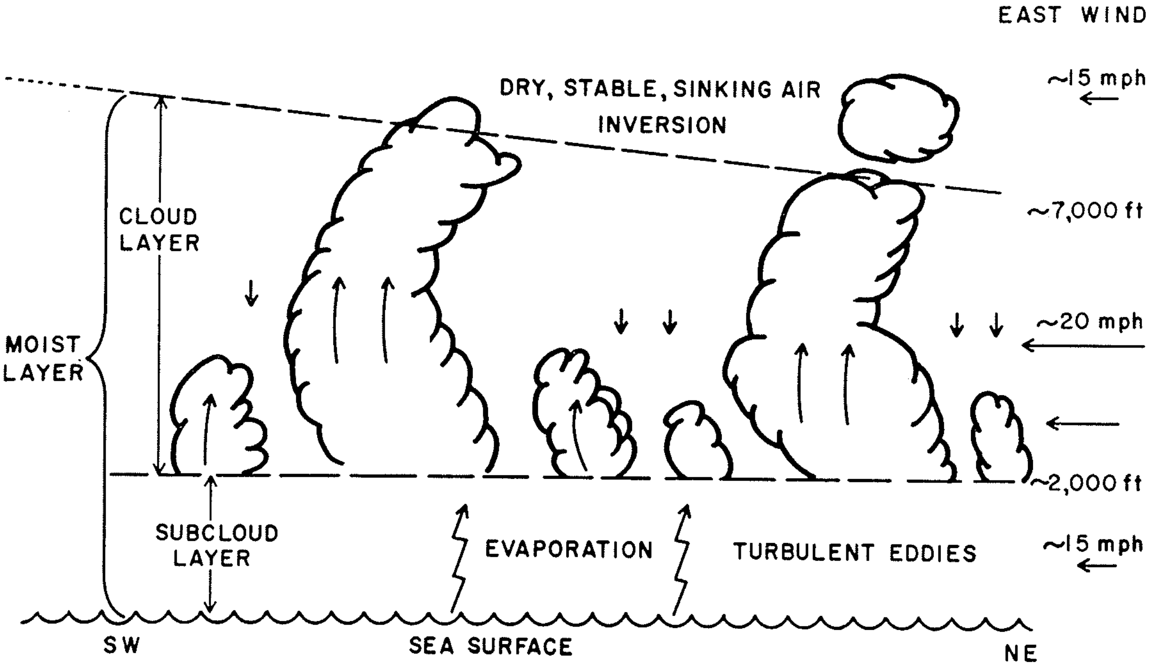


FIGURE 1. Schematic vertical cross section along the path of the trade winds. Typical wind speeds at the various levels are indicated by arrows at the right. The moist layer deepens by about 1,000 feet in 500 miles horizontal distance; clouds are thus drawn much larger than to actual scale.

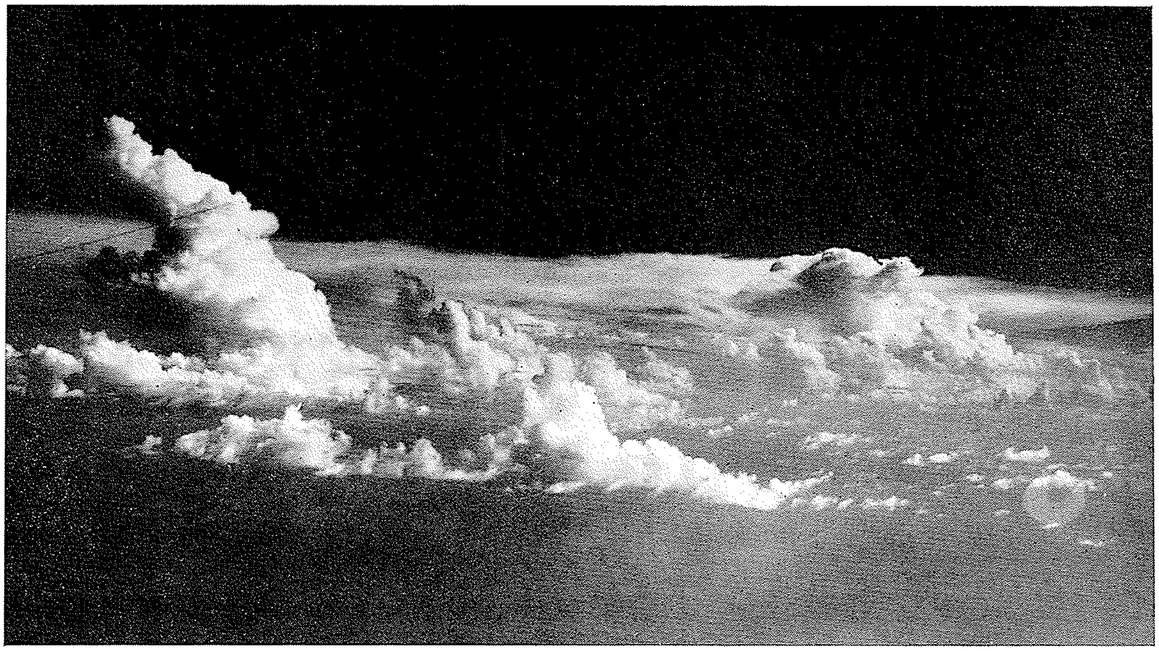


FIGURE 2. Typical aerial photograph of a trade cumulus group over the ocean near Puerto Rico, showing small cloudlets, larger towers with pronounced backslant (wind blows from left) and thin stratus sheet formed by cumulus spreading just below inversion base.

warming and consequently reduced subsidence would permit it to be restored. That the marked steadiness of the flow is confined to the convective layer supports this suggestion and turns our attention to variations in moist layer convection and its interaction with the larger-scale structure of the trade.

Alterations in its latent heat export are of particular significance since this constitutes the energy supply for large-scale circulations ranging from tropical storms to zonal westerlies. It is conceivable that fluctuations in these latter may be partially forced or triggered by variations in the energy source. And although the trades vary relatively little compared to other wind systems, the possibility that their small variations lead to large differences in local or even integrated moisture export is a real one, since their average speed of 6–7 m/sec is close to the critical wind speed for ocean whitecap formation. Riehl (16) cites evidence that the evaporation rate from the sea surface may increase sharply when whitecaps and spray appear, and has therefore suggested a correlation between tropical index cycle and that of the westerlies.

We propose here to tackle the tropical phase of the problem by inquiring from observations how the convective structure of the moist layer varies between conditions of weak and strong trade. After having described these variations, we further ask what might be the mechanisms producing them, and how they might affect the role of the trades in global circulations. Fortunately, suitable data are now available from one location and season in the western Atlantic in such widely different phases of the index cycle that a maximum contrast should be possible.

THE DATA AND METHOD OF OBSERVATION

Two sets of aircraft temperature and moisture soundings were obtained over the oceans near Puerto Rico (lat. 19°N; long. 66°W) in the spring season of different years. The first series was made during April 1946 by the Wyman-Woodcock expedition and later analyzed by Bunker, Haurwitz, Malkus, and Stommel (4). During this period the trades were strong from the northeast and trade cumulus convection was vigorous. Disturbances were few and relatively weak.

Seven years later, in March–April 1953, the Woods Hole group again visited the region, in collaboration with the Department of Meteorology of the Imperial College, London, and the British National Institute of Oceanography. This time the trades were subnormal and were veered around to south of east for most of the period. Ordinary trade cumulus convection was feeble, although several intense disturbances accompanied by large cumulonimbus build-ups passed through.

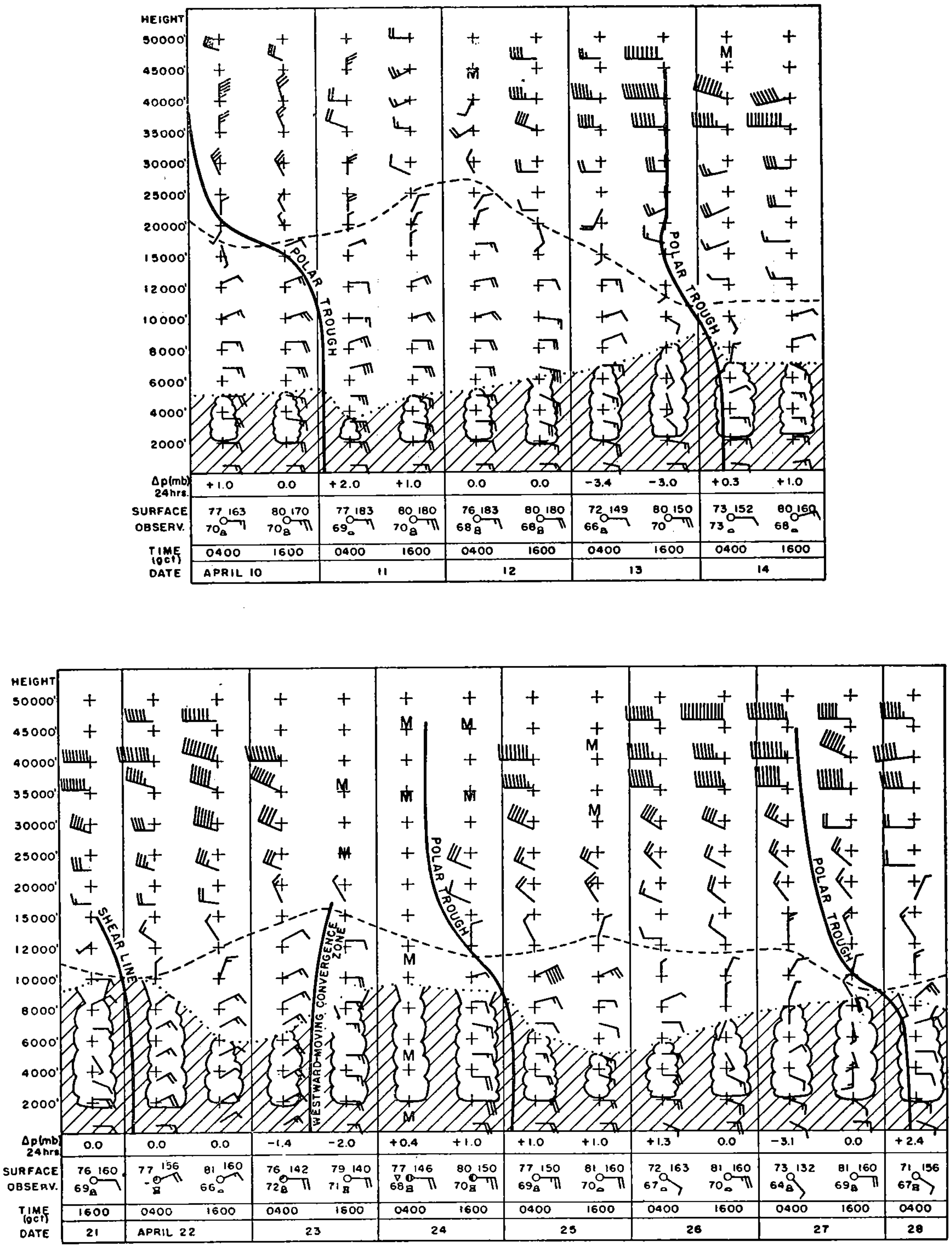
The instrumentation and method of obtaining the soundings were nearly identical in the two series. A revised version of the M.I.T. psychrograph was mounted on a PBY aircraft. Dry and wet-bulb temperatures were recorded as the plane spiralled upward at about 200 ft/min, a slow enough rate of climb for lag free readings to be obtained. The spirals were about two miles in diameter and in the 1953 series they were frequently made around smoke flares which had been dropped to determine the surface wind direction. Vertical wind structure was obtained from the British group which made double theodolite pilot balloon observations from Anegada Island (18° 50′N; 64°20′W) 120 miles east-northeast of San Juan (where the aircraft was based) and generally within twenty miles of the observing area. The 1946 spirals were in the vicinity of a small research vessel which supplied surface wind information.

For the 1953 series a wide-angle, time-lapse motion picture camera was used from the nose of the aircraft during all soundings. This made it possible to determine the location of the spirals relative to cloud groups and to assess the state of the sea surface. For the 1946 data this was done from the notes of the aircraft and ship observers.

The accuracy of the observations and the method of reduction has been described in detail in (4), in which the 1946 sounding data are tabulated. The 1953 soundings appear in Appendix I of this paper, where temperature, mixing ratio, virtual and potential temperature are given as functions of true altitude and pressure.

THE SYNOPTIC SITUATION IN THE WESTERN ATLANTIC DURING THE 1946 AND 1953 OBSERVING PERIODS

The period of April 10–28, 1946, was one of relatively strong undisturbed trade. The average (shipboard) wind speed for all observing days was 9.1 m/sec and the sea was generally rough with whitecaps present. The trajectories of the air reaching the observing region were from north of

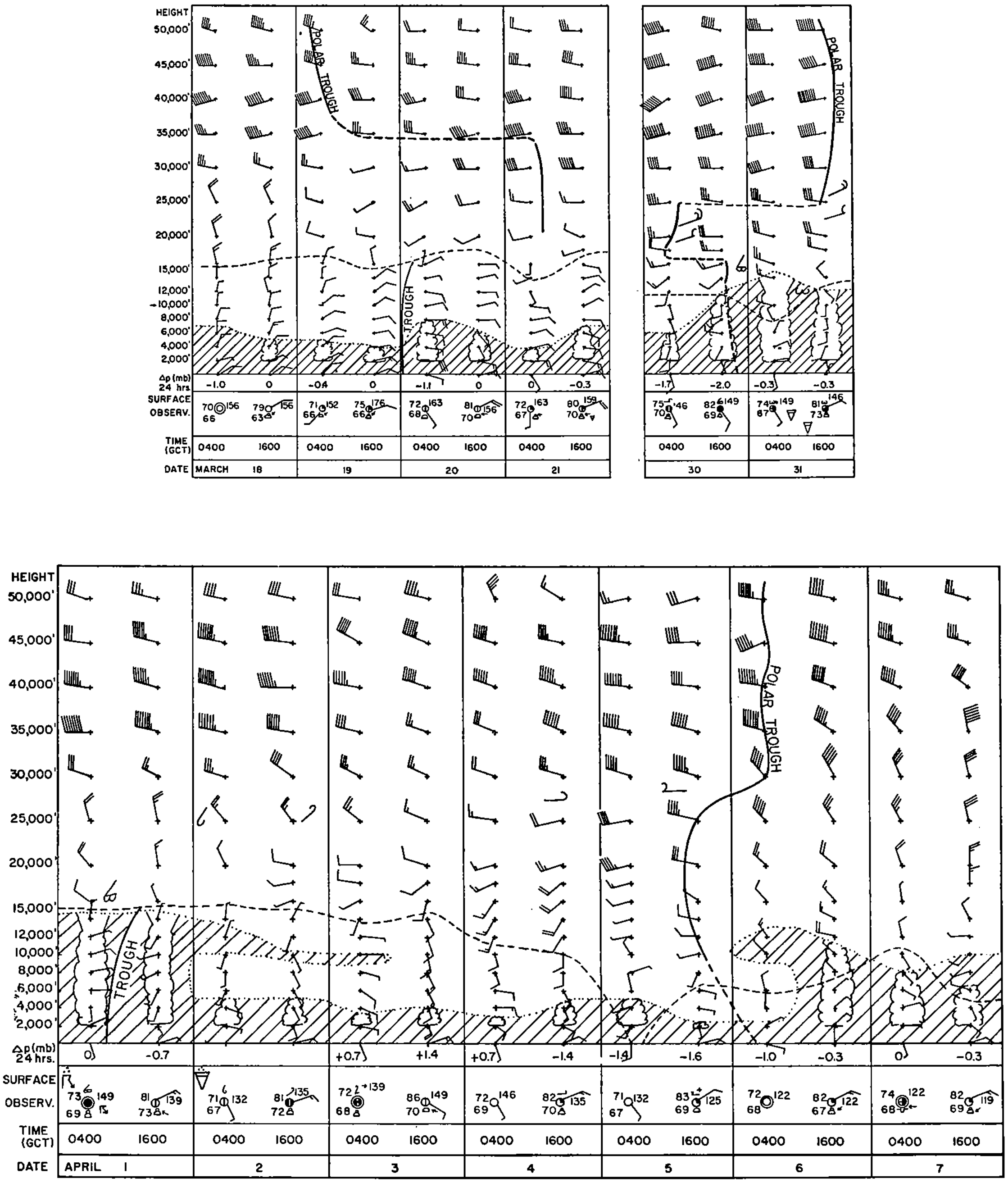


3A

Figure 3. Time cross sections for the two observing periods April 10–28, 1946 (H), Figure 3A, and March 18–April 7, 1953 (L), Figure 3B covering observation days only. Upper winds are radio winds. A short barb indicates a speed of 5 miles per hour, a long barb 10 miles per hour. Surface winds are in Beaufort scale. The hatched region is the moist layer, the top of which is represented by a dotted line. The base of the westerlies is indicated by a dashed line. The greater strength of disturbances in the L period is suggested by more middle and upper cloudiness.

east. The subtropical high-pressure cell was well developed, elongated from east to west, and maintained a central pressure departing little from 1023 mb. Rather little low-level flow across it occurred during the period. The time cross section for all observing days and a typical surface map are shown in Figures 3A and 4A.

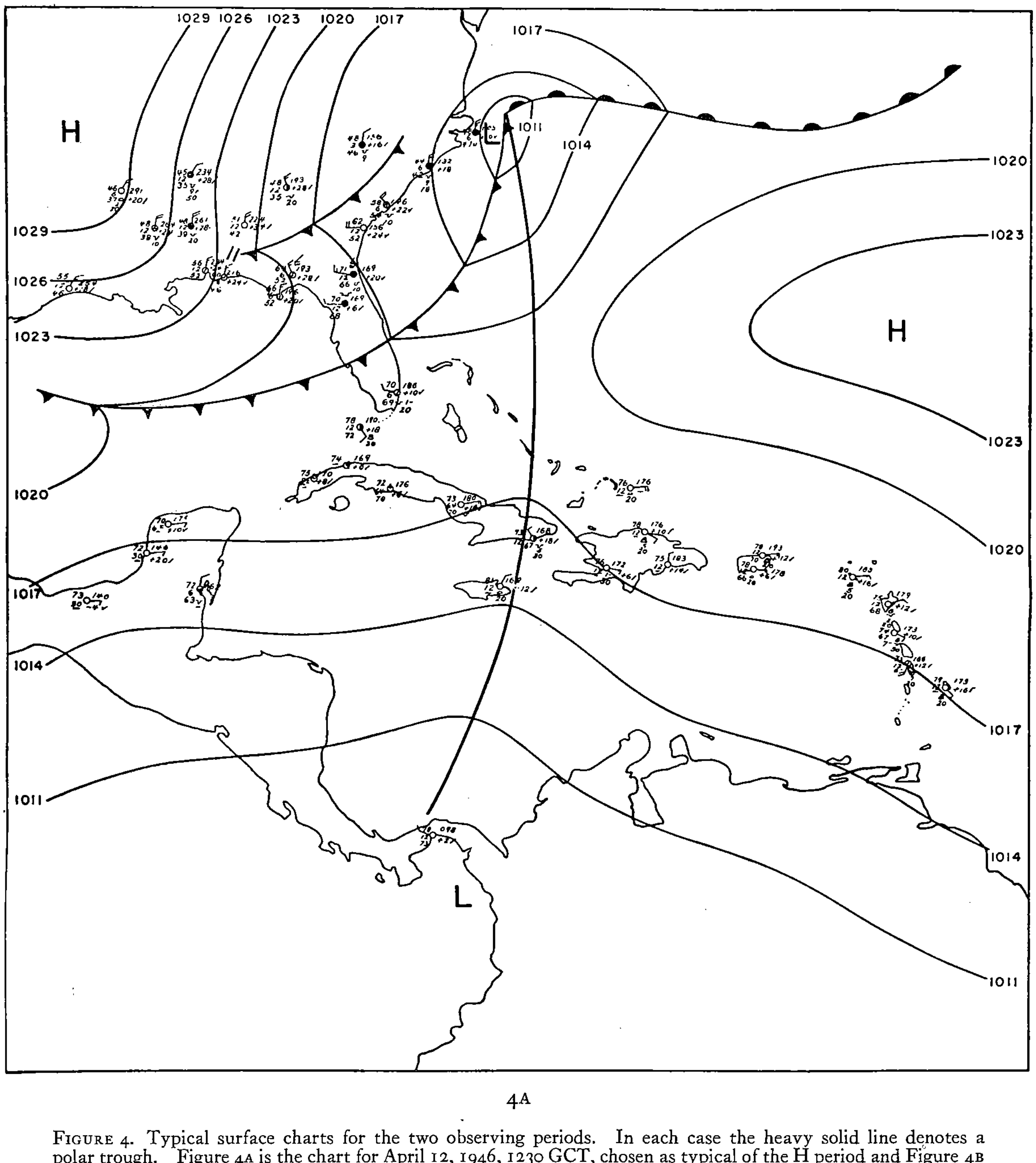
The period of March 18–April 7, 1953 was one of weaker, more disturbed trade regime. The surface winds in the observing area averaged 5.7 m/sec and no whitecaps were seen on seven of the nine days. The time cross section is shown in Figure 3B and a typical surface map in Figure 4B. They show that travelling disturbances were more intense at all levels than in the same period of 1946. Middle and high cloudiness are frequent on the 1953 time section, while none are reported on that of 1946. Relatively lower zonal index



3B

during the 1953 observation period is suggested by Figures 3 and 4 and further by Figure 5. The latter is a plot of the central pressure of the subtropical high cell, which averaged less than 1017 mb on all 1953 observing days and decreased markedly from the beginning to the end of the period. Not only did the zonal (easterly) wind component fall off, but it is likely that the meridional trade-wind cell in the western Atlantic was concomitantly running down. The equatorward component of flow disappears and actually reverses between March 30 and April 5, and the trajectories of the air reaching San Juan are from south of east.

It may thus be considered that the 1946 soundings show air structure typical of strong circulation (for the location and season) and the 1953 soundings show the features of weak circula-



4A

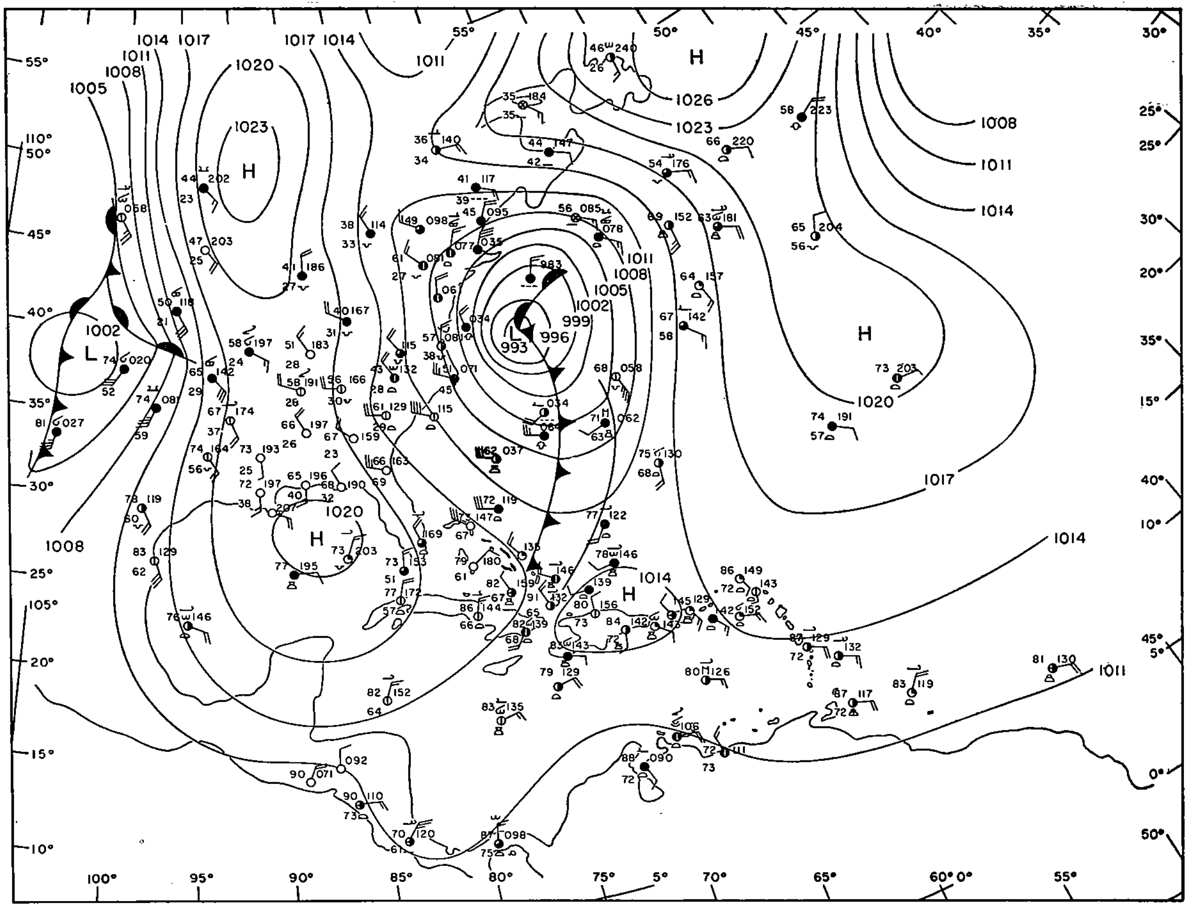
FIGURE 4. Typical surface charts for the two observing periods. In each case the heavy solid line denotes a polar trough. Figure 4A is the chart for April 12, 1946, 1230 GCT, chosen as typical of the H period and Figure 4B is the chart for March 29, 1953, 1830 GCT, chosen as typical of the L period. Note the weaker subtropical high-pressure cell and relative north-south elongation of pressure systems on the latter.

tion at the same place and season. They will therefore be designated as series H and L, respectively, throughout the rest of this report. It is interesting to note further that the mean wind strength in the two series falls clearly on opposite sides of the transition to rough sea and whitecaps, which were always present in series H and nearly always absent in series L.

Outline of the Present Study

The trade-wind moist layer is itself subdivided in the vertical into two superposed layers of different convective regime, because of the occurrence of water vapor condensation at about 600–700 m above the tropical oceans. Below the condensation level, in the so-called "subcloud" layer, unsaturated convective turbulence predominates. Eddies 50–150 m across are characteristic and recent studies (11) suggest that larger scales of motion with dimensions 10–50 km (size of cloud groups) are also significant. No evidence of cloud-scale motions below cloud base have been found, except in precipitating downdrafts. Above the condensation level, cumulus convection is the major transport process; small-scale turbulence is confined to the neighborhood of clouds, which form in bunches separated by wider, weakly subsiding clear areas.

The lower four-fifths of the subcloud layer is well-stirred and has been christened the "mixed layer". The lapse rate is close to dry adiabatic and the moisture content of the air is nearly constant with height, decreasing only 3–6% from 15 m above the sea to its top at about 550 m. The thickness of the mixed layer commonly shows variations of 20% in space and as much as 100% in time, with extreme day-to-day variations of about 300–700 m. Recent evidence suggests that its space variations on a 10–50 km scale are associated with the bunchy grouping of trade cumuli. It appears that the clouds are grouped in places where the mixed layer is thickened, reaching close to the condensation level of the air within it.



4B

The trade-wind mixed layer thus plays the crucial role of a "valve" in the earliest phases of the atmosphere's energy supply. Its structure regulates both the input from the sea below through evaporation and the output aloft through cumulus formation. The present study has therefore been divided into three parts. Part I examines the structure of air below cloud; Part II is concerned with the features of the cloud layer and cumulus convection; and Part III attempts to construct a physical model of the operation of the moist layer as a whole.

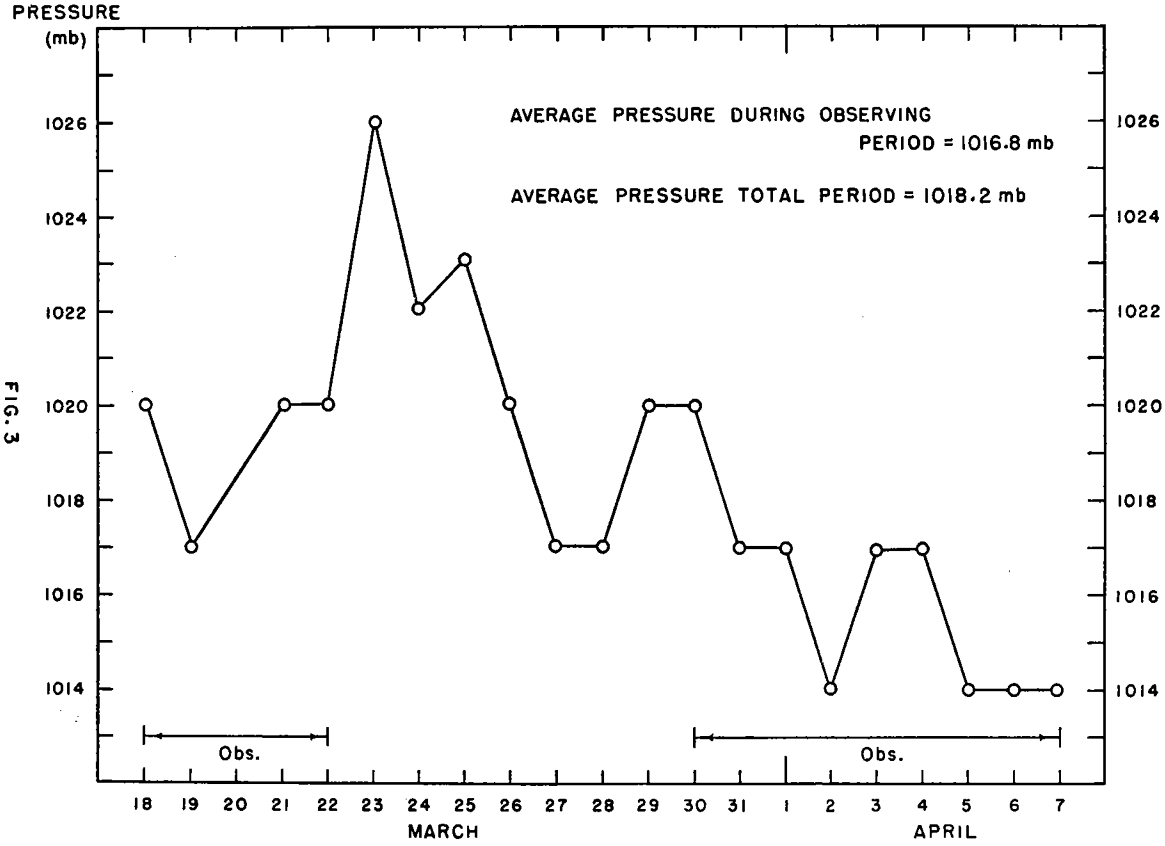


FIG. 3

FIGURE 5. Plot of the central pressure of the subtropical high cell during the 1953 (L) observing period as a function of time as taken from the daily surface chart at 1830 GCT.

PART I

ON THE STRUCTURE OF TRADE-WIND AIR BELOW CLOUD

THE QUESTIONS RAISED

This section concerns the structure of the lowest air and how it varies between conditions of strong and weak trade. Specifically we wish to study the functions and properties of the mixed layer (defined and located on temperature-moisture soundings by its nearly constant mixing ratio and close to adiabatic lapse rate). In the context of the Introduction, some questions of particular interest are:

1. What are the vertical fluxes of sensible and latent heat? According to classical turbulence theories, the former should be nearly always downward in the trades, since potential temperature almost invariably increases with height above the lowest few meters. Recently countergradient heat flows have been hypothesized and confirmed observationally elsewhere in the atmosphere (3). Although the sensible heat accumulation by the lower trade is only about 25% that of the latent, it has been shown (18) essential in the maintenance of the flow. Thus the direction and magnitude of its vertical flux remains an important unresolved question. The water vapor flux, on the other hand, is clearly always upward but, as suggested in the introduction, may vary widely. We wish to inquire how this variation affects and is affected by the structure of the lower trade.
2. Why were trade cumuli both sparse and poorly developed in series L (1953) compared to series H (1946)? Is the difference in cumulus convection attributable to suppression of convective transports in the subcloud layer or must we look for brakes such as abnormal stability or dryness in the cloud layer itself?
3. What is the mechanism of maintenance of convective-turbulence in the mixed layer itself and the relative roles of buoyancy and wind stirring therein? The vertical transports in the lower trades are undoubtedly a combination of turbulent shear flow and thermal turbulence in a fluid heated from below. The relative importance of these and the effect of their interaction has not been assessed.

COMPARISON OF THE DATA

The series L soundings have been analyzed and compared with those of series H (already analyzed and discussed in (4)) with these questions in mind. Although it is not yet possible to give definite answers to the first and third, nor to make an experiment isolating a single factor alone (such as wind strength or sea surface roughness), the differences in subcloud air structure in the two periods suggests that important fluctuations in energy input and transfer accompany changes in flow regime in this critical source region. The nature and magnitude of these differences give some clues as to their origin and possible effects upon other parts of the atmosphere.

A summary of the major features of the mixed layer for series L is presented in Table 1. A comparison of the H and L series appears in Table 2, subdivided into clear and cloudy area soundings. The right-hand five columns of Table 1 were obtained by calculations from the soundings as follows: Plots of temperature, virtual temperature, and mixing ratio against height were made and the lapse rate of each determined graphically and then checked by the method of least squares. The height, h, of the mixed layer was determined as in (4) for series H, by picking the height at which the mixing ratio lapse rate increased suddenly. This level was usually well defined and was accompanied in most cases by a stabilization in temperature lapse rate. The lifting condensation level, LCL, was found from a tephigram, using the mean properties of the mixed layer.

In series H, the temperature lapse rate in the mixed layer was always slightly subadiabatic. In series L, on the other hand, one case of superadiabatic mixed layer was found, namely, that of the sounding of April 2. This was a day of particularly light wind and the nose camera film showed the calmest sea of the period. On the remaining L days the lapse rate was slightly stable, varying around an average value of 0.9 dry adiabatic, as in series H. The lapse rate of virtual temperature averaged 4% greater than the temperature lapse rate, but in no case went over to superadiabatic when the temperature lapse rate was subadiabatic.

A rough calculation sheds light on the role of buoyancy. In the case of the average lapse rate of virtual temperature, T*, it may be shown that buoyant bubbles leaving the sea surface with

TABLE 1. SUMMARY OF FEATURES OF MIXED LAYER FOR 1953 (SERIES L) SOUNDINGS.

Date	Time	Location	Local Wind Direction	Anegada Wind		Sea	h	Lapse rate of temp. T	Lapse rate of virt. temp. T*	Lapse rate of mixing ratio w	LCL
	LST		° from N	°	m/sec		m	°C/100m	°C/100m	$\times 10^9$cm^{-1}	m
March 18	1450	Cloudy area.	23	18	4	Calm. No whitecaps.	686	.94	.98	29	500
March 21	1400	Cloudy area.	83	93	5	Small waves. No whitecaps.	450	.93	M	M	500
March 25	1115	Cloudy area.	90	89	10	Large waves. Rough white-caps everywhere.	550	.82	.90	28	655
March 30	1112	Clear area near edge of cloudy area. High cirrus pres.	Estimated 110	110	5	Medium waves. Some white-caps.	382	.95	.97	28	450
April 1	1045	Clear area near cloudy. Some cirrus. Cunimb buildups 70 mi. north	130	146	4	Small waves. No whitecaps.	382	.95	.98	7.4	580
April 2	1445	Clear area north of small cloudy area. Some cirrus.	118 (smoke)	120	4	Sea calm. No whitecaps.	570	1.04	1.05	11	760
April 4	1150	Clear area. No clouds except over islands.	140 (smoke)	140	6	Small waves. No whitecaps.	700	.90	.93	13	850
April 5	1300	Clear area. No cu except over islands. Middle clouds 8/10.	130 (smoke)	140	7.5	Medium-small waves. No whitecaps.	446	.67	.76	32	855
April 7	0950	Cloudy area.	88 (smoke)	96	5.5	Small waves. No whitecaps.	666	.91	.98	15	760
Average			101	105	5.7		537	.90	.94	20.4	653

TABLE 2. COMPARISON BETWEEN 1946 (H) AND 1953 (L) MIXED LAYERS

	h	LCL - h	Relative Humidity (bottom)	Relative Humidity (top)	Mixing Ratio (bottom)	Mixing Ratio (top)	Lapse Rate of Mixing Ratio	Lapse Rate of Temperature	Wind		Tım
	m	m	%	%	gm/kgm	gm/kgm	$\times 10^9$cm^{-1}	°C/100m	°	m/sec	°C
April 10–28, 1946(H)											
clear	549	186	71	89	15.0	14.6	− 6.4	.90	87	8.9	25.7
cloudy	620	87	71	91	15.1	14.8	− 4.9	.85	96	9.5	25.8
average	575	150	71	90	15.05	14.7	− 5.8	.88	90	9.1	25.7
March 18–April 7, 1953(L)											
clear	496	204	76	85	15.3	14.4	−18.3	.90	131	5.3	25.6
cloudy	588	14	81	94	15.6	14.2	−24	.90	74	6.1	24.5
average	537	120	78	89	15.44	14.3	−20.4	.90	106	5.7	25.1