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THE HUMIDITY GRADIENT OVER THE SEA SURFACE[1]

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ABSTRACT

Observations of humidity and temperature at three levels above the sea surface are discussed, using new data obtained by Lt. F. L. Black, U.S.N., in 1937 at wind velocities up to 16.5 m sec^{-1}. It is shown that these and earlier data indicate that the transfer of water vapor and momentum obey similar laws and that the sea surface at wind velocities below 5 m sec^{-1} behaves as a hydrodynamically smooth surface and at velocities above 7 m sec^{-1} as a hydrodynamically rough surface with roughness length 0.6 cm. The observations indicate a great variability in the humidity gradient between heights of 6 m and 30 m and a relatively small variability in the difference between the vapor pressures at the sea surface and at 6 m.

Humidity gradients above the sea surface were measured by Wüst and Montgomery (2) prior to 1937, but all these measurements were carried out at wind velocities of less than 7 m sec^{-1}. In 1937 Lt. F. L. Black, U.S.N., at the suggestion of the author, carried out a number of observations at three different heights above sea level and at wind velocities up to 32 knots (16.5 m sec^{-1}). A brief reference has been made to some results of these observations (4), which are communicated and discussed here.

Observations

The observations were made at three well exposed heights as far forward as possible on board the U.S.S. *Indianapolis*. No observations were taken with the wind astern. Three observers equipped with psycrometers were stationed at the three heights and each took ten readings during the same ten-minute periods.

Individual readings gave consistent values of the vapor pressure. In most cases the highest and lowest values derived from the ten readings differed by less than 0.5 mb and the averages should therefore be correct within ± 0.1 mb.

The sea surface temperature was taken as the injection temperature and since it was read only to the nearest 1 F it may be about 0.3 C in error. The computed vapor pressure at the sea surface may therefore be up to 0.4 mb in error.

The observations are summarized in Table 1 which contains the following information:

1. Number, date, time and position.
2. Wind direction (true) and wind speed in knots.
3. Heights above sea level in meters. "Surf." refers to the sea surface.
4. Average "potential temperature" in C at the stated heights. "Potential temperature" equals observed temperature plus 0.01 h where h is height in meters.
5. Average vapor pressure in millibars, and vapor pressure at sea surface assuming a salinity of 35 per mille.
6. Amount in tenths and type of clouds, direction of cloud motion and, in a few cases, height of cloud base.
7. Remarks about presence of spray and stability of stratification. The stratification is called *stable* if at least *two* of the potential air temperatures exceeded the sea surface temperature by 0.1 C or more.

Theoretical considerations

The terms and symbols used by Montgomery (2) will be employed and several of the equations in his paper will be quoted without including their derivations.

Montgomery introduces a dimensionless quantity, the evaporation coefficient,

$$\Gamma \equiv -\frac{1}{e_s - e_a}\frac{de}{d\ln z}, \tag{1}$$

to describe the vertical gradient of water vapor. Here e_s is the vapor pressure at the sea surface and e_a is the vapor pressure at a standard level above the sea surface. If the vapor pressure is a linear function of the logarithm of height, one has

$$\frac{de}{d\ln z} = \frac{e_b - e_a}{\ln b/a} = -\frac{e_a - e_b}{\ln b/a}$$

and

$$\Gamma \equiv \frac{e_a - e_b}{e_s - e_a}\frac{1}{\ln b/a}, \tag{2}$$

where e_b is the vapor pressure at the height b.

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[1] Contributions from The Scripps Institution of Oceanography, New Series, No. 271.

TABLE 1. Observations of air temperature and vapor pressure at three heights and of temperature and vapor pressure at sea surface. U.S.S. *Indianapolis*, 1937, Lt. F. L. Black.

No.	Date Time Position	Wind direction and speed knots	Height m	Potential temp. C	Vapor pressure mb	Clouds	Remarks
1	16 April	NW	27.5	14.38	10.96	0	Spray blowing
	1030	30	11.4	13.49	10.88		Stable
	33°36′N		6.2	13.62	11.64		
	119°33′W		Surf.	13.3	15.00		
2	17 April	NNW	27.5	12.00	11.44	7 St	Spray
	0830	25	11.4	12.22	12.40	NW	Unstable
	32°51′N		6.2	12.06	12.61	500 m	
	123°14′W		Surf.	13.3	15.0		
3	17 April	N	27.5	12.94	11.87	6 St	A little spray
	1410	26	11.4	13.22	12.00	N	Unstable
	32°39′N		6.2	12.78	12.50		
	124°30′W		Surf.	13.9	15.6		
4	18 April	NNE	27.5	13.55	11.10	9 Stcu	Unstable
	0830	18	11.4	13.63	11.26	N	
	31°50′N		6.2	13.67	10.96	900 m	
	128°59′W		Surf.	15.0	16.7		
5	18 April	NNE	27.5	15.56	13.44	5 Stcu	Stable
	1400	16	11.4	15.28	13.23	N	
	31°33′N		6.2	15.00	12.93	1100 m	
	130°07′W		Surf.	15.0	16.7		
6	19 April	NE	27.5	15.38	10.56	10 Stcu	Light spray
	0900	18	11.4	15.62	12.62	NE	Unstable
	30°25′N		6.2	15.34	14.21		
	134°37′W		Surf.	17.8	20.0		
7	19 April	ENE	27.6	15.66	13.64	10 Stcu	Spray occasionally
	1330	23	11.4	15.78	13.71	NE	Unstable
	30°08′N		6.2	15.89	14.61		
	135°15′W		Surf.	17.8	20.0		
8	20 April	NE	27.6	16.28	13.74	10 Stcu	Unstable
	0830	18	11.4	16.28	13.47	E	
	29°40′N		6.2	16.41	13.65		
	139°02′W		Surf.	17.2	19.2		
9	20 April	ENE	27.6	17.95	13.60	10 Stcu	Spray blowing
	1400	17	11.4	18.44	15.94	E	Unstable
	29°36′N		6.2	17.78	15.95		
	140°09′W		Surf.	18.4	20.7		
10	21 April	ENE	27.6	17.45	14.92	3 Cu	Unstable
	0840	17	11.4	18.17	15.20	E	
	28°49′N		6.2	17.37	16.00		
	144°15′W		Surf.	18.3	20.6		
11	21 April	ENE	27.6	18.45	16.27	7 Stcu, Cu	Unstable
	1340	18	11.4	18.11	16.19	ENE	
	28°43′N		6.2	18.28	16.12	600 m	
	145°11′W		Surf.	18.9	21.4		
12	22 April	ENE	27.6	17.22	16.67	7 Cu	Unstable
	0910	22	11.4	18.00	17.86	E	
	28°07′N		6.2	18.39	19.06		
	149°17′W		Surf.	20.0	22.9		
13	23 April	E	27.6	21.59	18.06	4 Cu	Unstable
	1430	23	11.4	21.14	18.22	E	
	26°02′N		6.2	20.96	19.91		
	155°22′W		Surf.	21.7	25.4		
14	24 April	E	27.6	22.23	20.00	4 Cu	Spray blowing
	0845	22	11.4	22.66	22.22	E	Unstable
	23°04′N		6.2	22.56	22.22		
	157°53′W		Surf.	22.8	27.2		
15	24 April	ENE	27.6	23.45	21.64	3 Cu	Light spray
	1405	29	11.4	23.33	22.21	E,	Unstable
	22°00′N		6.2	23.17	21.97	3 Ci	
	158°13′W		Surf.	23.3	28.1		
16	25 April	NE	27.2	24.05	20.06	2 Cu	Unstable
	0900	16	11.4	24.00	20.76	E,	
	21°13′N		6.2	24.62	23.12	1 Ci	
	153°04′W		Surf.	24.4	30.0		
17	25 April	NNE	26.4	23.15	21.62		
	1330	32	11.4	23.55	22.40		
	20°58′N		6.2	23.17	22.72		
	156°57′W		Surf.	23.3	28.1		

TABLE 1.—*Continued.*

No.	Date Time Position	Wind direction and speed knots	Height m	Potential temp. C	Vapor pressure mb	Clouds	Remarks
18	26 April	SW	27.6	24.72	20.96	2 Cu	Stable
	0910	2	11.4	24.83	22.69	2 Ci	
	20°55′N		6.2	23.56	20.29		
	151°40′W		Surf.	23.9	29.1		
19	5 May	NE	27.6	22.50	19.14	7 Stcu	Light spray
	0900	21	11.4	22.64	20.44	NE	Unstable
	23°38′N		6.2	22.45	20.20	800 m	
	157°28′W		Surf.	23.9	29.1		
20	5 May	NE	27.6	22.28	18.56	3 Cu	Unstable
	1340	21	11.4	22.22	18.88	NE	
	24°14′N		6.2	22.34	20.07	1 Ci	
	157°39′W		Surf.	23.3	28.1		
21	6 May	ENE	27.6	21.06	14.37	6 Cu	Light spray
	0950	19	10.9	21.28	16.19	E	Unstable
	24°34′N		6.2	21.45	17.40	900 m	
	159°11′W		Surf.	23.3	28.1		
22	6 May	ENE	27.6	22.56	18.14	9 Stcu	Unstable
	1415	22	10.9	22.50	19.22	NE	
	24°00′N		6.2	21.78	19.91		
	159°56′W		Surf.	23.9	29.1		
23	8 May	NNE	27.6	23.78	24.45	6 Stcu	Light spray
	1400	21	10.9	23.94	24.81	NE	Unstable
	20°38′N		6.4	23.89	25.58		
	157°39′W		Surf.	26.1	33.2		
24	9 May	E	27.6	24.67	22.88	2 Cu	Stable
	1000	20	10.9	24.61	24.02	5 Ast	
	21°19′N		6.2	25.39	25.24		
	157°56′W		Surf.	24.4	30.0		
25	20 May	ENE	27.6	24.11	20.89	5 Cu	Light spray
	1100	27	10.9	24.22	21.63	NE	Unstable
	21°13′N		6.2	23.45	22.92	4 Cist	
	157°33′W		Surf.	24.4	30.0		
26	20 May	ENE	27.6	23.17	19.48	3 Cu	Light spray
	1410	24	10.9	23.50	20.33	NE	Unstable
	21°48′N		6.2	23.62	21.22	7 Cist	
	156°32′W		Surf.	23.9	29.1		
27	21 May	ENE	27.6	22.61	18.28	3 Cu	Unstable
	1000	25	10.7	22.89	19.04	NE	
	24°28′N		6.2	22.62	21.09	7 Cist	
	154°16′W		Surf.	23.3	28.1		
28	21 May	E	27.6	22.61	20.91	3 Cu	Unstable
	1415	15	10.9	22.50	20.80	E,	
	25°02′N		6.2	22.34	20.63	6 Cist	
	154°04′W		Surf.	24.4	30.0	S	
29	22 May	E	27.6	21.33	20.50	5 Cu	Stable
	1015	11	10.9	20.39	21.23	NE	
	27°16′N		6.2	20.62	20.69		
	150°59′W		Surf.	20.4	23.5		
30	23 May	SE	27.6	19.73	18.32	3 Cu	Unstable
	1000	8	10.9	19.83	18.03		
	29°18′N		6.2	20.50	17.97		
	146°29′W		Surf.	20.0	22.8		
31	23 May	E	27.6	20.06	16.90	2 Cu	Unstable
	1430	3	10.9	19.44	16.21	E	
	29°40′N		6.2	19.17	16.31		
	145°35′W		Surf.	20.0	22.8		
32	24 May	W	27.6	19.50	18.04	Frst	Stable
	1545	10	10.9	19.44	17.69		
	31°48′N		6.2	20.45	17.27		
	141°21′W		Surf.	18.9	21.4		
33	25 May	NNE	27.6	16.88	16.95	9 St, Stcu	Unstable
	1025	12	10.9	15.94	16.78	N	
	33°23′N		6.2	17.06	16.18	Drizzle	
	137°29′W		Surf.	17.2	19.2		
34	25 May	NE	27.6	16.17	14.05	7 Stcu	Unstable
	1430	8	10.9	16.78	14.10	E	
	30°—		6.2	15.86	13.97		
	——		Surf.	16.7	18.6		

TABLE 1.—*Continued.*

No.	Date Time Position	Wind direction and speed knots	Height m	Potential temp. C	Vapor pressure mb	Clouds	Remarks
35	26 May	N	27.6	14.95	11.75	8 Stcu	Unstable
	1100	17	10.9	14.89	11.98	N	
	35°13′N		6.2	15.28	12.08		
	132°30′W		Surf.	16.1	18.0		
36	26 May	NNW	27.6	14.72	11.84	7 Stcu	Light spray
	1545	23	10.9	14.22	12.49	N	Unstable
	35°04′N		6.2	14.46	12.32		
	131°23′W		Surf.	16.1	18.0		
37	27 May	NW	27.6	13.67	13.21	5 Stcu	Unstable
	1000	28	10.9	13.22	12.83	N	
	36°15′N		6.2	13.17	13.40		
	127°30′W		Surf.	13.9	15.55		
38	27 May	N	27.6	13.84	12.75	Frst	Spray blowing
	1430	25	10.9	13.50	13.26	N	Stable
	36°14′N		6.2	14.01	13.59		
	126°40′W		Surf.	13.3	15.0		
39	28 May	NW	27.2	11.10	11.30	0	Stable
	0945	16	10.9	11.16	11.07		
	37°37′N		6.2	12.01	12.01		
	122°40′W		Surf.	11.1	13.0		
40	29 June	SSE	30.6	15.92	15.82	10 Stcu	Unstable
	0930	8	19.3	16.30	15.53	SSE	
	37°23′N		5.8	16.23	16.23		
	123°04′W		Surf.	16.7	18.6		
41	29 June	SW	30.6	15.76	16.00	10 Stcu	Unstable
	1400	11	19.3	14.63	15.67		
	38°17′N		5.8	16.73	16.30		
	123°52′W		Surf.	17.8	20.0		
42	30 June	NNW	30.6	15.70	14.45	10 Stcu	Unstable
	1430	14	19.3	15.58	14.74		
	45°03′N		5.8	15.84	15.64		
	125°10′W		Surf.	17.8	20.0		
43	6 July	E	31.9	17.23	12.91	2 Stcu	Unstable
	1400	6	15.2	17.22	13.66	3 Cu	
	49°06′N		6.1	17.86	14.27	NW	
	125°00′W		Surf.	18.9	21.4		
44	8 July	W	31.9	11.71	9.30	3 Stcu, Cu	Unstable
	1530	12	15.2	11.65	10.74	6 Ast	
	54°35′N		6.1	12.28	10.73		
	133°45′W		Surf.	12.8	14.5		
45	9 July	ENE	31.9	12.88	11.50	4 Cu	Stable
	1100	3	15.2	13.78	12.52		
	57°00′N		6.1	15.78	12.84		
	140°39′W		Surf.	13.3	15.0		
46	9 July	E	31.9	12.60	11.37	2 Cu	Unstable
	1315	5	15.2	12.82	11.27	E	
	57°19′N		6.1	14.76	11.71		
	141°39′W		Surf.	14.4	16.1		

Montgomery also shows that with a logarithmic distribution of water vapor the rate of evaporation from the sea surface is

$$E = \rho k_0 \gamma_a \Gamma (q_s - q_b) W_a, \tag{3}$$

where E is the evaporation mass per unit area and time, ρ is the density of the air, k_0 is von Kármán's constant ($k_0 = 0.4$), γ_a is the resistance coefficient referred to the level a, q_s is the specific humidity at the sea surface, q_b the specific humidity at the height b, and W_a is the wind velocity at the height a.

The resistance coefficient is defined by the relationship

$$\tau = \rho \gamma_a^2 W_a^2, \tag{4}$$

where τ, the stress exerted on the boundary surface, is assumed to be constant in the layer near the surface. The resistance coefficient, γ_a, and the evaporation coefficient, Γ, in the immediate vicinity of a boundary surface, depend upon the hydrodynamic characteristics of this surface, and can both be evaluated from the theory of turbulence.

Unstable conditions, smooth surface. Over a hydrodynamically smooth surface there exists a *laminar* *boundary layer* which has a thickness of a fraction of a centimeter, and above this lies a *turbulent boundary layer.* In the turbulent boundary layer von Kármán's general equation for flow over a smooth surface applies:

$$\frac{1}{\gamma_a} + \frac{1}{k_0} \ln \frac{1}{\gamma_a} = 5.5 + \frac{1}{k_0} \ln \frac{W_a a}{\nu}, \tag{5}$$

where ν is the kinematic viscosity of the air. Rossby (3) has shown that equation (5) holds for wind profiles over the sea, provided that the wind velocity as measured at a height of 6 to 12 meters does not exceed about 6 m sec^{-1}.

Assuming that within the boundary layers the vertical transfer of water vapor is independent of height, Montgomery obtains for a smooth surface:

$$\Gamma = \left(\frac{\lambda \nu k_0}{\kappa} + \ln \frac{k_0 \gamma_0 W_a a}{\kappa} \right)^{-1}, \tag{6}$$

where λ is a numerical factor which occurs in the equation for the thickness, δ, of the laminar boundary layer and κ is the kinematic coefficient of diffusion of water vapor through air. According to von Kármán $\lambda = 11.5$, whereas Montgomery obtains $\lambda = 7.8$. With $\lambda = 11.5$ and $a = 600$ cm, the following numerical values of Γ apply at a temperature of 20 C:

ν	κ	Γ-values		
cm^2 sec^{-1}	cm^2 sec^{-1}	$W_6 = 2$	$W_6 = 4$	$W_6 = 6$ m sec^{-1}
0.15	0.25	0.087	0.0825	0.080

At 0 C the corresponding values are about one per cent larger.

Unstable conditions, rough surface. Over a hydrodynamically *rough* surface the resistance coefficient, γ_a, has the value

$$\gamma_a = \frac{k_0}{\ln \frac{a + z_0}{z_0}} \tag{7}$$

where z_0 is the roughness length of the surface. Determinations of the wind profiles over the sea (3) indicate that the sea surface is hydrodynamically rough at wind velocities exceeding 6 m sec^{-1} as measured at a height of 6 to 12 meters above the sea surface. The roughness length of the sea surface has been found to be about 0.6 cm, independent of the wind velocity. The same value has been obtained from a study of the piling up of water against coasts by the action of wind stress and is further substantiated by recent studies of the growth of wind waves.

In the turbulent boundary layer the kinematic eddy viscosity increases linearly with increasing distance from the sea surface:

$$\nu_e = k_0(z + z_0)\gamma_a W_a. \tag{8}$$

In discussing the humidity gradients over a hydrodynamically rough surface, Montgomery, following a suggestion by Millar, introduces an intermediate boundary layer between the laminar and the turbulent boundary layers and arrives at the conclusion that the numerical values of the evaporation coefficient are less than one half of those for a smooth surface. The observed humidity gradient gives, however, larger values; Montgomery attributes the discrepancy to the effect of spray.

A simpler theoretical approach is proposed here, based on the assumptions that the turbulent boundary layer extends to the very sea surface and that in this layer the kinematic coefficient of eddy diffusion of water vapor equals the kinematic eddy viscosity. On these assumptions the vertical flux of water vapor through the boundary layer is

$$E = -\rho \nu_e \frac{dq}{dz} = -\rho k_0 \gamma_a W_a (z + z_0) \frac{dq}{dz}. \tag{9}$$

If the flux of water vapor is independent of height, one obtains by integration:

$$q_s - q_b = \frac{E}{\rho k_0 \gamma_a W_a} \ln \frac{b + z_0}{z_0} \tag{10}$$

or

$$E = \rho k_0 \gamma_a \left(\ln \frac{b + z_0}{z_0} \right)^{-1} (q_s - q_b) W. \tag{11}$$

Comparison with (3) gives for a rough surface

$$\Gamma = \left(\ln \frac{b + z_0}{z_0} \right)^{-1}. \tag{12}$$

With $b = 600$ cm and $z_0 = 0.6$ cm, one obtains

$$\Gamma = 0.145 \tag{13}$$

independent of the wind velocity.

Comparison of observed and theoretical Γ-values

The Γ-values have not been computed for each set of observations; instead, the observations have been arranged according to increasing wind velocity, and average vapor pressures at different heights have been formed for groups. Stable and unstable cases have been treated separately and for the unstable cases averages for all observations at wind velocities above 8 m sec^{-1} have also been formed. The average values are shown in Table 2 and in Figures 1 and 2. From the graphs it

TABLE 2. Average vapor pressures at different heights.

Group	No. of observations	Wind speed		Average heights, m			Vapor pressures, mb, at stated heights				Γ
		Range m sec^{-1}	Average m sec^{-1}	h_3	h_2	h_1	h_3	h_2	h_1	Surf.	
					Instability						
I	6	1.5–4.1	3.3	29.5	13.7	6.1	14.90	14.80	15.08	20.05	0.070
II	5	5.6–7.7	6.7	29.7	13.1	6.0	15.32	15.75	15.90	20.74	0.050
III	9	8.2–9.8	9.1	27.5	11.3	6.2	14.04	14.85	15.50	21.63	0.159
IV	6	10.8–11.3	11.1	27.6	11.2	6.2	19.49	20.57	21.17	28.27	0.155
V	6	11.8–12.9	12.3	27.6	11.1	6.2	15.46	16.03	16.96	22.60	0.176
VI	5	13.4–16.5	14.1	27.3	11.2	6.2	17.85	18.21	18.70	23.47	0.122
III–VI	26	8.2–16.5	11.4	27.5	11.2	6.2	16.36	17.09	17.75	23.74	0.156
					Stability						
VII	4	1.0–5.7	3.3	28.7	12.1	6.2	17.75	18.53	17.77	22.25	——
VIII	5	8.2–14.5	11.2	27.5	11.1	6.2	14.27	14.49	15.08	17.85	0.192

is evident that in all groups except the two containing the lowest wind velocities the vapor pressure is nearly a linear function of the logarithm of height. Straight dashed lines have been entered to approximate the relationships, and from these straight lines the Γ-values in Table 2 have been computed.

In the *unstable* cases the Γ-values are small for the average wind velocities 3.3 and 6.7 m sec^{-1}. When dealing with the first group, $W_a = 3.3$ m sec^{-1}, the Γ-value is based on the two lowest observations only, because at the lowest wind velocities the thickness of the turbulent layer is probably less than 27 meters (see p. 8). For the four groups with average wind velocities exceeding 8 m sec^{-1} the values are large and do not differ very much from the theoretical value of 0.145.

In Figure 3 the Γ-values for the unstable cases are plotted against wind velocity, as well as all values obtained previously under unstable conditions and listed by Montgomery (2) in his tables 7 and 8. In the same graph are shown the theoretical values according to the concepts set forth above.

At wind velocities below 6 m sec^{-1}, when the sea surface should be expected to be hydrodynamically smooth, the Γ-values fall somewhat below the theoretical values for a smooth surface. The discrepancy would have been greater if Montgomery's value for λ, 7.8, had been used. The great spread of the Γ-values at wind velocities between 6 and 7 m sec^{-1} indicates that at these wind velocities the sea surface may be smooth or rough. The character probably depends upon the past history of the wind, e.g., whether it was increasing or decreasing. At velocities exceeding 9 m sec^{-1} the Γ-values fall close to the theoretical value for a rough surface. The average value for all unstable cases with wind velocity exceeding 8 m sec^{-1} is 0.156 against theoretically 0.145 and there is no indication of a relation to wind velocity. This result supports the simple theory proposed here and renders no support to Montgomery's suggestion that the large Γ-values are caused by the effect of spray. It seems highly improbable that such an effect, if present, should be independent of wind velocity and should lead to a numerical agreement of the Γ-values with the simplest possible theoretical value.

Further evidence for the correctness of the present theory is found in the fact that graphs prepared by Burke (1) for computing the transformation of cP to mP air, using the simple assumption introduced here, have been shown to give results in good agreement with observations.

Under *stable* conditions the Γ-values are generally higher. This is seen from Figure 4, in which the available values are plotted against wind speed and in which 7 of 8 values lie above the theoretical curves for indifferent equilibrium.

A satisfactory theory for the stable case has not been developed, but the larger Γ-values are in agreement with earlier suggestions made by the author (5). According to these the eddy viscosity in the lowest

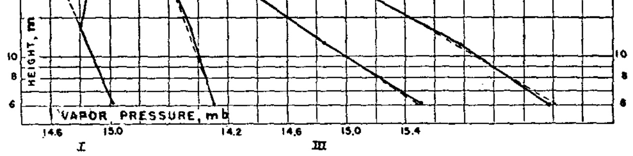

FIG. 1. Average vertical distribution of vapor pressure, groups I–IV.

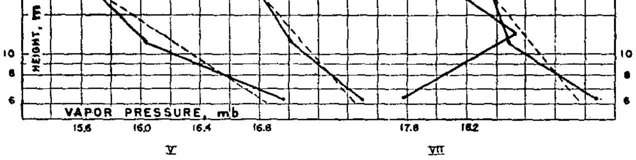

FIG. 2. Average vertical distribution of vapor pressure, groups V–VIII.

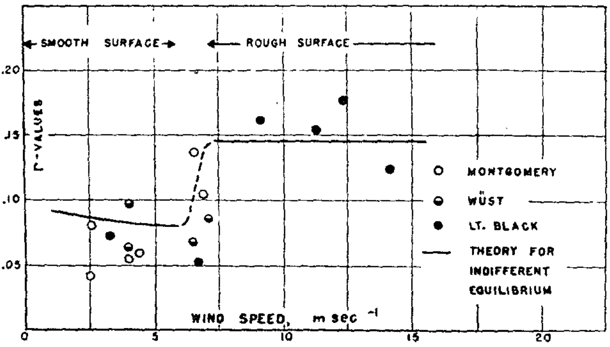

FIG. 3. Γ-values for instability.

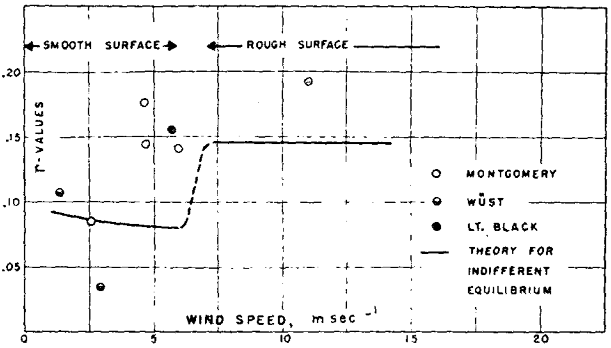

FIG. 4. Γ-values for stability.

50 to 100 cm is independent of the stability but at greater distances it is smaller under stable conditions. Consequently, at a given wind velocity the vertical flux of water vapor

$$E = -\mu_e \frac{dq}{dz}$$

depends, very near the sea surface, only upon the humidity gradient. At some distance from the sea surface where μ_e is smaller under stable conditions, the humidity gradient, dq/dz, must be greater because the flux is supposed to be independent of z. Consequently Γ as defined by equation (1) must be larger.

For the unstable cases the Γ-values derived from averages agree well with theory but the individual values show a wide spread. At wind velocities exceeding 8 m sec^{-1} nearly all humidity observations were made at the heights 27.6, 11.4 and 6.2 meters. Using only the observations at the greatest and smallest height one obtains from (2) and (13):

$$\frac{e_1 - e_2}{e_s - e_1} = 0.145 \ln \frac{27.6}{6.2} = 0.218, \qquad (14)$$

where the subscript 1 refers to the height of 6.2 m and the subscript 2 to the height of 27.6 m. Forming averages for all 26 cases with $W > 8$ m sec^{-1} one obtains

$$\overline{\frac{e_1 - e_2}{e_s - e_1}} = 0.231. \qquad (14a)$$

The single values, however, deviate widely from the average, as is evident from Figure 5, in which the values of $e_1 - e_2$ are plotted against the corresponding values of $e_s - e_1$.

The scatter of the observed differences in vapor pressure at two heights cannot be ascribed to errors of measurement, which appear to be less than ± 0.1 mb, and must represent a real feature. The correlation coefficient is only 0.33, but the regression line of $(e_1 - e_2)$ against $(e_s - e_1)$ agrees fairly well with the theoretical relationship. This fact suggests that the spread is primarily due to random variations in $(e_1 - e_2)$ and *not* to random variation in the difference $(e_s - e_1)$.

The *Indianapolis* data as well as those of Wüst and Montgomery all indicate that observations which are taken at different times give greatly different humidity gradients, but combinations of a small number of such observations are consistently in agreement with the theory of turbulence. It appears probable that observations which were taken simultaneously at different localities but within the same air mass would also give conflicting results but combinations of observations from a few localities would agree with theory. If this is true it may mean that superimposed upon the small-scale turbulence which governs the vertical flux of water vapor there exist large-scale random motions which lead to a large-scale variability in the character of the humidity gradient. This concept can also be expressed by stating that the vertical flux of water vapor is not independent of height at any given locality and any given time, but that on an average over a relatively large area and long time it is constant. How large the area or how long the time need be cannot be stated.

The above reasoning, if correct, implies that under unstable conditions the *average* vertical humidity gradient at a height z can be computed from the

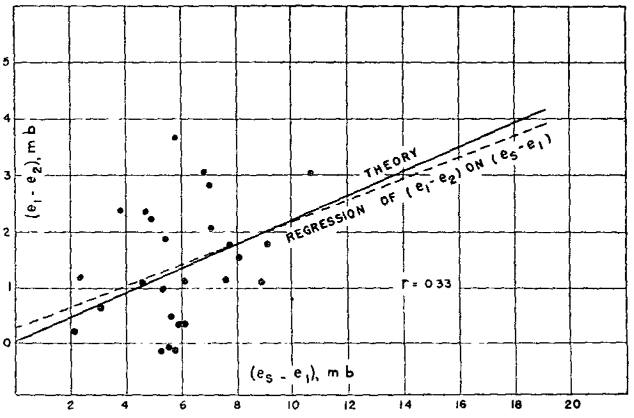

FIG. 5. Comparison of $e_1 - e_2$ with $e_s - e_1$.

equation

$$\frac{dq}{dz} = -\frac{\Gamma_a}{z}(q_s - q_a) \qquad (15)$$

where Γ_a is obtained from (6) or (12). Thus the gradient at any height z can be found if wind velocity and humidity are observed on board ship (at height a) and the sea surface temperature has been observed. The height to which the computation can be expected to be valid depends, according to Montgomery, upon latitude and at about 43° is:

Wind speed, m sec^{-1}		2	4	6	8	10
Thickness of turbulent boundary layer, m	smooth	15	28	40		
	rough				86	99

At a given time the gradient may, however, have values between zero and twice the computed amount. These conclusions may be important if the problems involved require knowledge of both the average gradients and their variability.

Under *stable* conditions a rough value of the humidity gradient may be obtained by using equation (15) and introducing the appropriate Γ-value from Figure 4.

The successful application of the theory of turbulence to the problem of air mass transformation indicates that there exists no large difference in the processes by which heat and water vapor are diffused, and the temperature observations on board the *Indianapolis* support this contention. If heat and water vapor are diffused by the same processes, for wind velocities about 8 m sec^{-1}, one should have (see equations 14 and 14a)

$$\theta_1 - \theta_2 = 0.218(\theta_s - \theta_1). \qquad (16)$$

The 26 cases that represent unstable conditions have been grouped according to the hour of the day when the observations were made and averages formed:

Hour of day	0800–0959	1000–1359	1400–1559
Number of cases	10	8	8
$\overline{\theta_s - \theta_1}$, C	1.17	0.72	1.11
$\overline{\theta_1 - \theta_2}$ observed, C	0.26	−0.08	−0.23
$\theta_1 - \theta_2$ comp. from (16), C	0.25	0.16	0.24

This compilation shows that the expected decrease in "potential temperature" was observed in the morning but not in the afternoon. The reason for this difference between morning and afternoon is probably that during the day the ship's heat has a systematic effect on the temperature distribution. The agreement between observations and theory which is obtained in the morning indicates that the processes of heat and water-vapor transfer are essentially similar.

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