PAPERS IN PHYSICAL OCEANOGRAPHY AND METEOROLOGY

PUBLISHED BY

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

AND

WOODS HOLE OCEANOGRAPHIC INSTITUTION

VOL. VII, NO. 4

OBSERVATIONS OF VERTICAL HUMIDITY DISTRIBUTION ABOVE THE OCEAN SURFACE AND THEIR RELATION TO EVAPORATION

BY

R. B. MONTGOMERY

Contribution No. 235 from the Woods Hole Oceanographic Institution

CAMBRIDGE AND WOODS HOLE, MASSACHUSETTS

February, 1940

CONTENTS

INTRODUCTION

In order to obtain information on the effect of eddy viscosity and eddy diffusion at the boundary between sea and atmosphere, simultaneous measurements of humidity at two, three or four levels between 1 and 38 meters above the sea surface were made from *Atlantis* during its cruises off the east coast of the United States during the summer of 1935. The 340 series are published in the form of averages for 115 ten-minute intervals.

It is now generally accepted that the wind speed in the lowest dekameters of the atmosphere varies as the logarithm of height, provided the lapse rate is not too far from the adiabatic (Lettau, 1939, p. 72 etc.). This is valid within the layer where the normal shearing stress[1] may be considered constant with elevation and equal to the *surface resistance*, τ_0. Accordingly the eddy viscosity coefficient must increase linearly with elevation.

In formulating these relationships it is common to introduce the *friction velocity*, defined as

$$W_* = \sqrt{\frac{\tau_0}{\rho}}, \tag{1}$$

where ρ is the density of the fluid (air). The wind speed is further proportional to this friction velocity, and is usually and most conveniently expressed in terms of the height z above the surface by

$$\frac{W}{W_*} = \frac{1}{k_0} \ln \frac{z + z_0}{z_0}. \tag{2}$$

k_0 is the *universal turbulence constant* ($k_0 = 0.4$). The *roughness parameter* z_0 depends on the nature of the surface; for a fixed, solid surface it is independent of wind speed although, when the surface has more than a single roughness scale, it may increase with elevation (Rossby, 1936a, p. 11). The roughness parameter is a small quantity, so in the sum $z+z_0$ it is negligible except very near the surface. The accompanying eddy viscosity must be

$$\frac{\eta}{\rho} = k_0 W_* (z + z_0) = k_0^2 (z + z_0) \frac{W_a}{\ln \frac{a + z_0}{z_0}}, \tag{3}$$

where a is a fixed height (anemometer level).

In particular Rossby (1936a) has shown that the few existing observations of wind variation with height over the sea surface follow a logarithmic distribution. For certain conditions, namely when (a) the sea surface acts as a *rough* boundary and (b) the waves are in equilibrium with the wind,[2] the roughness parameter is apparently independent of wind speed and is approximately 0.6 cm. When (b) is not fulfilled, the roughness

[1] That is, the shearing stress across horizontal surfaces and due to vertical shear and vertical (eddy) viscosity (Rossby, 1936b, p 6).

[2] By condition (b) is meant that the length of fetch, the depth of water, and the time during which the wind has been blowing steadily are all sufficiently great so that they have no effect on the wave form.

parameter may be much larger (20 cm). From his comparison with other determinations of the surface stress, the proportionality factor in (2) is at least roughly substantiated.

Under other conditions, namely with light winds when the sea surface may act as a *smooth*[3] boundary, Rossby concludes that the wind stress is transmitted to the water through a thin laminar boundary layer. In this case there is "surface slip" so the wind does not follow the simple expression (2), but seems to be given as a function only of the friction velocity and of the logarithm of height by a universal law established by von Kármán (1934) (see below, eqs. 7 and 10).

The description above applies for a steady wind uniform over a large water surface. Under such conditions, and if the air is not saturated with respect to the water surface, there is a steady evaporation and the upward transport of water vapor by turbulence is constant with elevation. It will be shown on page 27 that eddy diffusivity[4] may in most cases be assumed identical in magnitude with eddy viscosity. Hence vapor pressure should decrease upward as the logarithm of height. If this is found to be the case, it further substantiates the linear increase of eddy viscosity and logarithmic increase of wind. This substantiation is especially valuable, because measurements of humidity over the ocean are probably more reliable than those of wind. Thus studies of the humidity gradient above the ocean surface are of considerable importance, for instance, in the determination of the surface resistance.

It is to be hoped, furthermore, that such studies will eventually make possible an independent and accurate calculation of evaporation from the ocean surface. The evaporation is given as the product of the eddy diffusivity and of the vertical rate of decrease of specific humidity. If the laws governing these two quantities can once be established, it should be possible to express them in terms of the wind speed, the water temperature, and the air temperature and humidity at a single height. The measurements of these four quantities are standard observations, so the calculation of evaporation would be entirely practicable.

Discussions of this problem, employing the modern knowledge of the eddy viscosity above the sea surface, have been made by Sverdrup (1936b, 1937) and by Millar (1937). Thornthwaite and Holzman (1939) have computed evaporation from land surfaces using measurements of humidity at two levels and the eddy diffusivity distribution according to (3).

In his second paper Sverdrup employs the humidity observations which I made in 1935. He shows that the averages for a number of groups of the measurements follow a logarithmic distribution satisfactorily. He follows the method outlined above and further assumes that, whether the surface is hydrodynamically rough or smooth, there is always next to the surface a thin laminar layer of air through which the water vapor is transported by molecular diffusion. From each of the groups he computes the thickness of the laminar layer and the rate of evaporation, both for rough surface and for smooth. Then, using these empiric values of the thickness of the laminar layer and climatic values of water temperature, specific humidity at one level and wind speed, he computes the evaporation from successive zones of the Atlantic Ocean for the two types of surface. He finds that the results for rough surface agree in general with Wüst's (1920) values of the evaporation from the same zones, if the latter are multiplied by 1.22 to bring them in

[3] It is to be emphasized that the words *rough* and *smooth* are used throughout this paper in a special sense. They do not refer to the appearance of the surface, but to its hydrodynamic character.

[4] This nomenclature follows Brunt (1939, p. 225).

accord with subsequent estimates of the average evaporation from the whole ocean.

Due to the importance of the whole problem the measurements from *Atlantis* are published here in detail, and they are furthermore subjected to a renewed discussion. The measurements under conditions of thermal stability, which Sverdrup did not use, are included in the discussion.

The method here followed is to compute the expected vertical humidity distribution from our knowledge of the vertical distribution of eddy viscosity—assumed identical with eddy diffusivity—as sketched above. It is postulated, following Millar (1937, p. 55), that von Kármán's law for a hydrodynamically smooth surface applies for a limited distance above a rough surface also. A theoretical expression for the thickness of the laminar layer in accord with von Kármán's law is utilized. Since certain details of Millar's treatment also appear unacceptable, the development is given entirely afresh here. Finally the results are compared with the observed humidity distribution.

Values of evaporation are not computed, for this appears premature until our knowledge of the whole subject can be better founded by means of further measurements. That Sverdrup finds agreement in general with another estimate of the zonal distribution of evaporation does not offer conclusive evidence that his formulation for rough surface, together with his empirical values of the thickness of the laminar layer, gives the true evaporation. Furthermore, if it is hoped that this approach to the evaporation problem will eventually yield absolute values, not just relative values, we must not check our results by comparison with other estimates of evaporation.

Wüst (1937) has published a number of series of humidity measurements at various levels above the sea surface in the Baltic. Average values for his Group II at 50, 100, 200 cm plotted against logarithm of elevation (his Abb. 5) follow closely a straight line even for the sub-groups with thermal stability, but he emphasizes that all sub-groups show relatively greater gradients between 20 and 50 cm than higher up. His observations are included in the discussion below.

METHODS OF OBSERVATION

The flow lines of the air stream are lifted and crowded in passing over a ship. Due to the crowding, wind speed measured at a given height above sea level is greater than at the same height away from the ship's influence, or it may be smaller if measured too near the deck. Only along the upper part of a tall mast in the absence of rolling can a well-exposed anemometer be expected to read approximately free air conditions; such readings alone cannot determine accurately the vertical gradient, for it is small except near the surface. Temperature measurements are not affected by the crowding, so these can be more representative than wind measurements provided the lifting of the flow lines is not too great and provided radiation and contamination from the ship are avoided. Usually the temperature gradient is smaller than that for humidity, so the latter can be measured still more accurately. Small errors make the temperature gradients presented here of little value, while the humidity gradients are not too greatly affected.

Preliminary experiments showed that it was impractical to determine gradients by using one instrument successively at different heights, since the conditions often change during such a series. Thus in order to have measurements at four levels it is essentially necessary to have four instruments.

In the present case the four instruments available were three Assmann psychrometers of different types and a hygrothermograph. It is generally disadvantageous to use dissimilar instruments because their errors are different (with psychrometers chiefly because of different ventilation speeds), but in this case each was peculiarly adapted to the position where it was used.

The hygrothermograph was used near the masthead at 38 meters (sometimes at 18 meters). This instrument was converted from an aircraft barothermograph by replacing the aneroid with a hair element. It could be read to a tenth of a degree and to a fifth of one per cent. When not in use it was kept in a moist chamber, which was partly responsible for the fact that the hair element was very reliable; during the summer its calibration changed by only about 2%. The temperature element, a closed Bourdon tube, behaved very badly due to corrosion; its readings were reliable only when a daily calibration was made. Since the instrument was left in position for long intervals, its lag was of no disadvantage. The cover of the original barothermograph was removed and the bare instrument suspended by elastic tape inside a portable shelter. This shelter was closed on the four sides with an insulating material and partly open at the bottom, the air being circulated outward through radiation baffles at the top by an electric fan. In use the shelter was suspended from a shackle running free on the forestay and could be hoisted to any height; the rubber-covered cable for the fan served as downhaul and was kept under strain to prevent the shelter from swinging. Calibrations were made under cabin or deck conditions against one of the Assmanns.

A Fuess spring-driven Assmann was used at the 8-meter level. It was held rigidly 15 cm aft of the forestay in a wooden bracket, and was read directly by an observer in the boatswain's chair suspended nearby. The exposure seemed a good one except occasionally when the observer was unable to keep entirely clear of the instrument. This psychrometer was kindly lent for the purpose by the Blue Hill Meteorological Observatory.

An electric Assmann by Casella was suspended at the ship's stem with its mouth pieces on a level with the rail and a half meter forward of it, 4 meters above the water. It was read directly by an observer in the extreme bow of the boat.

The third Assmann was a reversing one by Richter and Wiese (Böhnecke, 1933). This was suspended from the rail at the stem and tended by the same observer who read the electric psychrometer, and who also recorded all the readings. It was lowered to 2 or 1.5 meters, or alternately to 2 and 1, above the surface as the sea permitted.

By keeping the reversing psychrometer outside the rail while reading and winding it, it could safely be reversed a minute after lowering it again; thus the series of readings could be repeated every three minutes. After dipping the wet bulbs at least two minutes was usually allowed before reading. The psychrometers at times seemed to be affected by direct solar radiation, but this could not be proven or evaluated. All the psychrometer thermometers were calibrated at 2°-intervals under total immersion. Corrections in nearest tenths of a degree have been applied to all readings.

The exposures of the four instruments are shown in Figures 1 and 2. No explanation seems necessary other than that the positions were chosen with three ideals in mind: (a) a spacing such that each was roughly twice as high as the one below it, so that approximately equal differences of humidity would occur between successive pairs, (b) exposures that would give as near to free air conditions as possible, and (c) availability in rigging and reading.

Readings were made only when the wind relative to the ship was forward of the beam; at other times the air reaching the instruments was disturbed in its flow or even contaminated. The other work of the ship frequently required much maneuvering, so the measurements were often interrupted due to this necessity of head winds. The measurements were further interrupted by necessary repairs to the apparatus (including washing the reversing psychrometer after immersion by unusually large waves), and by fog or rain or fresh winds, the last causing so much salt spray that accurate readings were impossible. At other times an additional observer was not available for taking readings at 8 meters. The bow of *Atlantis* is the only part which gives a suitable exposure close to the water. Unfortunately this part experiences greater vertical motion than any other, which often made measurements close to the surface impossible. The following gives approximately the maximum wind which was accompanied by a sea permitting readings at the various levels:

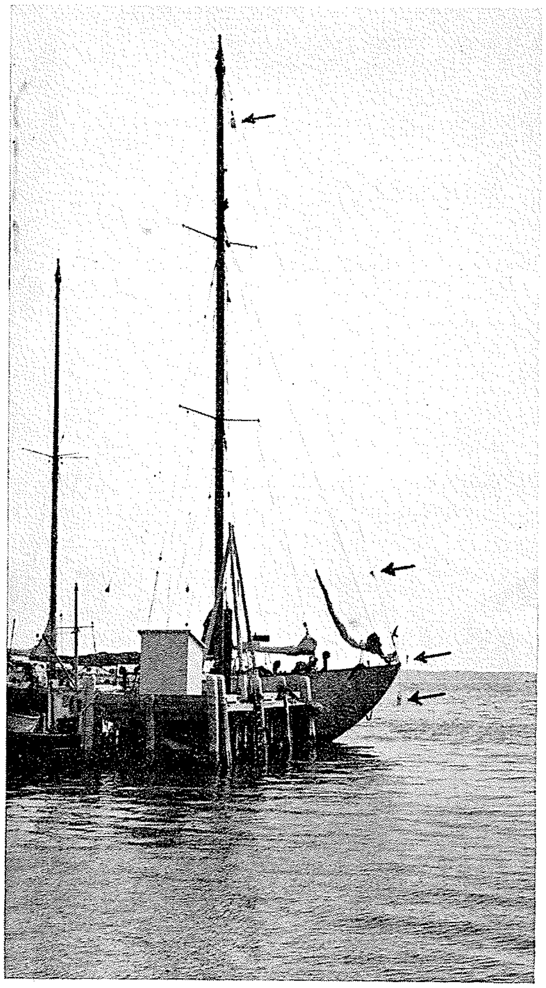

FIG. 1. Positions of four instruments when in use. From top to bottom: hygrothermograph, spring-driven Assmann (bracket only), electric Assmann, reversing Assmann.

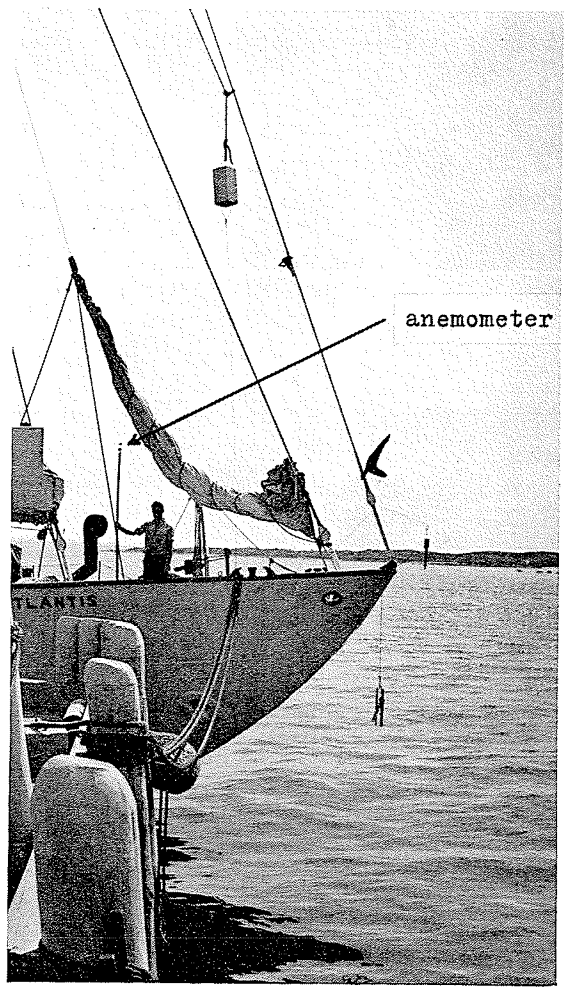

FIG. 2. Closer view of the same instruments as in Figure 1. The hygrothermograph is lowered nearly to the deck.

1	meter	2.5 m sec^{-1}
1.5		4
2		5.5
4		7.5

The wind speed was measured whenever the ship was stationary or moving slowly; when under way the Beaufort estimate was considered just as reliable as a measurement roughly corrected for the ship's motion. A small portable anemometer attached to the top of a hand pole was exposed over the windward rail 6 meters above the water, in the position shown in Figure 2. The readings have been corrected according to a careful calibration (Montgomery, 1936), as well as for the ship's headway.

During the humidity measurements the water temperature was frequently determined with a surface thermometer, always used so as to avoid any possible contamination or upwelling due to the ship.

TABULATION OF DATA

The Smithsonian Meteorological Tables (Smithsonian Institution, 1933, Table 79) were used for obtaining saturation values of vapor pressure. The percentile lowering of saturation vapor pressure by a salinity of S°/₀₀ is 0.000537 S (Witting, 1908, p. 173), so saturated air over ocean water has a vapor pressure 98% of that over fresh water of the same temperature. (This constant value is correct within 0.1 mb for water below 25° with salinity between 27 and 39 °/₀₀.) From this has been found the saturation vapor pressure e_s corresponding to the surface water temperature T_s.

The psychrometer readings were reduced by means of the following formula from the Smithsonian Tables:

$$e = e' - 0.000660p(T - T')(1 + 0.00115T') \tag{4}$$

Here e is the resulting vapor pressure, e' the saturation pressure corresponding to the wet bulb temperature T', T the dry bulb temperature and p the barometric pressure. p may be assumed constant at 760 mm or 1013.3 mb, so the relation used was:

$$\begin{aligned} e &= e' - 0.68(T - T') \qquad 8° \leqq T' \leqq 21.5° \\ e &= e' - 0.69(T - T') \qquad 21.6° \leqq T' \leqq 34° \end{aligned} \tag{5}$$

Tables 1 and 2 present the data.

On the date line are given the *Atlantis* cruise number, the noon position, and the true wind direction and sea direction and disturbance (scale of 0–9) during the period covered by the

TABLE 1

TEMPERATURE (T IN °C.) AND VAPOR PRESSURE (e IN MB) AT DIFFERENT HEIGHTS FOR CRUISE 45. W_6 IS WIND SPEED 6 METERS ABOVE THE SURFACE IN M SEC^{-1}.

Time	W_6	Series	T_S	T_1	$T_{1.5}$	T_2	T_4	T_8	T_{38}		T_S-T_4	e_S	e_1	$e_{1.5}$	e_2	e_4	e_8	e_{38}		e_S-e_4	Γ	Clouds
									July 21, 39°23′N. 69°52′W., wind ENE, sea ENE 2													
1055	2.9	1	22.4		21.5		21.5		21.5	21.1	0.9	26.6		24.1		23.7		23.1	22.5	2.9	.14	very thin Stcu+Ci
1110	2.9	1	22.4		21.9		21.8		21.8	21.4	0.6	26.6		24.3		23.9		23.4	22.9	2.7	.15	
1120	(2.9)	1	22.4		22.2		22.0		21.1	21.6	0.4	26.6		24.3		24.0		23.7	22.95	2.6	.12	
1231	2.8	1	23.6		23.0		23.1		23.0	22.7	0.5	28.6		25.5		25.0		24.8	24.35	3.6	.14	3 Frcu
1325	2.8	1	23.9		23.3		23.3		23.4	22.9	0.6	29.1		25.3		24.9		24.5	23.7	4.2	.10	6 Frcu
1416–23	2.5	2	23.8	23.0		22.9	22.9		23.3	22.5	0.9	28.9	26.1		25.9	25.7		25.6	24.4	3.2	.09	2 Cu, Ci haze
1456	2.2	1	23.8			23.1	23.3	22.9	23.2	22.8	0.5	28.9			26.4	26.0	26.1	25.4	24.8	2.9	.07	
1610–17†	2.6	2	23.8	23.3		23.1	23.1	22.8	23.4	22.65	0.7	28.9	26.0		25.7	25.5	25.45	25.5	24.4	3.4	.08	slight haze only

July 23, 36°27′N. 68°07′W., wind SWxW, sea SWxW 2																						
1355	(4.6)	1	27.4		27.1		27.0		27.0		0.4	35.8		26.5		25.6		23.4		10.2-	.09	clear, Cu in distance
1438–43	(4.2)	2	27.5		27.0		27.1		27.0		0.4	36.0		27.4		26.0		25.1		10.0-	.14	
1510–14	3.9	2	27.5		27.15		27.35		27.3‡		0.15	36.0		27.6		26.7		25.6‡		9.3-	.04	Cu overhead
July 25, 35°45′N. 68°24′W., wind SW, sea SW 4																						
1112–13	7.8	2	27.4				26.9*	26.85	26.9‡	26.75‡	0.5	35.8				30.7*	29.05	27.4‡	27.15‡	5.1-	.46	2 Cu
1120–23	7.8	2	27.4				27.0*	26.95	26.8	26.65	0.4	35.8				30.2*	28.85	26.7	26.5	5.6-	.27	
July 29, 35°54′N. 68°46′W., wind WxN, sea W 2–3																						
1850–55	3.7	2	26.3			25.75	25.85	25.4	25.6		0.45	33.5			25.4	24.6	24.8	24.2		8.9-	.05	7 Cu+Ast
1905	3.4	1	26.3			25.5	25.6	25.3	25.5‡		0.7	33.5			25.9	25.1	25.3	24.7‡		8.3-	.07	
1919–24	3.0	2	26.2			25.4	25.4	25.3	25.5‡		0.8	33.3			26.0	25.6	25.45	25.1‡		7.7-	.05	
1936–46	2.5	3	26.2			25.4	25.4	25.3	25.2		0.8	33.3			25.9	25.6	25.1	24.8		7.7-	.08	6 Cu+Ast
July 30, 35°31′N. 68°46′W., wind WSW, sea SWxW 3																						
1106	6.4	1	26.1				25.3	25.0	25.55	24.7	0.8	33.2				23.3	23.05	21.9	20.8	9.9-	.11	6 Ast
1115–17	6.2	2	26.1				25.05	25.0	25.6	24.7	1.05	33.2				24.15	24.2	22.75	21.5	9.1	.13	
1253–1303†	5.0	4	26.2				25.4	25.4	25.8	25.1	0.8	33.4				25.6	25.7	25.6	24.5	7.8	−.02	2 Cu, 2 Acu
1447–50	4.0	2	26.2				26.0	25.8	26.1	25.5	0.2	33.4				25.45	25.55	25.35	24.5	8.0-	−.02	
1454–58	4.0	3	26.2				25.9	25.6	26.1	25.3	0.3	33.4				25.5	25.6	25.5	24.4	8.0-	−.02	5 Cu+Ast+Cist
1556–1602	4.3	2	26.2				25.7	25.35	26.0	25.05	0.5	33.4				25.45	25.45	25.85	24.5	8.0-	.00	5 Cu+Ast+Cist
1606–07	4.3	2	26.2				25.75	25.3	26.0	25.0	0.45	33.4				26.1	25.8	25.9	24.5	7.3-	.06	
July 31, 37°12′N. 69°48′W., wind W, sea WxS 3																						
1104–09	(4.6)	2	25.3			23.9	23.95	23.6	24.4	23.3	1.35	31.7			18.3	17.4	16.65	15.6	14.55	14.3-	.08	5 Ast+Acu
1120–28	(4.6)	3	25.3			23.9	23.9	23.6	24.4	23.3	1.4	31.7			18.3	17.5	16.6	16.1	15.0	14.2-	.09	
1242–52	(4.6)	3	25.2			24.3	24.1	23.9	24.5	23.6	1.1	31.5			20.3	19.6	18.7	17.6	16.7	11.9	.10	6 Ci+Cicu
1256–1303	(4.7)	3	25.2			24.3	24.1	23.9	24.5	23.6	1.1	31.4			20.6	19.6	18.9	18.15	17.1	11.8	.10	
1342–45	(5.9)	2	25.0			24.75	24.4	24.15	24.65	23.85	0.6	31.1			21.75	21.15	20.3	19.7	18.7	10.6	.10	4 Ci+Cicu
1350–56	(5.9)	3	25.0			24.7	24.4	24.2	24.7	23.9	0.6	31.1			22.3	21.9	21.3	20.6	19.7	8.8	.10	
1440–47	(5.9)	3	24.9			24.6	24.5	24.2	24.9	23.9	0.4	30.9			22.3	22.2	21.75	21.3	20.1	8.7	.09	7 Ci+Cicu
1450–57	(6.0)	3	24.9			24.7	24.6	24.3	24.9	24.0	0.3	30.9			22.8	22.3	21.5	21.5	20.3	8.6	.10	
1555–1605	7.1	4	24.8			24.75	24.65	24.5	25.05		0.15	30.7			22.45	22.4	21.4	21.35		8.3-	.04	9 Cist
1608–16	6.9	3	24.8		24.9		24.9	24.6	25.1		−0.1	30.7		21.8		20.2	19.75	20.0		10.5-	.05	
August 1, 37°21′N. 70°26′W., wind SW, sea SW 3																						
1101–08	(7.2)	6	25.0				25.8	25.8	26.95		−0.8	31.1				30.4	30.3	30.9		0.7	—	7 Cu+Acu
1454–58	6.5	4	25.0				26.15	25.7	26.8		−1.15	31.1				30.15	30.4	31.4		0.95	—	6 Cist
1601–06	6.6	6	25.0				25.9	26.0	27.1		−0.9	31.1				30.8	30.8	31.8		0.3	—	8 Cist
August 2, 37°36′N. 70°29′W., wind WSW, sea WxS 2–3																						
1603–06	(4.6)	2	24.8		25.25		25.25	25.1	25.9		−0.45	30.7		29.75		29.65	29.45	29.1		1.1	.16	6 Acu
1611–19	(4.3)	3	24.9		25.3		25.3	25.1	25.9		−0.4	30.9		29.7		29.6	29.6	29.2		1.3	.05	
1715–20	(2.6)	3	25.1		25.5		25.5	25.3	25.9		−0.4	31.1		28.6		28.3	28.2	27.6		3.0	.08	5 Cicu
1723–26	(2.6)	2	25.1		25.45		25.4	25.15	25.9		−0.3	31.3		28.75		28.5	28.35	27.75		2.8	.09	
1854–1902	(2.6)	3	25.2			25.0	24.9	24.8	25.4		0.3	31.4			28.9	28.75	28.7	28.4		2.7	.05	1 Ci
1906–12	(2.6)	2	25.2			25.05	24.95	24.8	25.3		0.25	31.4			28.9	28.7	28.6	28.4		2.7	.08	
August 3, 40°38′N. 71°13′W., wind NE, sea NE 2																						
1218–25	(4.6)	3	23.0		21.6		21.4	21.1	21.0	20.8	1.6	27.5		18.2		17.7	17.2	16.1		9.8	.06	9 Ast
1230–34	(4.6)	2	23.0		21.6		21.4	21.1	21.0	20.8	1.6	27.5		18.0		17.5	17.0	16.1		10.0	.06	
1317–26	(4.6)	3	23.0		21.8		21.6	21.5	21.1	21.1	1.4	27.5		16.45		15.75	15.2	14.3		11.8	.06	1 Acu
1330–38	(4.6)	3	23.0		21.7		21.4	21.3	21.1	21.0	1.6	27.5		17.1		16.7	16.05	14.8		10.6	.06	
1415–24	(3.0)	3	23.2	21.7	21.6	21.7	21.5	21.4	21.2	21.1	1.7	27.9	16.2	15.9	16.0	15.75	15.6	14.5		11.7	.02	1 Ci+Acu
1430–39	(2.6)	3	23.3	21.8		21.8	21.6	21.6	21.3	21.3	1.7	28.0	14.7		14.6	14.3	14.3	13.6		13.7	.01	
1442–49	(2.6)	3	23.4	22.1		22.0	21.8	21.7	21.3	21.4	1.6	28.1	13.9		13.3	13.3	13.4	12.3		14.8	.02	

* Interpolated.

† Air samples also were obtained at this time.

‡ At 18 instead of 38 meters.

TABLE 2

TEMPERATURE (T IN °C.) AND VAPOR PRESSURE (e IN MB) AT DIFFERENT HEIGHTS FOR CRUISES 46 AND 47. W_6 IS WIND SPEED 6 METERS ABOVE THE SURFACE IN M SEC^{-1}.

Time	W_6	Series	T_S	T_1	$T_{1.5}$	T_2	T_4	T_8	T_{33}	T_S-T_4	e_S	e_1	$e_{1.5}$	e_2	e_4	e_8	e_{33}	e_S-e_4	Γ	Clouds
Cruise 46, August 7, 39°38′N. 72°27′W., wind ENE, sea ENE 3																				
1443	6.3	1	22.2		20.9		20.8		20.1	1.4	26.3		18.5		17.6		15.3	8.7	.11	10 Acu
1525	(6.6)	1	22.3			20.8	20.6		20.2	1.7	26.4			18.6	18.5		15.7	8.5	.12	9 Acu
1539–45	(6.8)	6	22.3				20.5		20.3	1.8	26.4				18.0		15.9	8.4	.11	
1631–38	(7.2)	8	22.5				20.9		20.2	1.6	26.7				17.95		16.0	7.75	.11	8 Acu
August 9, 37°40′N. 73°53′W., wind NExE, sea NExE 3																				
1913–19	4.6	2	24.9			22.8	22.55		22.45	2.35	30.9			17.8	17.35		15.75	13.55	.06	clear
1933–40	4.3	3	24.9			22.6	22.55		22.3	2.35	20.9			16.9	16.65		14.95	14.35	.03	
1944–49	4.1	3	24.9			22.7	22.6		22.3	2.3	30.9			17.3	16.8		15.2	14.1	.05	
August 10, 37°26′N. 74°29′W., wind NExE—ExS, sea ExS 1 (swell ENE 2)																				
1230	3.9	1	24.8			22.9	22.5		22.4	2.3	30.7			17.3	17.6		15.2	13.1	−.03	clear
1300–09	3.5	4	24.9		22.7	22.9	22.4		22.4	2.5	30.9		17.7	17.4	17.1		15.55	13.8	.04	
1314–23	3.4	4	24.9			22.7	22.5		22.4	2.4	30.9			17.0	16.8		15.8	14.1	.02	clear
1407–14	2.9	3	24.9		22.5		22.3		22.3	2.6	30.9		17.6		17.2		16.5	13.7	.03	
1417–26	2.9	3	24.9		22.6		22.3		22.3	2.6	30.9		16.9		16.9		15.9	14.0	.00	clear
1510–18	2.9	3	24.8		22.6		22.4		22.3	2.4	30.7		17.7		17.2		16.4	13.5	.04	
1520–29	2.9	4	24.8		22.6		22.4		22.4	2.4	30.7		17.7		17.8		16.45	12.9	−.01	clear
August 11, 38°10′N. 73°51′W., wind SSW, sea S 2																				
1548–50	6.0	3	23.8				24.5		24.2	−0.7	28.9				26.8		26.3	2.1	.11	10 Stcu
1600–06	6.0	3	23.8			24.5	24.5		24.2	−0.7	28.9			27.1	26.9		26.5	2.0	.10	
1758–1801	5.2	4	23.8				24.4		24.15	−0.6	28.9				27.4		26.95	1.4	.14	10 Stcu
August 12, 38°26′N. 73°31′W., wind ExS—SSE, sea SSE 1 (swell S 2—confused 1)																				
1100–06	2.5	2	22.8	22.65			22.45		22.85	0.35	27.15	24.65			24.45		23.8	2.7	.06	clear
1117–23	2.2	3	23.0	22.8		22.7	22.6		22.7	0.4	27.5	24.3		24.25	24.25		23.7	3.25	.01	
1253–1300	(2.3)	4	23.2	22.9		22.7	22.4		22.65	0.8	27.9	24.7		24.7	24.55		24.1	3.35	.03	clear
1304–07	2.3	2	23.3	22.7		22.7	22.45		22.5	0.85	28.0	24.6		24.4	24.55		24.0	3.45	.01	clear
1624–28	(2.3)	2	23.75		23.3		22.7		23.0	1.05	28.8		24.3		24.2		23.8	4.6	.02	3 Cu
1647–57	(2.3)	2	23.8		23.05		22.75		22.95	1.05	28.9		24.6		24.25		23.8	4.65	.08	clear, slight haze
1700–02	(2.3)	2	23.8		22.9		22.8		22.9	1.0	28.9		24.5		24.3		23.85	4.6	.04	
1837–47	(2.3)	4	23.7		23.2		23.0		23.1	0.7	28.7		24.8		24.45		24.0	4.25	.08	
August 13, 39°32′N. 72°20′W., wind SSW, sea SSW 1																				
1047	4.7	1	21.9		22.8		22.6	22.5	22.5	−0.7	25.8		24.8		24.2	24.1	24.0	1.6	.26	2 Ast, slight haze
1054–59	4.7	2	21.9		22.8		22.55	22.55	22.6	−0.65	25.8		24.6		24.15	24.3	24.15	1.65	.11	
1130–37	4.8	2	22.1		22.85		22.5	22.6	22.6	−0.4	26.1		24.85		24.5	24.35	24.2	1.6	.19	
1143–48	4.8	2	22.2		22.85		22.55	22.6	22.6	−0.35	26.2		24.55		24.4	24.35	24.2	1.8	.07	
1322	4.8	1	22.7		23.4		22.9	23.0	22.8	−0.2	27.1		25.7		25.2	25.1	24.9	1.9	.19	1 Ast, slight haze
1408–13	4.3	2	22.8		23.2		22.9	22.9	23.1	−0.1	27.2		26.1		26.1	25.7	25.5	1.1	.22	
1418–21	4.4	2	22.9		23.2		22.9	23.0	23.15	0.0	27.4		26.1		26.1	25.8	25.6	1.3	.14	
1605–08	5.3	2	22.9		23.6		23.25	23.2	23.1	−0.35	27.4		26.9		26.55	26.45	25.8	0.85	—	
1620–24	5.4	2	22.9				23.4	23.25	23.15	−0.5	27.4				26.6	26.55	25.9	0.8	—	
Cruise 47, August 20, 42°08′N. 69°58′W., wind SW—SxE, sea SxE 2																				
1016–20	3.0	3	21.0				20.3		21.1	0.7	24.4				22.5		22.0	1.9	—	3 Ci, becoming thick fog
1539–49	4.1	4	21.4	20.9		21.1	20.9		21.5	0.5	25.0	22.7		22.65	22.45		20.15	2.55	.07	7 Cist
1551–59	4.4	4	21.5	21.2		21.25	21.15		21.8	0.35	25.2	22.8		22.85	22.4		20.6	2.8	.10	
2012	3.8	1	22.0				22.0		22.3	0.0	25.9				25.3		24.5	0.6	—	5 Cist
2052–58	3.6	2	22.0		22.15		22.05		22.3	−0.05	25.9		25.45		25.3		24.5	0.6	—	3 Cist
2103–07	(3.6)	2	22.0		22.15		22.1		22.3	−0.1	25.9		25.45		25.3		24.5	0.6	—	

August 21, 41°39′N. 69°00′W., wind SxE, sea SxE 2																
1232–38	(4.6)	3	22.3	22.7	22.5		22.6	−0.2	26.3	25.3	25.1		23.8	1.2	.17	4 Ci+Cicu etc.
1242–45	(4.6)	2	22.15	22.55	22.5		22.6	−0.35	26.15	25.3	25.0		23.8	1.15	.27	
1338–44	(4.7)	3	22.2	22.6	22.4		22.7	−0.2	26.2	25.4	25.2		24.0	1.0	.20	6 Ci+Acu
1347–52	(4.9)	3	21.9	22.3	22.2		22.7	−0.3	25.9	25.2	25.0		24.1	0.9	—	
1429–36	(5.8)	3	21.5	22.0	21.9	21.9	22.4	−0.4	25.1	24.7	24.5	24.3	23.7	0.6	—	5 Ci
1439–45	(5.6)	3	21.0	21.8	21.7	21.8	22.5	−0.7	24.3	24.45	24.4	24.2	23.8	−0.1	—	
1529	(4.6)	1	20.5	20.0	20.0		22.1	0.5	23.6	23.0	22.8		23.1	0.8	—	3 Ci
August 23, 42°00′N. 69°16′W., wind NxE, sea NxE 3																
1527–35	7.8	8	21.9		19.9		19.45	2.0	25.8		18.95		17.6	6.85	.09	3 Frcu
1621–29	8.2	8	21.8		20.1		19.4	1.7	25.6		17.7		15.6	7.9	.12	clear
1811–19	6.3	8	21.25		20.1		19.5	1.15	24.75		15.0		12.7	9.75	.10	clear
1913–15	(5.4)	3	20.8		19.9		19.4	0.9	24.1		15.3		13.7	8.8	.08	clear
August 25, 40°51′N. 68°44′W., wind NW—WxN, sea NW 3																
1310–15	6.8	6	14.2		15.0		15.2	−0.8	15.9		13.65		13.1	2.25	.11	9 Cist
1428–32	5.3	5	14.3		14.9		15.2	−0.6	16.0		14.1		13.3	1.9	.20	10 Cist
1535–40	5.8	6	14.35		15.1		15.3	−0.75	16.05		14.2		13.6	1.85	.14	10 Cist
1623–33	(6.9)	7	14.2		15.1	15.1	15.2	−0.9	15.9		14.5	14.5	13.9	1.4	.19	10 Cist
1748–57	(8.4)	7	18.2		17.0	16.9	16.3	1.2	20.5		14.1	13.7	13.2	6.4	.06	10 Acu
1843–49	(7.1)	4	18.4		17.9		17.5	0.5	20.75		14.05		13.2	6.7	.06	9 Cicu+Cist
1853–54	(6.9)	2	18.7		18.1		17.5	0.6	21.2		14.0		13.0	7.2	.06	
1924–30	(6.0)	6	19.3		19.05		18.3	0.25	21.95		13.1		11.6	8.85	.08	8 Acu+Cist
August 26, 40°45′N. 70°53′W., wind WxN, sea WxN 3																
0725–31	(4.6)	6	23.0		21.3		20.9	1.7	27.45		16.5		15.9	10.95	—	9 Acu
0839–48	(4.6)	3	22.1	21.4	21.2	21.1	20.8	0.9	26.2	16.5	15.8	14.9	14.6	10.4	.09	8 Acu
0852–59	(4.6)	3	21.4	21.2	21.1	21.1	20.8	0.3	25.0	17.0	16.6	16.1	14.8	8.4	.06	
0933–39	(4.6)	3	21.1	21.2	21.3	21.1	20.9	−0.2	24.5	17.3	16.6	16.4	15.1	7.9	.07	5 Acu+Ast
0943–49	(4.8)	3	21.1	21.3	21.3	21.1	21.1	−0.2	24.5	18.4	17.8	17.6	16.0	6.7	.07	
0952–55	(4.9)	2	21.1	21.3	21.3	21.2	21.1	−0.2	24.6	18.0	17.1	17.0	15.7	7.5	.08	

day's measurements.

The first column is standard time of the 60th meridian. The wind speed, second column, is enclosed in parentheses if an anemometer reading was not made within one hour of the observation. The third column gives the number of series of humidity measurements made within the time interval of the first column (the interval never exceeds 10 minutes); if readings are shown at both 1 and 2 meters, the number of readings at each of these is less than the number of series, since the same psychrometer was used at both levels. In the following columns of temperature and vapor pressure, the subscript s refers to the sea surface and the numerical subscripts to heights in meters above the surface. Then follows Γ, and in the last column the cloud amount in tenths of the sky covered.

The quantity Γ is introduced to represent the vertical gradient of vapor pressure. The air in immediate contact with the water is assumed to be saturated with respect to the sea water. Since the vertical distribution of diffusivity is unaffected by humidity, it follows that under steady conditions the vapor pressure gradient is proportional to $e_s - e_b$, where b is any standard level for vapor pressure. Accordingly the effect of $e_s - e_b$ may be immediately eliminated by the following definition, which furthermore assumes a logarithmic distribution:

$$\Gamma \equiv -\frac{1}{e_s - e_b}\frac{de}{d \ln z} \tag{6}$$

For the present measurements the standard level is chosen to be 4 meters. In cases where the wind is stronger than 5 m sec^{-1}, $de/d \ln z$ is computed from the humidity measurements at the two extreme levels. Since the turbulent boundary layer may at times be of limited height (see p. 20), the gradient is computed from the lowest level and from the highest below 38 meters in cases where the wind does not exceed 5 m sec^{-1}. No value is given for Γ when $e_s - e_4 < 1$ mb, because the error is large when the air is nearly saturated with respect to the water.

As mentioned in the last section, the temperature readings of the hygrothermograph are unreliable for days when no calibration was carried out (July 21, 25, 30, 31 and August 1–3). Accordingly for such days (except the last two lines for July 31 and for August 1 and 2, when $T_{38} > T_s$ indicates at least possible thermal stability) the vapor pressure has been computed from the observed relative humidity and from the temperature extrapolated from the temperatures at 4 and 8 meters according to a lapse rate of 1° per 100 meters. These days occur only during Cruise 45, which is therefore given separately in Table 1. Here the columns for T_{38} and e_{38} are double, the first sub-column giving the observed value and the second the computed one. The computed vapor pressures are used in determining Γ on July 25, 30, 31.

DISTRIBUTION OF EDDY VISCOSITY ABOVE THE SEA SURFACE

It is convenient in discussing vertical mixing processes to divide the atmospheric layer of frictional influence into three mutually exclusive parts. The *outer layer of frictional influence* constitutes about 90% of the thickness of the whole layer and is characterized by a turning of the wind according to a modified Ekman spiral. Beneath this is the *turbulent boundary layer*, constituting about 10% of the whole thickness. It is characterized by the relationships (2) and (3), that is by a logarithmic wind distribution. Immediately in contact with the sea surface, or with any object over which the wind blows, there is apparently a *laminar boundary layer* of the order of magnitude of one millimeter, in which turbulence is absent. Only the two lower layers are of importance in the present study.

Within the turbulent boundary layer the distribution of eddy viscosity is given by (3) in terms of the wind speed and of the roughness parameter. In the laminar boundary layer only molecular viscosity is present. To specify the distribution of viscosity completely, then, it is necessary to know the thickness of the laminar layer and the roughness parameter.

There are two means by which the normal shearing stress, which is nearly constant throughout the turbulent boundary layer,[5] can be transmitted to the bounding surface. It may be transmitted as a normal stress through the laminar layer, as over smooth surfaces like the sea in light winds (and thermal stability). Or the process may occur chiefly by means of local horizontal pressure gradients against the sloping sides of obstacles, as over hydrodynamically rough surfaces like the ground or the sea in strong winds (and thermal instability). In the latter case the logarithmic wind distribution cannot be expected to hold within the hollows of the roughness elements, so that it will be necessary in treating evaporation from a hydrodynamically rough sea surface to consider an *intermediate boundary layer* between the turbulent and laminar boundary layers. This fourth division of the whole frictional layer is of small importance for momentum transfer, but is necessary in considering diffusion processes.

[5] For discussions of the extent to which the stress may be considered constant within the turbulent boundary layer see Rossby and Montgomery (1935, pp. 40–44) and Calder (1939).