OBSERVATIONS OF THE SALT CONTENT

OF THE LOWER MARINE ATMOSPHERE

by

Theodore Howard Benttinen Jr.

B.S., University of Washington

(1967)

SUBMITTED IN PARTIAL FULFILLMENT

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Signature of Author . . . .
              Department of Geology and Geophysics
                            August 19, 1968

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                                   Thesis Supervisor

Accepted by . . . .
              Chairman, Departmental Committee
                            on Graduate Students

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Abstract

Measurements of the total sea-salt content of the air were made from shipboard at a height of 10 meters. The majority of the data were taken in the Indian Ocean, but data from the Mediterranean Sea, Red Sea and adjacent waters were included.

Small diameter wires were exposed to the wind. The sodium found on the wires was converted into total mass of sea-salt by assuming the ion ratios of sea water.

At winds above 8 to 10 knots, the sea-salt content increased logarithmically with increasing wind speed and an empirical formula was obtained. For the lighter winds no clear-cut relationship was found. The sea-salt content shows no obvious relationship to geographical position for maritime environments.

The effect of low-level instability on the sea-salt content was measured and found to be significant. For winds above 15 knots, greater instability resulted in a higher sea-salt content. The converse was true for low winds, i.e. those below 7 knots. In this case, greater instability was associated with a lowering of the sea-salt content.

The effects of washout and sedimentation on the sea-salt values were observed and qualitatively discussed.

Thesis Supervisor: Henry G. Houghton

Title: Professor of Meteorology, Head of the Department
         of Meteorology

ACKNOWLEDGEMENTS

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[Both tables calculated from Langmuir and Blodgett, 1946]

I. INTRODUCTION

Interest in natural aerosols was initiated by the clas-
sic papers of John Aitken. These were published in the lat-
ter quarter of the nineteenth century and subsequently col-
lected in a convenient volume (Aitken, 1923). Aitken was
able to show that the condensation of vapours depended upon
the presence of free surfaces in the form of tiny particles
of "dust." In one of his major papers, "On Dust, Fogs, and
Cloud," published in 1881, Aitken realized the important role
which the oceans could play in producing the "dust" particles
so necessary for condensation. "In all probability the spray
from the ocean, after it is dried and nothing but a fine
salt-dust left, is perhaps one of the most important sources
of cloud producing dust." These particles having their origin
in the sea have since become known as sea-salt particles or
more commonly, sea-salt nuclei.

With the invention of the Aitken nuclei counter, a de-
vice which works on the general principles of the Wilson cloud
chamber, many observations were made of the number of "dust"
particles in the air. However, only the total number of par-
ticles in a particular sample was determinable, and because
of the very great differences in concentration, the presence
of the larger particles was masked by the much more numerous
small particles. Hereafter, in general accordance with the

literature, those particles with a radius of one-tenth micron
or less will be referred to an Aitken particles, those with
a radius between one-tenth and one micron as large particles
and those with a radius of one micron or more as giant parti-
cles.

Because of the widespread use of the Aitken counter
very little work was done on the large and giant nuclei during
the first part of this century. Various observors came to
realize that particles could be produced by the sea and that
these particles would probably consist of sea-salt but data
pertaining to the actual measurement of these particles were
virtually nonexistent until the work of Owens (1926). He
measured the sizes of some of the largest salt particles
found in clear air near the sea surface. Houghton (1932) felt
that at least the smaller droplets in the fogs which he inves-
tigated were the result of condensation onto sea-salt parti-
cles. After measuring the size spectrum of fog droplets,
Köhler (1936) was convinced that sea-salt particles were a
major contributor to the supply of cloud condensation nuclei.
Working with visibility measurements, Wright (1940) was able
to confirm the hypothesis that the opacity of marine air varies
with humidity in such a way as to indicate that condensation
on hygroscopic particles is the cause. Those particles respon-
sible for this effect were found to lie mainly in the so-called
large category.

Simpson (1941a) stated that breaking waves were the source

of the sea-salt nuclei. He also argued (Simpson, 1941b) that
the sea-salt particles were far too few in number to account
for normal cloud formation. He was perhaps the first to
actively further this latter point and more recent work has
affirmed his belief. It was not until the detailed work
of Woodcock and Gifford (1949) and Woodcock (1950a, 1950b,
1952, 1953) that significant amounts of data on the size (and
weight) distributions of sea-salt particles were obtained.
Even though those particles in the giant range were found in
very small numbers in comparison to the Aitken nuclei, it
soon became evident (Woodcock, 1950b) that they were impor-
tant for the formation of rain in clouds above freezing.

Since the publication of Woodcock's work, many other
investigators have become active in the field. Lodge (1955)
investigated the concentrations of sea-salt nuclei over the
island of Puerto Rico. His work tended to support Woodcock's
earlier endeavors. Moore (1952) and Moore and Mason (1954)
made measurements of the size distribution of these nuclei
over the North Atlantic at a height of about ten meters.
Twomey (1954) and Junge (1954, 1957a) have also been quite
active in the field.

More recently, Woodcock et al (1963) suggested that the
latent heat released by the condensation of water vapor onto
the surfaces of airborne sea-salt particles may be an addi-
tional stability factor, particularly during periods of high
salt production. Isono et al (1966) found these giant parti-

cles important in the formation of snowfall from convective
cells over the sea. Toba (1965a, 1965b, 1966) presented a
detailed account of the world-wide distribution and produc-
tion rate of the giant sea-salt nuclei. Reviews of the sub-
ject of sea-salt nuclei may be found in Mason (1957), Junge
(1963) and Roll (1965).

During the investigations of the size distribution of
these sea-salt nuclei the question of their origin constantly
arose. Many early investigators felt that the spray generated
by breaking waves at sea (as well as by coastal surf) presented
the most obvious source. However, Jacobs (1937) theorized
that perhaps bubbles and not wind blown spray were the pri-
mary source of the sea-salt nuclei. Kientzler et al (1954)
Knelman et al (1954) and Blanchard and Woodcock (1957) did
detailed work on the problem, often employing high speed pho-
tographic techniques. In the latter paper, the authors were
able to show that droplets from the jets of bursting bubbles
could account for the majority of the giant sea-salt parti-
cles found in marine air.

It thus appears that the production of these giant par-
ticles will be linked quite closely to the white cap coverage
and hence the wind speed near the surface of the ocean. Such
a correlation has indeed been found by several observers for
the total amount of sea-salt in the marine atmosphere (Fig.1)
(Junge, 1958). While information on the size and weight dis-
tributions of the individual particles is perhaps more valu-

FIG. 1
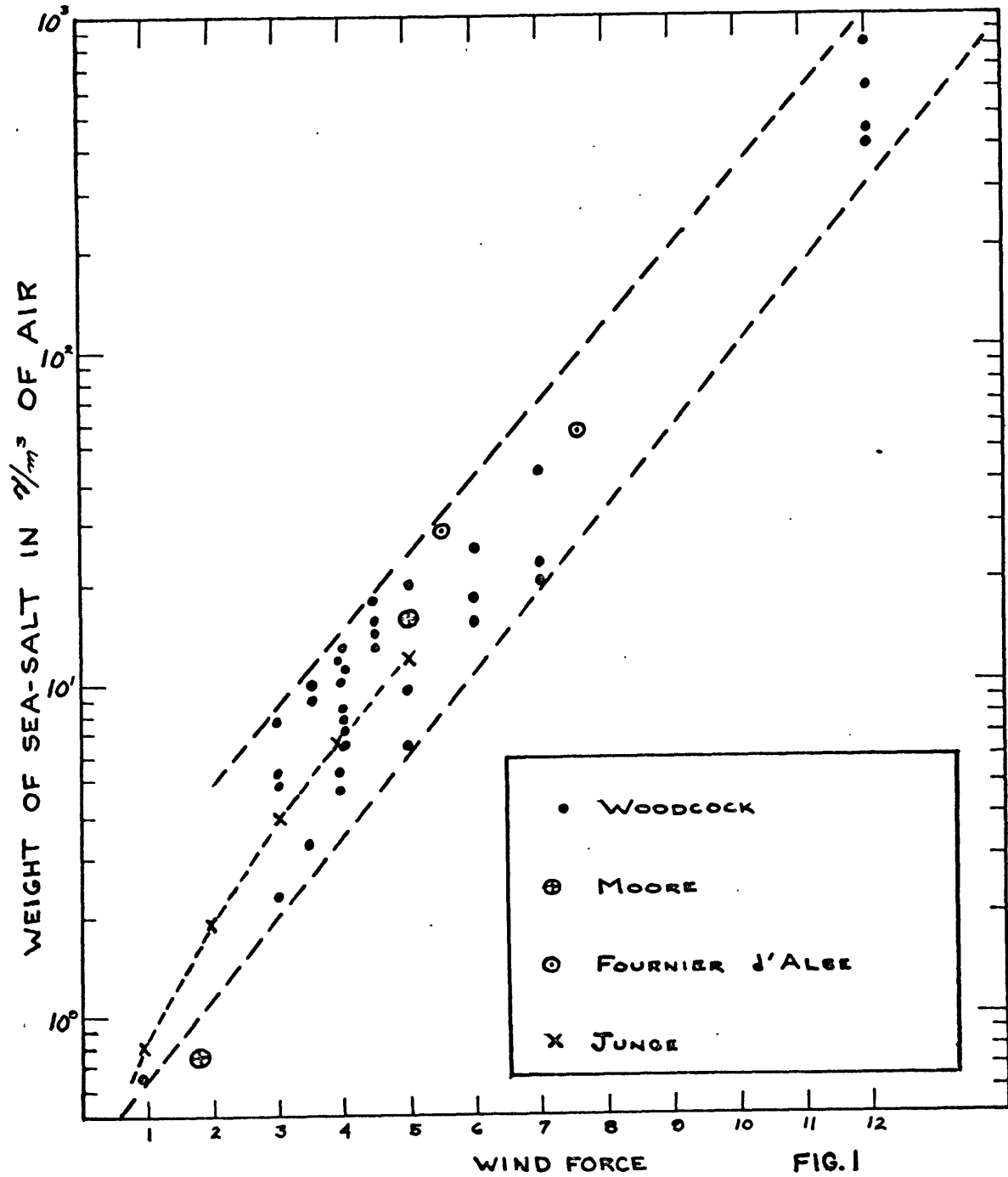
able, knowledge of the total amount of sea-salt in the air is important for a complete understanding of the air-sea coupling process. Therefore,after some preliminary discussions with Dr. D.C. Blanchard, then of the Woods Hole Oceanographic Institute, I decided to attempt to determine the variations (at a height of about 10 meters) of the total sea-salt content with various meteorological parameters as well as geographical position. These parameters were wind speed and direction, relative humidity, present meteorological conditions (e.g. were showers present or not), cloud type, low level instability and the like. This paper is a presentation of the methods and results of my experimentation on board the R.V. Atlantis II during cruise 15 which took place in 1965. The relevant part of the cruise track is presented in Fig. 2.
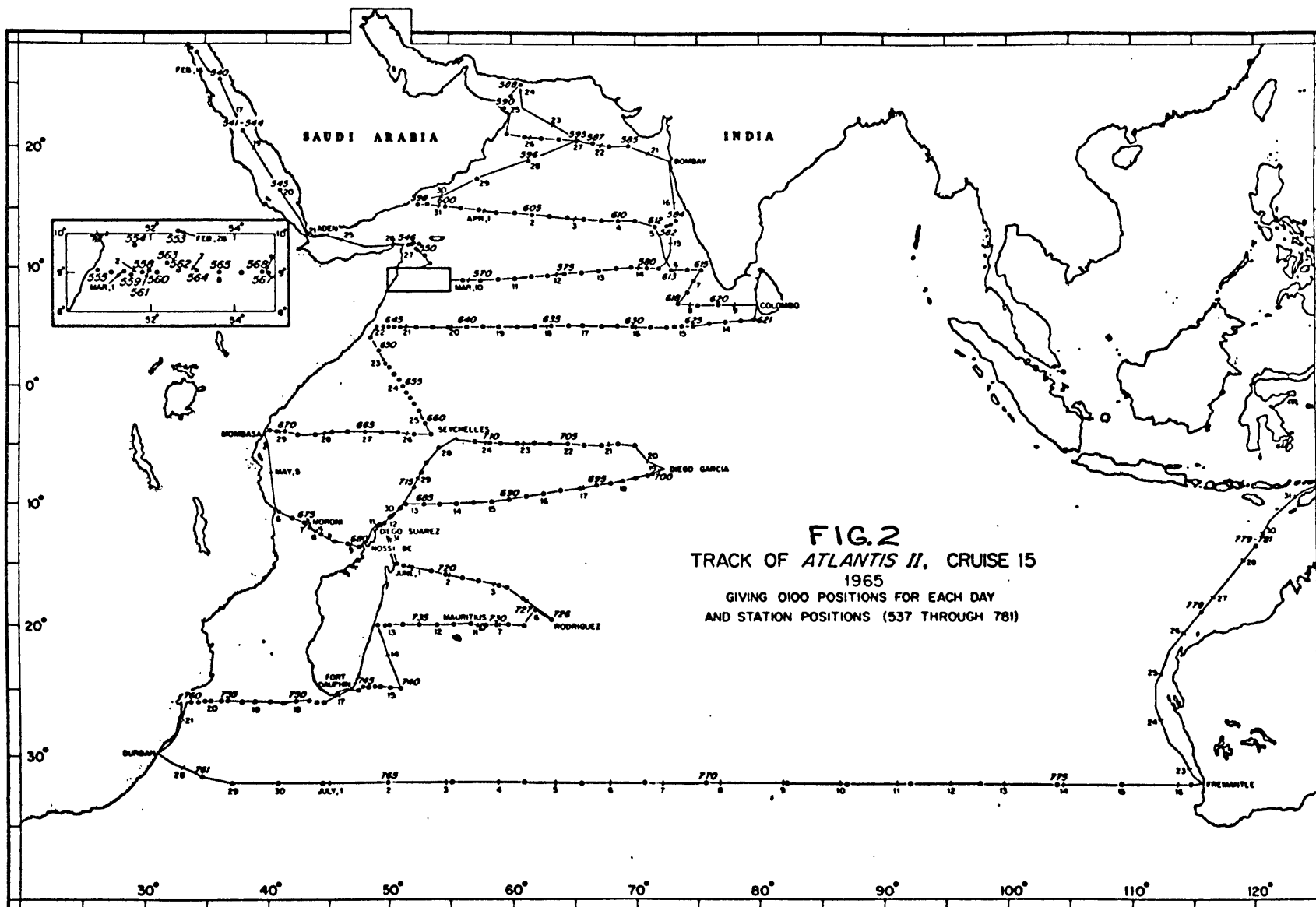
FIG.2
TRACK OF *ATLANTIS II*, CRUISE 15
1965
GIVING 0100 POSITIONS FOR EACH DAY
AND STATION POSITIONS (537 THROUGH 781)

II. COLLECTION METHODS

The salt was collected on 152μ diameter stainless
steel wire which was attached to a frame consisting simply
of a base and two upright metal dowels (Fig.3). These frames
(and hence the wires) were kept normal to the wind by mount-
ing them on a wind vane built for that purpose. The vanes
and their frames were secured onto pipes and the latter were
extended forward from the railing above the bridge of the
R.V. Atlantis II. This procedure insured that when the re-
sultant wind was anywhere forward of abeam, an unobstructed
flow of uncontaminated air would pass by the collecting wires.
The collection height was approximately 10 meters above the
sea surface. One set of pipes was fastened on the port side,
and another on the starboard side in order to facilitate
the taking of double samples. The collecting wires were
approximately 10 m. apart in the horizontal.

In order to obtain the flow of air past the wires, a
standard four-cup anemometer system which drove a simple digi-
tal counter was employed. The counter and the necessary
batteries were placed in a waterproof PVC container with one
end made of clear plastic. This insured that the counter
and batteries would remain free from corrosion while still
permitting the counter to be read with ease. An insulated
set of leads ran from the container along a set of pipes on
which the anemometer was mounted. It was mounted amidships,

WIRES

COLLECTING FRAME

WIND VANE   FRAME

FIG.3

PIPES

RAILING

WIND
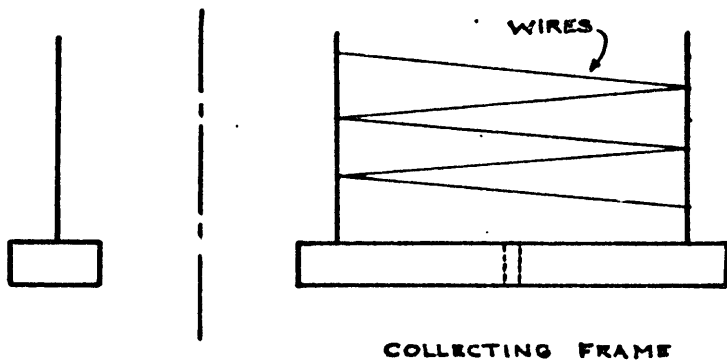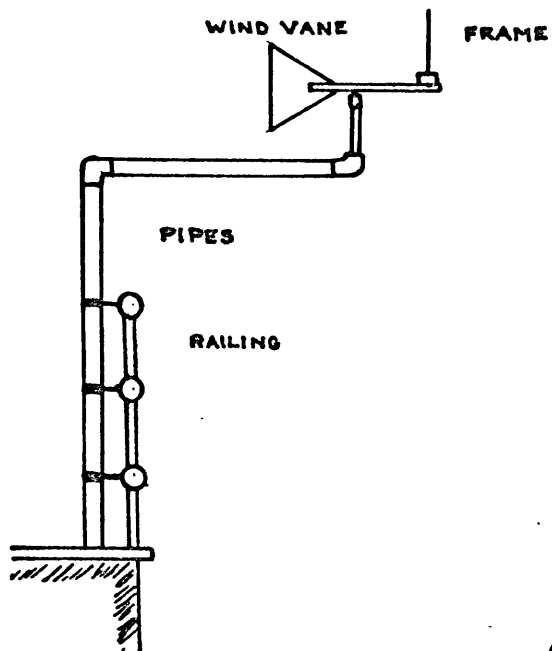
BOW REGION
R.V. ATLANTIS II
(NOT TO SCALE)

VANES WITH FRAMES

ANEMOMETER
AND
COUNTER
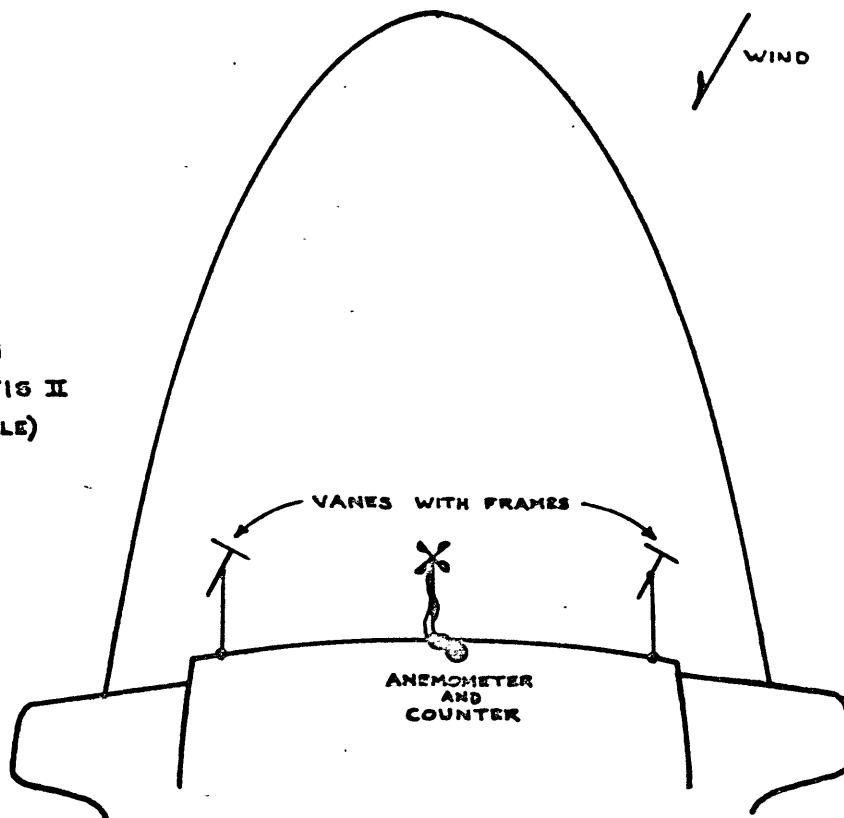
i.e. halfway between the two sets of exposed wires. Several
anemometers were checked against one another and since they
read the same, only one was employed for most of the observa-
tions. Before starting on the cruise, I calibrated the
four anemometers along with their counters in a wind tunnel
at the Woods Hole Oceanographic Institution. Therefore by
noting the counter readings before and after exposure of
the wires, I was able to determine the number of meters of
air which had passed.

A typical collection procedure would consist of the
folowing. First of all, I would wash the wires (which were
permanently attached to the frames) in distilled water and
then attach the frames to the wind vanes by means of a single
central bolt. The pipes were attached to the railing in
such a way that they could be swung in for this procedure.
I would then note the time, switch on the counter, and re-
cord the pertinent meteorological information. The latter
consisted of: vector wind and direction, (note: vector
wind is the resultant of the actual wind and the ship's velo-
city), actual wind and direction, sea state, wet and dry
bulb temperature readings, sea surface temperature, and a
verbal description which consisted of cloud type and amount
as well as the present and past "weather." Particular at-
tention was given to noting the number of showers visible
and to changes which occurred in the actual wind velocity
during a collection period.

The collecting wires were exposed for varying periods, depending on the wind velocity. At very low wind speeds they were not exposed unless the ship was underway. This was done in order to keep the collection efficiency of the wires reasonably high. During high winds when there was a chance of spray contamination from the bow waves, or when the wind was aft of the beam, the samples were taken during the various oceanographic stations. At these times, the ship would be headed into the wind and sea with little or no forward progress, a procedure known as "steaming on the wire." Thus by varying the manner of collection I was able to obtain samples during all the various winds encountered without either spray contamination or the obstruction of the ship's superstructure.

Generally there were no significant changes in the meteorological conditions during the one-half to two hour collection periods, but when there were, these were noted at the end of the collection period. When there had been a sufficient passage of air to insure a significant sample the frames were removed from the vanes, and the counter reading noted. The frames were then carefully clamped to the inside of a box especially made for this purpose and stored in a safe place until there were enough of them to warrant a run on the flame spectrophotometer.

III. ANALYSIS METHODS

When I obtained from 10 to 20 exposed frames, the material collected on the wires was analyzed for its sodium content. This was done by means of a standard Beckman DU flame spectrophotometer with a special small bore atomizer. The instrument was calibrated and tested according to the accompanying Beckman manual and no difficulties worthy of mention were encountered. Two large batches of standard solution were made up by mixing appropriate volumes of Copenhagen standard sea water and double distilled water. These were both 100 ppm (parts per million) by weight sodium ion. By pipetting various amounts of double distilled water into a known volume of the 100 ppm solution, standards from 0-100 ppm could be easily obtained.

These standards were run through the atomizer and a plot of net luminosity (transmittance minus a blank) versus the sodium concentration in ppm was obtained (Fig. 4). The standardization procedures always gave smooth curves and the results were repeatable at the end of each analysis. Over the months new standards were made up to check for any deterioration of the original ones but no significant changes were observed.

The collecting wires were washed in a large drop of double distilled water whose volume (1 ml) was known. In order to facilitate the ensuing calculations exactly one meter

NET LUMINOSITY

SODIUM *fiber*

FIG. 4

20
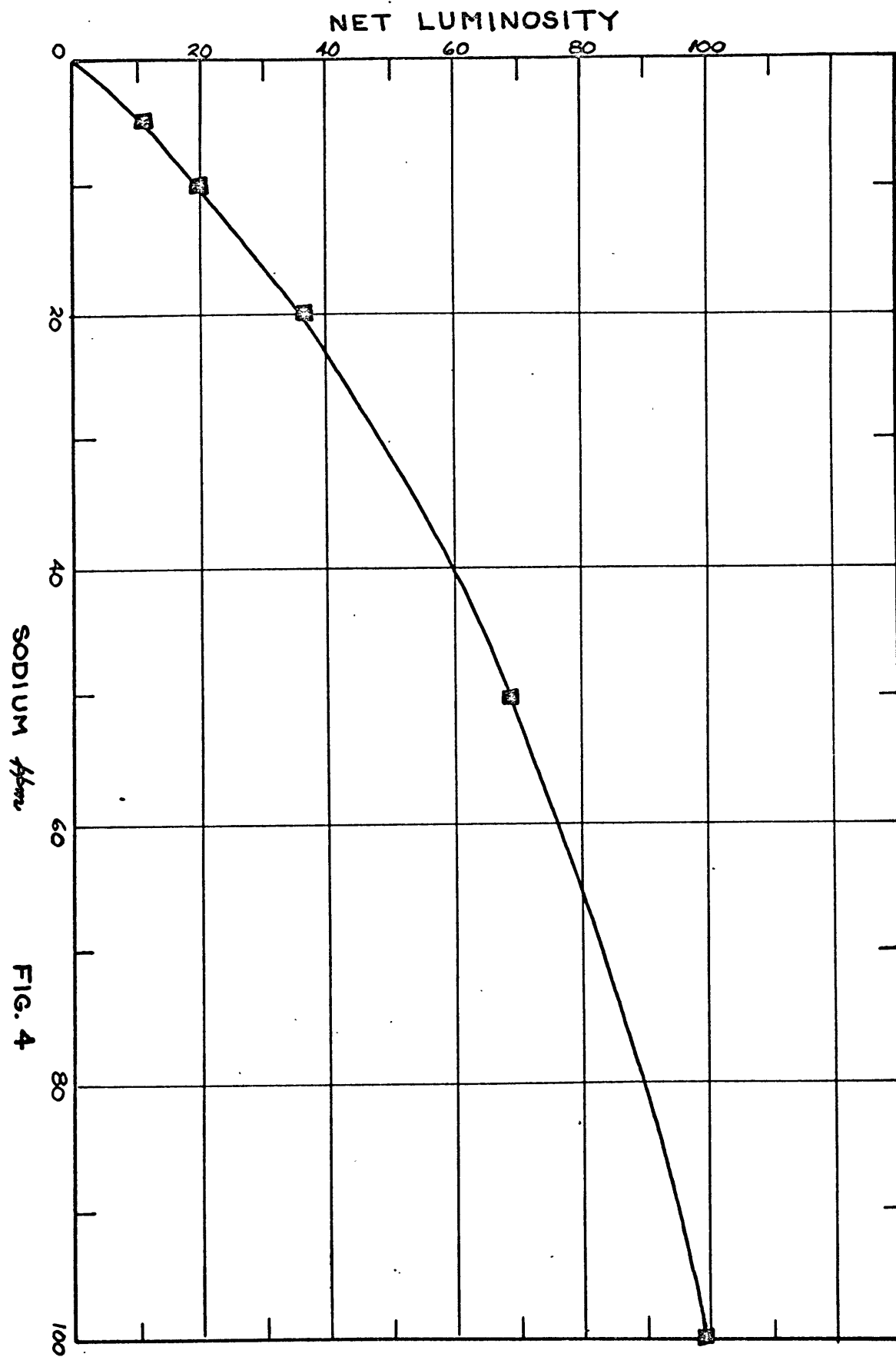
of wire was washed. This was a simple matter because the dowels on the frames (Fig. 3) were 25 cm apart. By using five sections of wire, each consisting of a 20 cm central section and two borders I was able to accurately wash the desired length of wire. The drops of wash water were pipetted onto biological slides which had a depressed central region. These slides were treated with Dri-Film[1]which caused the drops to become hemispherical and have a contact angle with the glass of nearly 90°. This shape made the drops handy for the washing procedure. Each 20 cm section of wire was washed by gently pulling it through the drop. After all five sections were washed, the drop was analyzed for its sodium content.

There were no problems with surface tension as might be expected, or with any significant amount of salt or solution remaining on the wires. The wires were washed twice before analysis. As a control test, I washed several frames again and was unable to find even a trace of salt in these drops. Clean wires which were left in the box with the exposed frames were tested for any salt contamination with negative results each time. On several occasions when double samples were taken I analyzed one immediately and left the other in the sample box for a month or so before analyzing it. This was meant as a check against the possibility of some of the salt falling off the wires due to jarring, lower humidity inside the ship, etc. Fortunately,

[1] Dri-Film no. 9987, General Electric Co., Silicone Prod. Div., Boston, Massachusetts.

these tests were negative each time. This meant I could store

a number of frames for several weeks before analyzing them

on the spectrophotometer. This resulted in a significant

saving of time and energy.

If the duration of the collection periods was properly

planned, the samples gave a transmittance (essentially the

brightness of the flame caused by the sodium ions) between

10 and 100. After subtracting the blank which was usually

about 1, the sodium content of the wash drop could be read

directly from the standard curves. For example, in figure 4

which is an actual standard curve used on one of the spectro-

photometer runs, a net luminosity of 50 corresponds to a

sodium content of 31.5 ppm. Knowing the volume of the drop

and its sodium concentration the total amount of sodium on

the wire could be calculated. Assuming that all the salts

which were present in any significant amount were sea-salts,

the total amount of sea-salt on the wires could be calculated

by multiplying the value for sodium by a factor of 3.25.

(Svedrup et al, 1942).

For a discussion of the reasonableness of this method

refer to the following section. The number of meters of air

which passed the wires was determined from the anemometer

counter readings. Multiplied by the cross sectional area

of the wires, this gave the volume of air swept out by the

wires. The amount of sea-salt found on the wires was divided

by the volume of air swept out. This gave the total sea-salt

content of the air in $\mu g/m^3$ (micrograms per cubic meter) averaged over the exposure interval.

IV. CHEMICAL COMPOSITION OF THE PARTICLES

It will be seen in the next section that the collecting wires acted as a filter which essentially sampled only the so-called giant particles, i.e. those with a radius $> 1\mu$. One of the main points of contention in the literature has centered around the actual chemical composition of the individual particles. Recent authors do not seem to doubt that the sea surface acts as an enormous source of both large and giant nuclei but there has been a vigorous debate as to whether these nuclei have the same chemical composition as sea water.

Woodcock and Gifford (1949) sampled those particles with   (approximately) at 80% R.H. They found that the changes in radii with relative humidity which they observed with natural particles were very similar to those observed with known sea-salt nuclei. They also found that within reasonable limits the chlorinities obtained by their isopiestic method agreed with those obtained by titration of the salts on a collecting slide. Junge (1954) was able to show that the sodium and chloride contents of a coastal aerosol were limited almost entirely to the giant particles, i.e. that the sea-salt particles have a sharp limit somewhere around 0.8 . In flights over southeastern Australia Twomey (1954) found that the vast majority of these particles in the giant size range were hygroscopic sea-salt nuclei. Some authors had predicted that the chemical composition of

these particles would change with time, the main effect being a loss of chloride. Twomey found no measurable change with time of the chloride content of the particles he sampled. Within the limits of his experimental method, Junge (1956) was able to establish that the sodium and chloride contents of individual giant particles were related as in sea water. Since NaCl is by far the main constituent of sea water (Svedrup et al, 1942), this seems to indicate that the giant particles are indeed sea-salt.

Junge (1957b) found that the giant particles collected in Hawaii consisted almost entirely of sea-salt nuclei and that only about 1% of the total mass of sea-salt in the air resided in those particles with radius less than $0.8\,\mu$. Wilson (1959) claimed that in freshly fallen New Zealand snows the K/Na ratio was about ten times its value in sea water. Even if his conclusions are valid, and there is reason to believe that they might not be, the error in the present calculations would be of the order of 10% if I assumed the sea-salt nuclei were of the same chemical composition as sea water. Oddie (1960) does feel there is some enrichment of K with respect to Na, but that the factor should be nearer 4 than 10. This would mean only a small error in the total salt content as calculated from ion ratios. In an interesting experimental investigation, Kombayasi (1964) determined the chemical composition of spray drops originating from various saline solutions. He found that for drops larger than $0.4\,\mu$

radius there was no difference between the drop concentrations and that of the parent solution.

Thus there is much evidence in the literature to support the assumption that those particles in the giant size range are composed of sea-salts in approximately the same ratios as in sea water. This is particularly true when the situation is thoroughly maritime and that this was the case in the present investigation is easily ascertained by examining the wind direction arrows in figure 5. Also, the vast majority of the total mass of sea-salt is found in the giant particles. Since the wires collected only the giant particles, I can compute the total amount of sea-salt in the air from the quantity of sodium found on the wires by means of the relevant ion ratio. This latter is about 3.25 for total salt to sodium. Therefore by multiplying the quantity of sodium found by 3.25 I obtain approximately the total amount of sea-salt in the air.
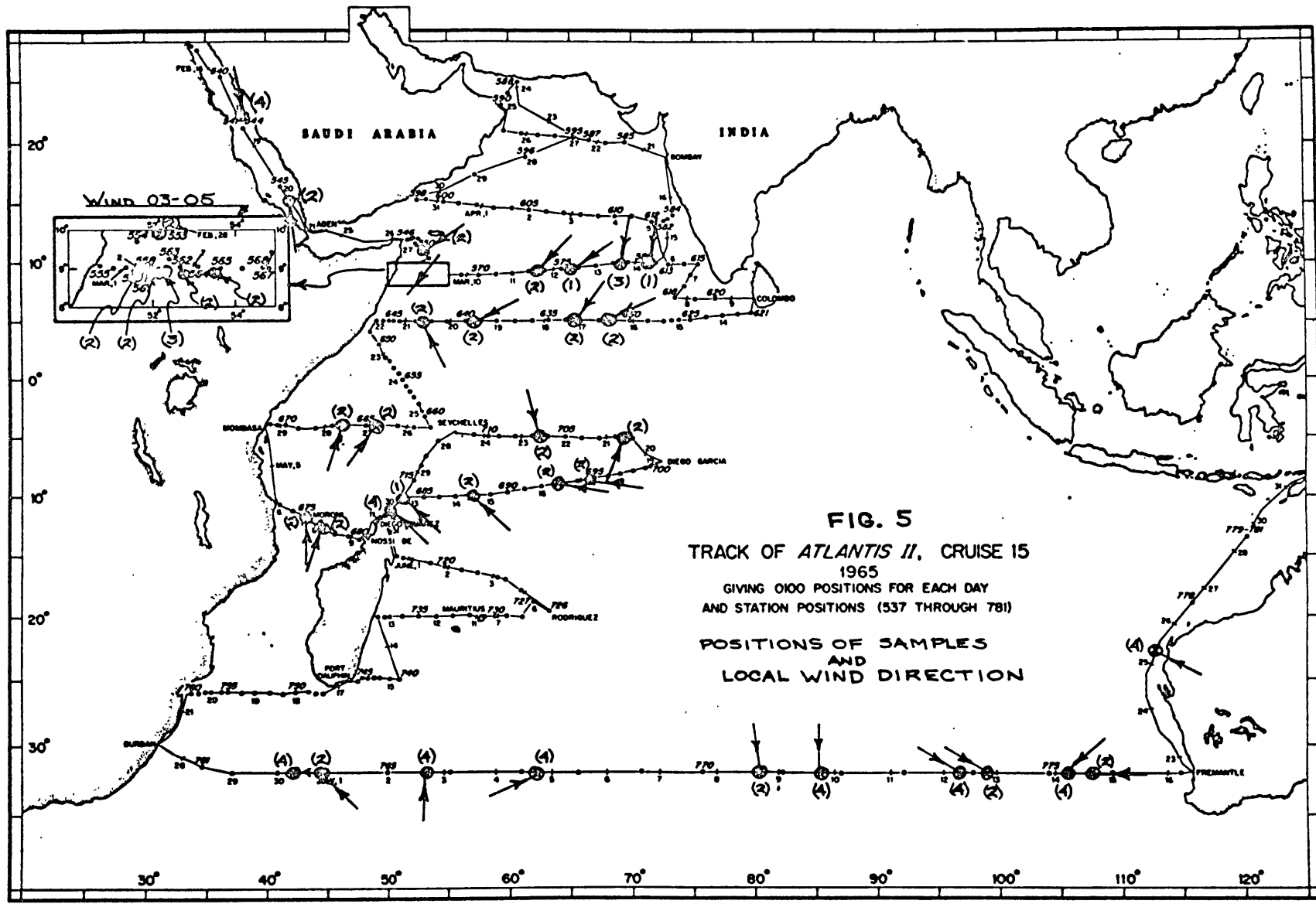
FIG. 5

TRACK OF *ATLANTIS II*, CRUISE 15
1965
GIVING 0100 POSITIONS FOR EACH DAY
AND STATION POSITIONS (537 THROUGH 781)

POSITIONS OF SAMPLES
AND
LOCAL WIND DIRECTION

V.   COLLECTION EFFICIENCIES AND OTHER SOURCES OF ERROR

The collection efficiencies of the wires were calculated according to the work of Langmuir and Boldgett (1946). Their work pertains to wind-driven particles which will stick to the wires upon contact. The question arises as to whether or not the sea-salt nuclei fulfill this latter criterion at the humidities observed during the collection periods.

It is well known that a crystal of pure NaCl (which makes up roughly 80% of the total sea-salt) undergoes a phase transition as the humidity is increased above approximately 78%. However, an interesting hysteresis was observed by Junge (1952). As the relative humidity was lowered he found that the solution remained supersaturated until the surprisingly low relative humidity of 30%. Woodcock and Gifford (1949) noted that in natural sea-salt particles there exist certain highly soluble salts such as $MgCl_2$ and $CaCl_2$ which remain in solution at humidities as low as 30-35%. They concluded that sea-salt nuclei would adhere to their collecting slides at humidities far below 70%. They also conducted shattering tests to see if any of the particles broke up and were consequently lost during impact. At humidities as low as 43% and wind speeds of up to 42 m/sec no shattering was observed. Junge (1954) was also able to show that the particles remained "sticky" down to humidities of 40-50%. Blanchard and Spencer (1964) observed that the more soluble salts formed a solution which appeared to envelop the NaCl "crystal." They also found (at least under laboratory conditions) that the supersaturation of saline drops was commonplace and extreme. Since the humidities I observed were all over 55% and the vast majority were between 65-80% there should be no difficulty in assuming that the sea-salt nuclei would stick to the wires upon impact. This allows the use of the Langmuir and Blodgett (1946) collection efficiencies for small cylinders, which is what the wires are.

In their paper Langmuir and Blodgett presented the collection efficiencies as a function of two dimensionless parameters, ϕ and K, which are defined by:

$$\phi = 18\left[\frac{\rho_a^2 \, c \, U}{\eta \, \rho_s}\right] \qquad\qquad K = \frac{2}{9}\left[\frac{\rho_s \, a^2 \, U}{\eta \, c}\right]$$

The following list defines the symbols in the above expressions and gives the values used in the calculations.

(1) ρ_a air density. Since the air temperature was often 20-25°C and the atmospheric pressure was approximately standard (760 mm Hg) a value of 1.2 x 10^{-3} g/cm^3 was used for ρ_a

(2) c radius of the collecting wire. In the present case this was 7.6 x 10^{-3} cm

(3) U wind speed. Almost all readings were made with a vector wind speed of at least 8 m/sec. Since a few were lower the collection efficiencies were evaluated for 4 m/sec and 8 m/sec.

(4) η air viscosity. With conditions as stated in (1), taken as 1.85 x 10^{-4} g/cm sec

(5) a radius of the impinging sea-salt nuclei. Plotted as the abscissa with collection efficiency E as the ordinate (Fig. 7). Values of 0.5 - 30.0 μ were used in order to cover the giant particles.

(6) ρ_s density of the impinging sea-salt nuclei. This will vary with the humidity. Two extreme values corresponding to relative humidities of 60% and 90% were used. These are 1.27 and 1.10 g/cm^3 respectively for NaCl solutions which will be

close to the values for a sea water solution.

Reference to table 2 and figure 6 will quickly show that for practical purposes ϕ may be considered zero throughout the determination. With this assumption, the values of E (collection efficiency) were determined as a function of drop size, relative humidity, and wind speed. They were read from figure 6 for ϕ = 0 and variable K, the latter calculated by the equation above. Since the effect of relative humidity is very small, a single value of 80% is used because of its frequent occurence in the literature. In figure 7 the collection efficiency is plotted as a ·function of the droplet radius for the two different wind velocities employed in the calculations. As was noted earlier, at low wind speeds the salt was collected while the ship was underway in order to increase the collection efficiency, the result being that nearly all the samples were obtained with a relative (vector) wind velocity of 7-8 m/sec or higher. The curve for a relative wind of 4 m/sec is included to indicate a lower limit of collection efficiency although very few samples were taken at this lower speed. In general, reference should be made to the 8 m/sec curve.

Since I am concerned only with the total sea-salt content of the air and the mass of the sea-salt nuclei is almost exclusively concentrated in the giant particles (Junge, 1957), I need to calculate the efficiency of mass collection only for those particles with a radius $>$ 1.0 μ . This will
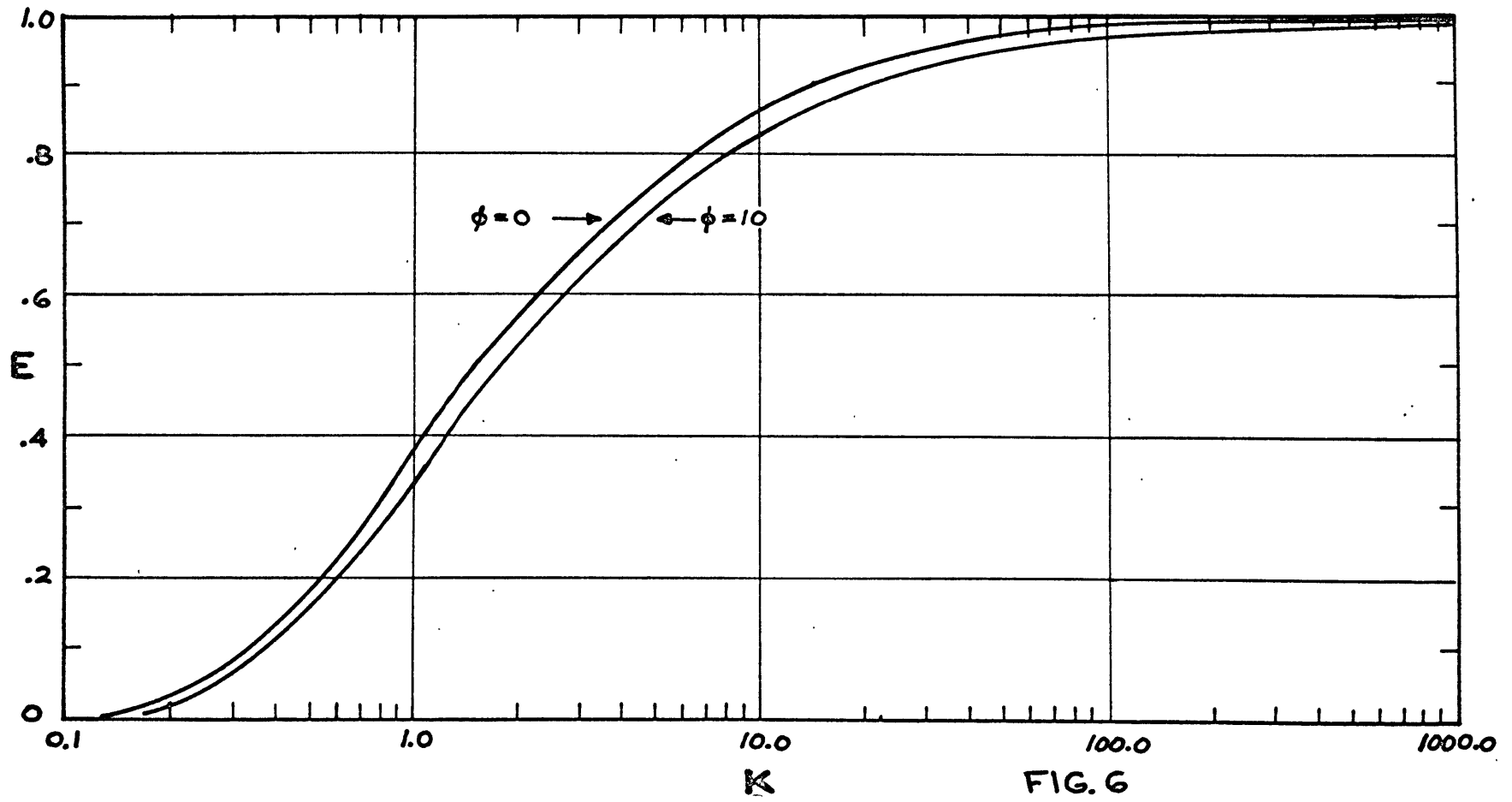
FIG. 6

TABLE 1

a, DROP RADIUS, μ	U = 4 m/sec.				U = 8 m/sec.			
	R.H. = 60%		R.H. = 90%		R.H. = 60%		R.H. = 90%	
	K	E	K	E	K	E	K	E
0.5	0.20	.02	0.18	.02	0.40	.13	0.36	.10
1.0	0.80	.33	0.69	.29	1.6	.51	1.4	.47
2.0	3.2	.67	2.7	.64	6.4	.80	5.4	.77
3.0	7.1	.83	6.2	.80	14.0	.91	12.0	.89
4.0	13.0	.90	11.0	.88	26.0	.95	22.0	.94
5.0	20.0	.93	18.0	.92	40.0	.96	36.0	.96
6.0	29.0	.95	25.0	.94	58.0	.97	50.0	.97
8.0	51.0	.97	44.0	.97	100.0	.98	88.0	.98
10.0	80.0	.98	69.0	.98	160.0	.99	140.0	.99
20.0	320.0	.99	270.0	.99	640.0	~1.00	270.0	~1.00
30.0	710.0	~1.00	630.0	~1.00	1400.0	~1.00	1200.0	~1.00

TABLE 2

R.H. %	U = 4 m/sec.	U = 8 m/sec.	
60	0.33	0.66	$\Big\} \phi$
90	0.38	0.76	

FIG. 7

essentially give the efficiency with which the total mass of sea-salt is sampled. The mass distribution curves of Woodcock and Gifford (1949) and Woodcock (1953) were used in conjunction with the efficiencies plotted in figure 7. Numerical integrations showed that for all wind speeds encountered the wires collected 90% (+10%) of the total amount of sea salt in the air. Except for the very low wind speeds, i.e. those below 5 kts, the percent error does 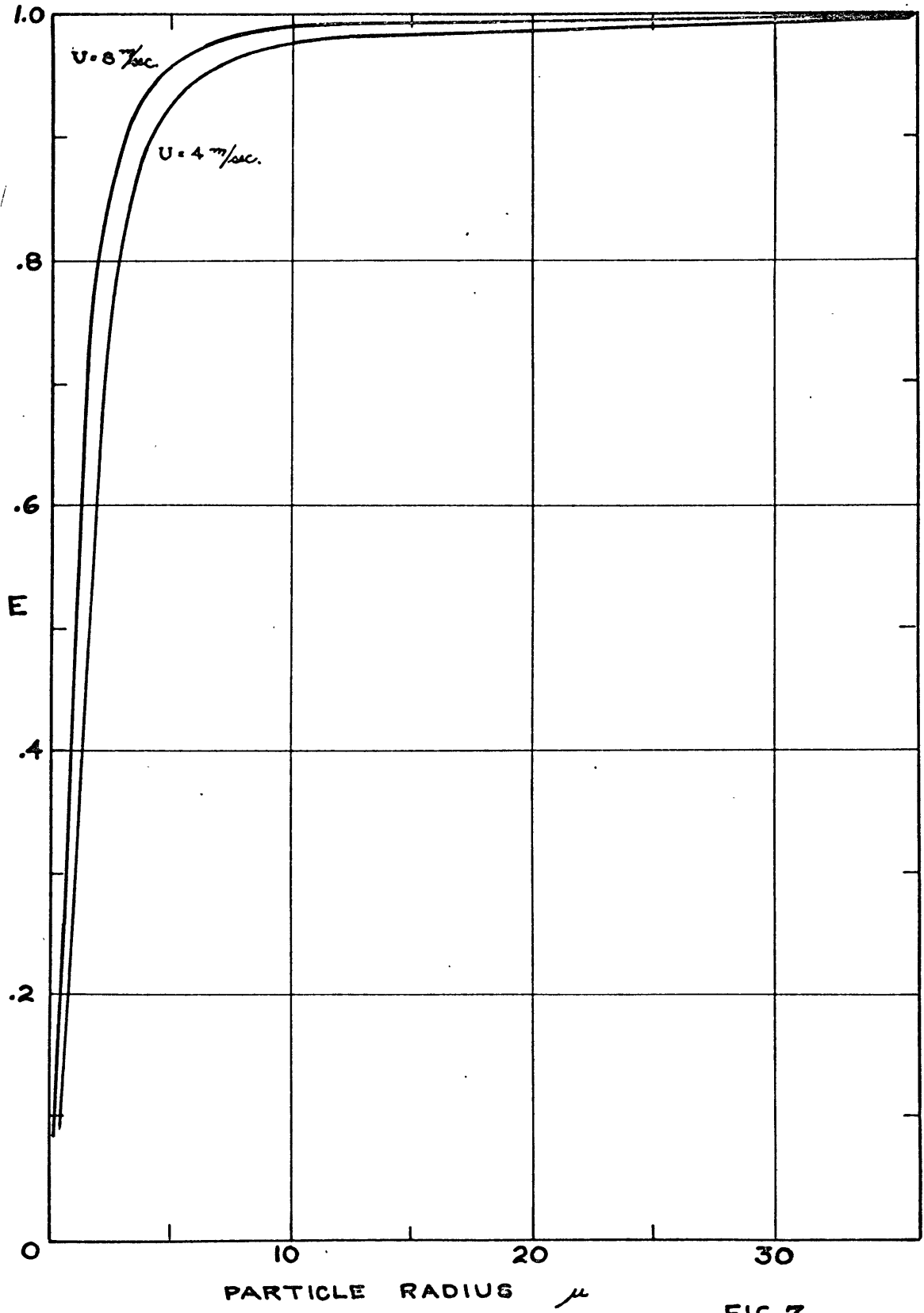not exceed 5 or 6%. Thus +10% is a conservative, maximum figure and only applies to certain limited cases whereas +5% is in general more realistic. Multiplying all the observed values of sea-salt by the factor 1.1 will give the actual total sea-salt content of the air corrected for collection efficiency. The maximum error in this result is +10%.

There are of course a number of sources of error in addition to the collection efficiencies. The possibility that salt fell off the wires while they were being stored prior to analysis was previously discussed and shown to be unimportant. Errors in the anemometer counter readings before and after a collection period combined with uncertainties in the anemometer calibrations are not expected to exceed 1%. After washing, no salt remained on the wires, but an error of roughly 1% is to be expected in the washing procedure due mostly to the impossibility of washing exactly 1 meter of wire. The total error resulting from the standardization procedure, the operation of the spectrophotometer, and the

graphical conversion method is estimated to not exceed 3%.
(The percentages apply to the actual total sea-salt content
as measured in $\mu g/m^3$.) Therefore for winds greater than
5 kts. the total error from all sources will not exceed 10%
while the total error for lighter winds may be as high as 15%.

VI.   RESULTS AND DISCUSSIONS

(a) The Relationship Between Sea-Salt Content and Wind Velocity

As a result of the preceeding arguments, it can be stated
that the data I collected do indeed represent the total sea-
salt concentration of the marine atmosphere at the collecting
level of 10 meters.   The maximum errors are small enough to
be disregarded in the following discussion.   The vast majority
of the data were collected in the western and southern por-
tions of the Indian Ocean.   The rest are from the Mediterranean
Sea, Suez Canal and Red Sea.   The Suez Canal data are inter-
esting in that they indicate there is significant inland
transport of the sea-salt even at the lower levels.   Cer-
tain data taken in the North Atlantic while the equipment was
being tested and a few values (3) which showed wide discre-
pancies between two simultaneous observations are not included
due to the possibility of error.

The main purpose of the investigation was to attempt a con-
firmation of the general relationship thought to exist be-
tween the total amount of sea-salt in the maritime atmosphere
and the near-surface wind velocities.   This relationship
has been discussed by several authors, among them Woodcock
(1953) and Junge (1958).

To this end all data have been plotted in figures 8-11 ir-
regardless of geographical position.   The first graph (Fig. 8)
gives the amount of sea-salt in $\mu g/m^3$ (or equivalently γ/m^3)

versus the wind velocity at the time of observation. The next three graphs (Figs. 9-11) give the sea-salt content versus the average wind velocities for periods of six, twelve, and twenty-four hours preceeding the observations. During certain intervals the ship travelled a considerable distance, but because of the spatial uniformity of martime conditions the effect on the average winds for the longer time intervals is not considered to be great.

Upon studying the graphs it becomes immediately obvious that there are two different regimes. Above a wind speed of 8-10 kits the values show a very definite increase with increasing wind speed. At a particular wind speed they vary by a factor of two to three. Below 8-10 kts where some sort of discontinuity is in evidence, the relationship of the total sea-salt to the wind veolcity becomes uncertain. Here values range over an order of magnitude at a given wind speed and some very low values occur.

The data present yet another piece of evidence for the apparent discontinuity in sea-surface and low-level phenomenon noted by Woodcock (1940), Svedrup (1946) and Munk (1947), among others. These authors found apparently discontinuous changes in various parameters as the wind speed increased above force 3, Beaufort, i.e. above approximately 10-12 kts. Since it is quite apparent that the sea-salt results from breaking waves and more particularly from the bubbles produced by the "whitecaps," (Keentzler et al, 1954; Blanchard

and Woodcock, 1957) it is to be expected that local pro-
duction of sea-salt will begin when whitecaps are first
formed. This production occurs whenever the wind exceeds
a certain critical value. Munk (1947) found no foam patches
at a wind speed of 9-10 kts and 10-15 per 10^4 m^2 for winds
exceeding 13 kts. Blanchard (1963) found that whitecaps
began to form when the wind reached 7-8 kts. On the basis
of these results, local production of sea salt should begin
somewhere in the vicinity of 8-10 kts. This appears to be
just the case in the data presented in figures 8-11. An
important conclusion is that when no local production occurs
(wind speed below 8-10 kts) the factors of sedimentation,
advection (from areas of active production), instability
(see later) and washout become much more determinative on
the sea-salt concentration than the local wind speed. This
accounts for the wide range of values which occurs below
the discontinuity.

Note that several pairs of values are not included within
the lines which I drew to emphasize the two drastically dif-
ferent regimes. The first pair, labelled "M," were taken
in the harbor of Moroni island (fig. 2) where a local effect
caused high gusty winds which were not indicative of the
general conditions at the time. Since the fetch was but
a mile or so, the values represent those found over the
adjacent waters with their lower wind speeds. The pair la-
belled "G" were taken in the Great Bitter Lake area of the

Suez Canal (just off the map north of the Red Sea) immediately

following a local increase in wind which again resulted in

no significant production. The wind near Port Said had

been onshore and fairly strong the previous day. The sea-

salt in the air over the canal and the lake was probably

blown inland from the Mediterranean Sea and not locally pro-

duced. The third pair of points, labelled W, represents a

case where the wind had just risen to about 11 kts after 18

hours of 6-7 kts. This becomes apparent in the graphs re-

presenting the salt content versus the average winds over

the various time intervals.

In figure 12 I have compared the boundary lines which I

felt were applicable to the data with those which were used

by Woodcock (1953) and cited in Junge (1958). (Also see

Fig. 1) These latter boundaries represent the range of data

gathered by Fournier d'Albe (1951), Moore (1952), Junge (1953),

and Woodcock (1953). Woodcock's data were generally taken

at or near cloud base level, that of the other observers

essentially a few meters above the sea surface. The general

agreement in slope above the discontinuity is quite close

and shows the same logarithmic increase of salt content

with wind speed. The values of Fournier d'Abbe and Moore

which occur above the discontinuity are found in or near

the lower part of the range I observed. This is significant

because they were also taken near sea level. Junge's data

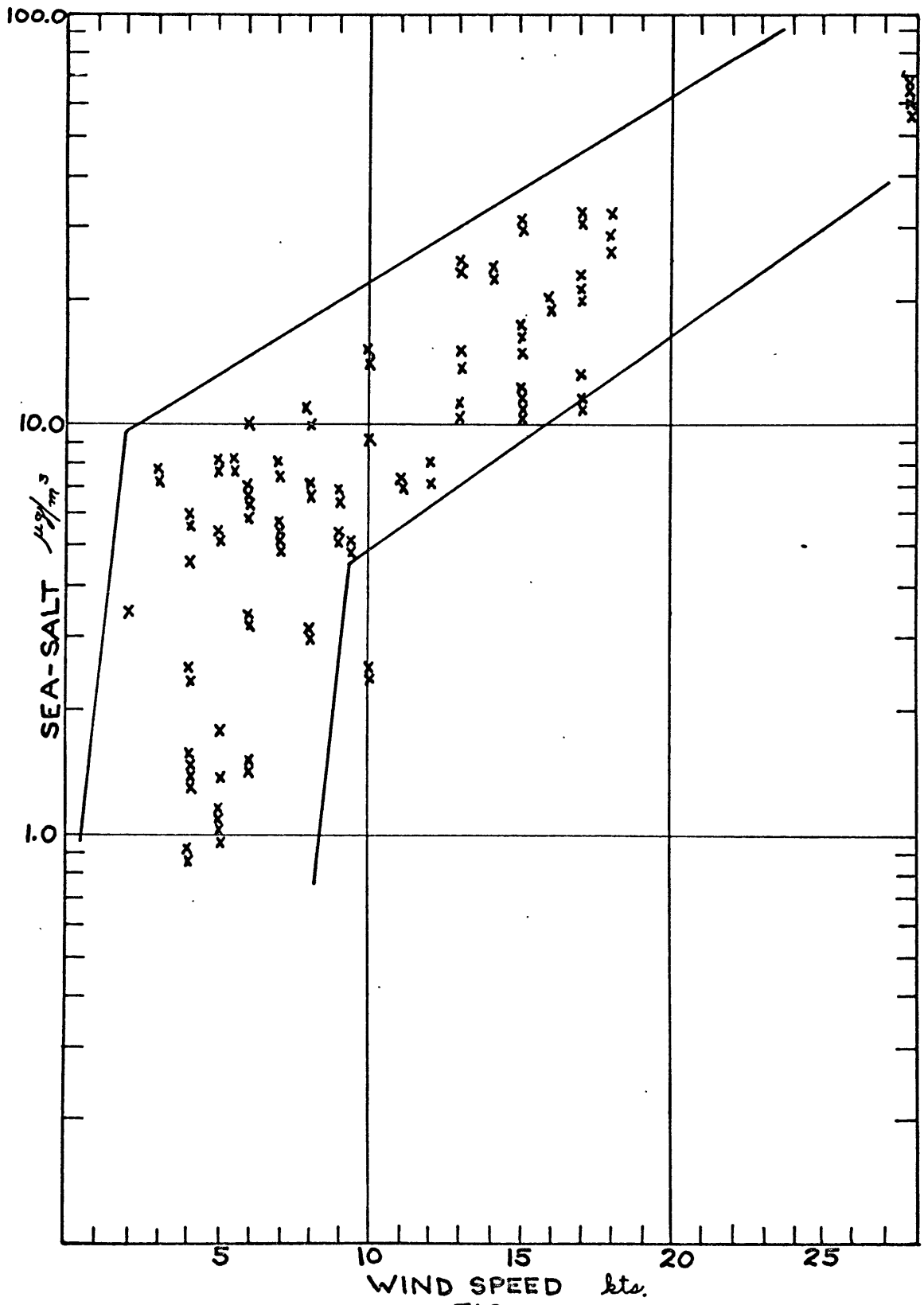were collected at the seashore in southeastern Massachusetts
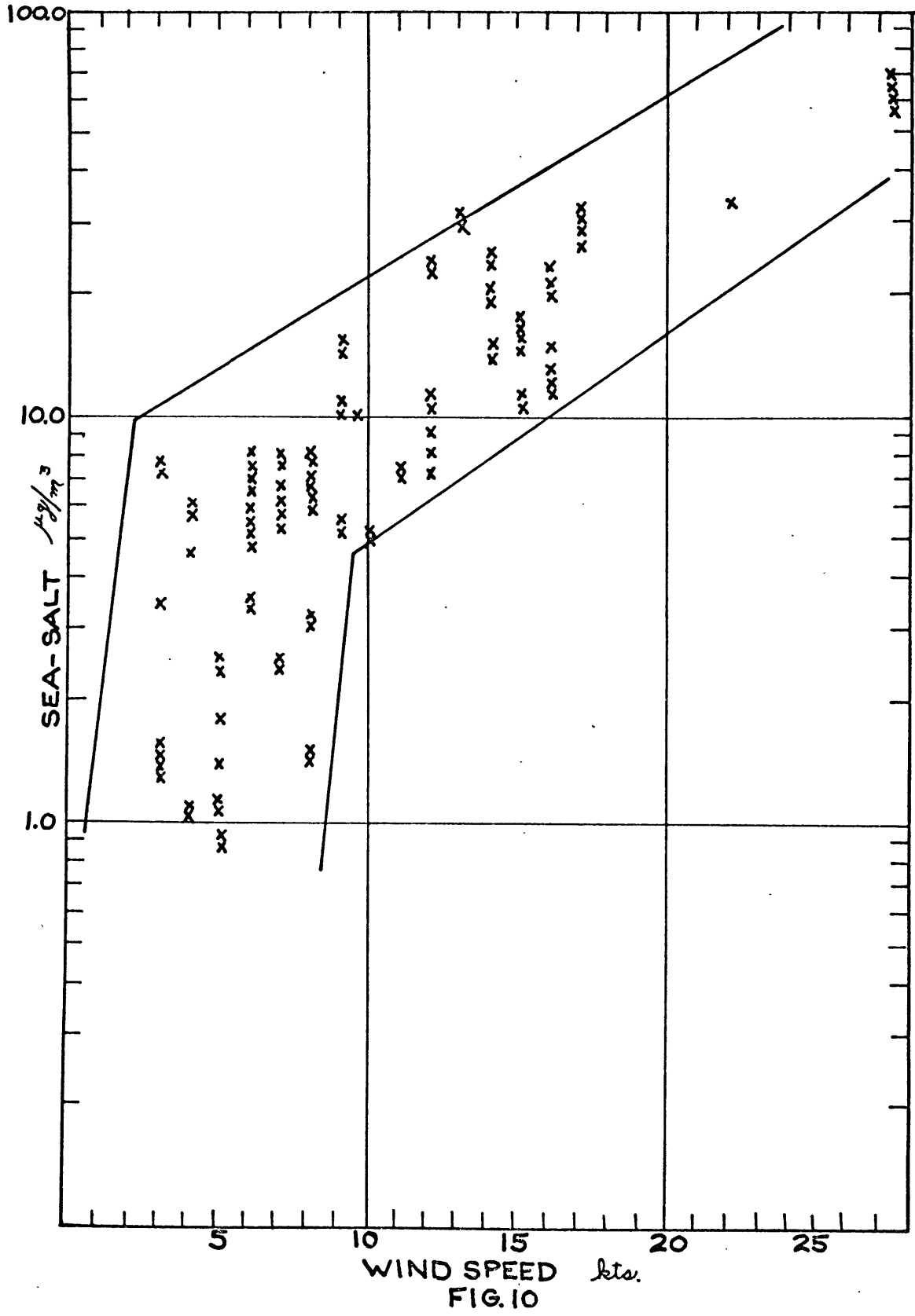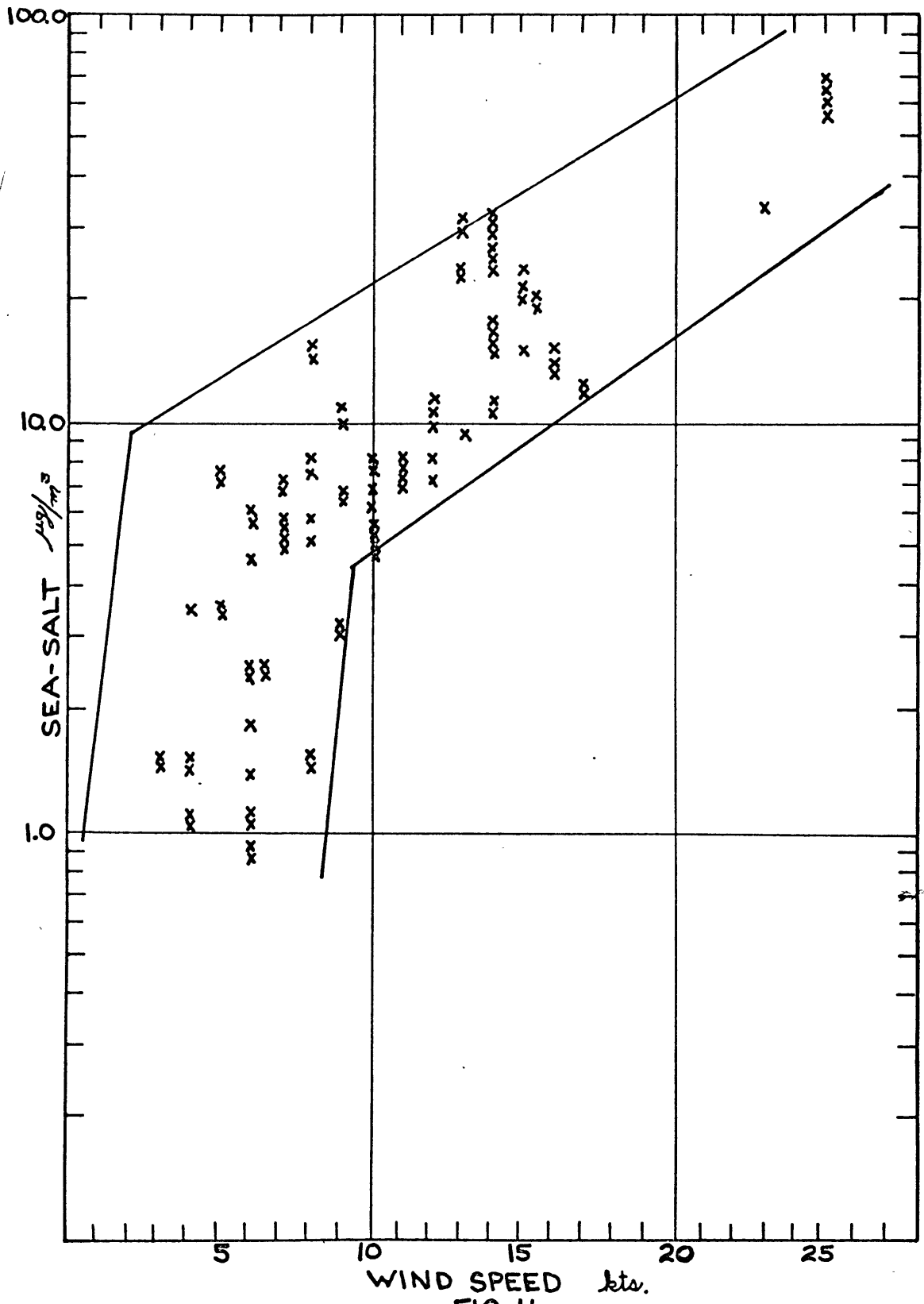
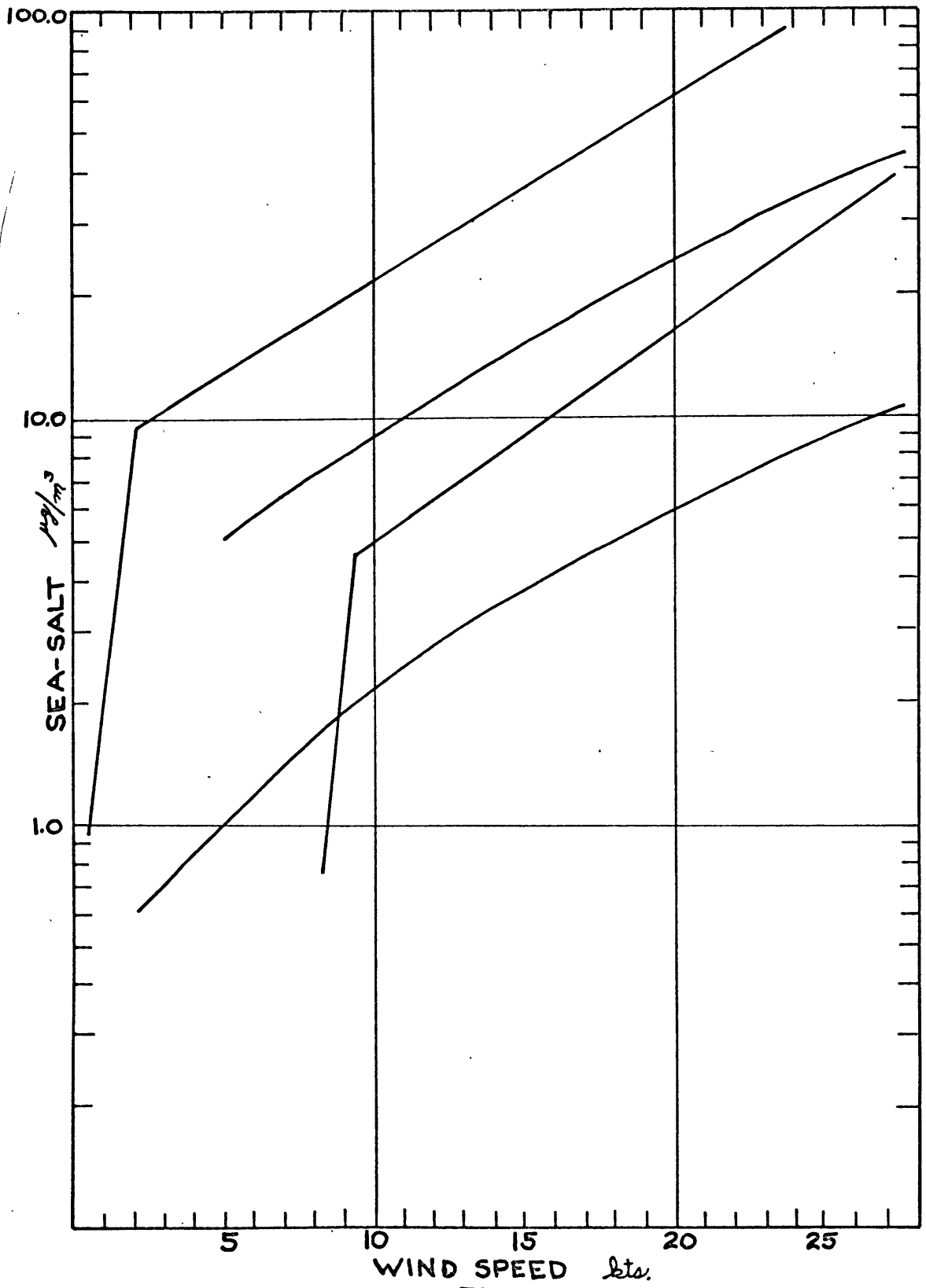FIG.8
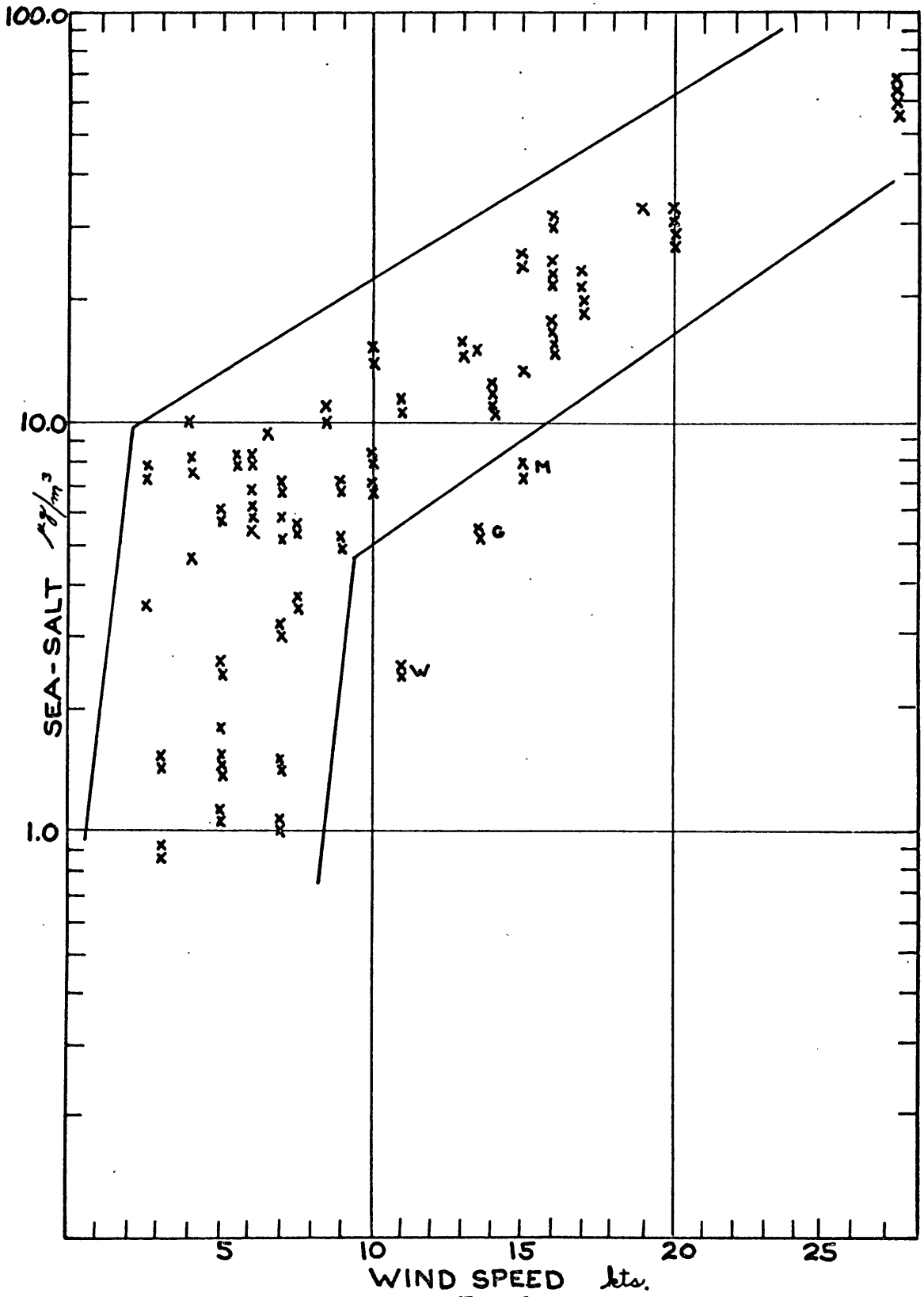
FIG.9

FIG. 10

FIG. 11

FIG.12

and cannot be considered typical of wholly maritime conditions although he was careful enough to only cite his higher values (Fig. 1). These were certainly closer to what would be expected under maritime conditions. As mentioned above, Woodcock's data was generally taken just below cloud base. Since he finds (Woodcock and Gifford, 1949) that at a level of 15 m the total salt content is roughly double that at cloud base the two "curves" representing the ranges are seen to be in excellent agreement above the discontinuity at 8-10 kts. More than likely, the presence of a few very large particles which never get carried aloft due to prohibitive sedimentation rates causes the increase in the total sea-salt content at the lowest levels. For winds below 10 kts I have many more data points than were presented by the other authors and therefore feel that the range curves I drew in figures 8-12 are more indicative of the real situation than those presented in figure 1 and repeated with a change of scale in figure 12(Junge, 1958). There just is no very clear relationship between sea-salt and wind speed for the lighter winds. An upper limit is perhaps feasible for the values of sea-salt in light winds but no empirical expression would be valid or useful.

This is not the case with the higher winds, i.e. those greater than 8-10 kts. For this case an empirical formula can readily be derived which will give the range of salt content at a given wind speed. This formula can be obtained

from the range "curves" (Fig. 12). Thus as an approxima-
tion to the total sea-salt content I obtain:

$$\text{Sea-Salt}(\mu g/m^3) = (2 \text{ to } 8) \times e^{0.1W}$$

where W is the wind speed in knots. For more limited geo-
graphical areas the range of (2 to 8) can be narrowed some-
what.

During the period February 27 to March 14, 1965 the
R.V. Atlantis II was occupying hydrographic and current
stations between the Somali Coast and southern India (Fig. 2).
Since the passage was roughly along the latitude circle $10^{\circ}N$,
and because of the season, the northeast monsoon winds were
present (Fig. 5). During the entire period no showers
were observed either at the ship or on the horizon. The
typical cloud cover was several tenths of undeveloped cumulus,
the so-callled "fair weather cumulus." Because of these
steady conditions, the sea-salt data fall within a narrower
range, as may be noticed by referring to figure 13. Values
for the period fall within the limits drawn and increase with
increasing wind speed according to the empirical relation
derived above. The difference is that the relationship may
now be written with a narrower range. Therefore, approximately

$$\text{Sea-Salt } (\mu g/m^3) = (3 \text{ to } 7) \times e^{0.1W}$$

KEY:

X FEB. 27 – MAR. 14
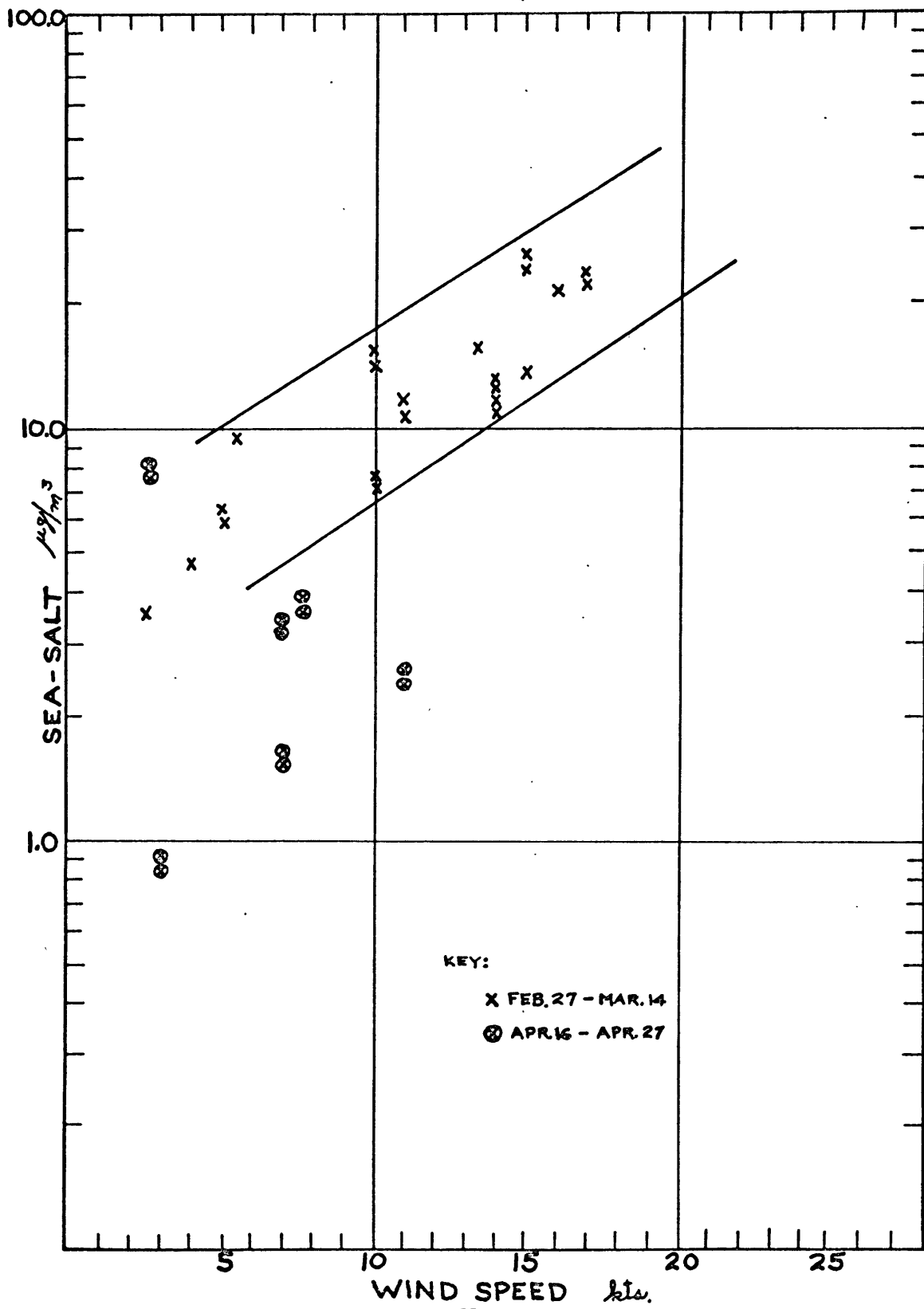⊗ APR. 16 – APR. 27

WIND SPEED kts.
FIG. 13

where as before, W is the wind speed in knots. It becomes

apparent that even with quite steady conditions and the

absence of washout values may vary by a factor of two be-

tween one observation and the next, even though the local

wind speed may remain unchanged. Since the collection method

results in an averaging over a fairly large parcel of air,

often ten to fifteen kilometers in length,this means the

lower atmosphere must be less homogeneous with respect to

large parcels than one might intuitively expect. This same

result was mentioned by Toba (1965a).

Also plotted in figure 13 are six pairs of values obtained

during the period April 16 to April 27, 1965. Although two

pairs were taken in an area somewhat remote from the others,

they are meteorologically similar and hence grouped together.

This was the period when the monsoon was in the process of

changing from northeast to southwest (Fig. 5) and the weather

was hot, humid and squally with generally light winds. There

were many showers both at the ship and on the horizon for

most of the period. The effect of low production and washout

is immediately obvious. The values are much more scattered,

and except for one aberrant pair for which no explanation

is available, all are significantly (by a factor of 2-4)

lower than the values recorded during the dry northeast

monsoon. Although it would be unwise to draw any strict

quantitative conclusions from this small amount of data, the

effect of washout is qualitatively well illustrated, and it

is seen to significantly effect the total sea-salt budget.
This process was noted by Lodge (1955) although he found
a stronger decrease, nearly an order of magnitude, for the
giant particles he measured before and after a local shower.

The period May 8 to May 22, 1965 was marked by generally
south or southeast winds with only minor exceptions (Fig. 5).
Several days of relatively high winds were experienced. Al-
though there were some rain squalls, with the exception of
one day they occurred for quite limited periods and were
nowhere near as prevalent as during the monsoon reversal
discussed above. The range is slightly lower overall (Fig.
14) but the slope of the sea-salt "curves" is essentially
identical to that found during the dry northeast monsoon
(Fig. 13). It is possible that the slightly lower values
do represent a small washout effect, but the data are not
numerous enough to quantitatively support this idea. For
the data garnered during both monsoons an empirical expres-
sion of the form discussed above in relation to figure 13.
gives a reasonable approximation to the total sea-salt con-
tent.

During the latter part of June and the first two weeks of
July, 1965, the R.V. Atlantis II made a crossing of the
southern Indian Ocean along the latitude circle 32^OS. Data
gathered on this crossing as well as four points from the
vicinity of the western coast of Australia (Fig. 5) are pre-
sented in figure 15. The winds were on the whole anomalously

FIG. 14
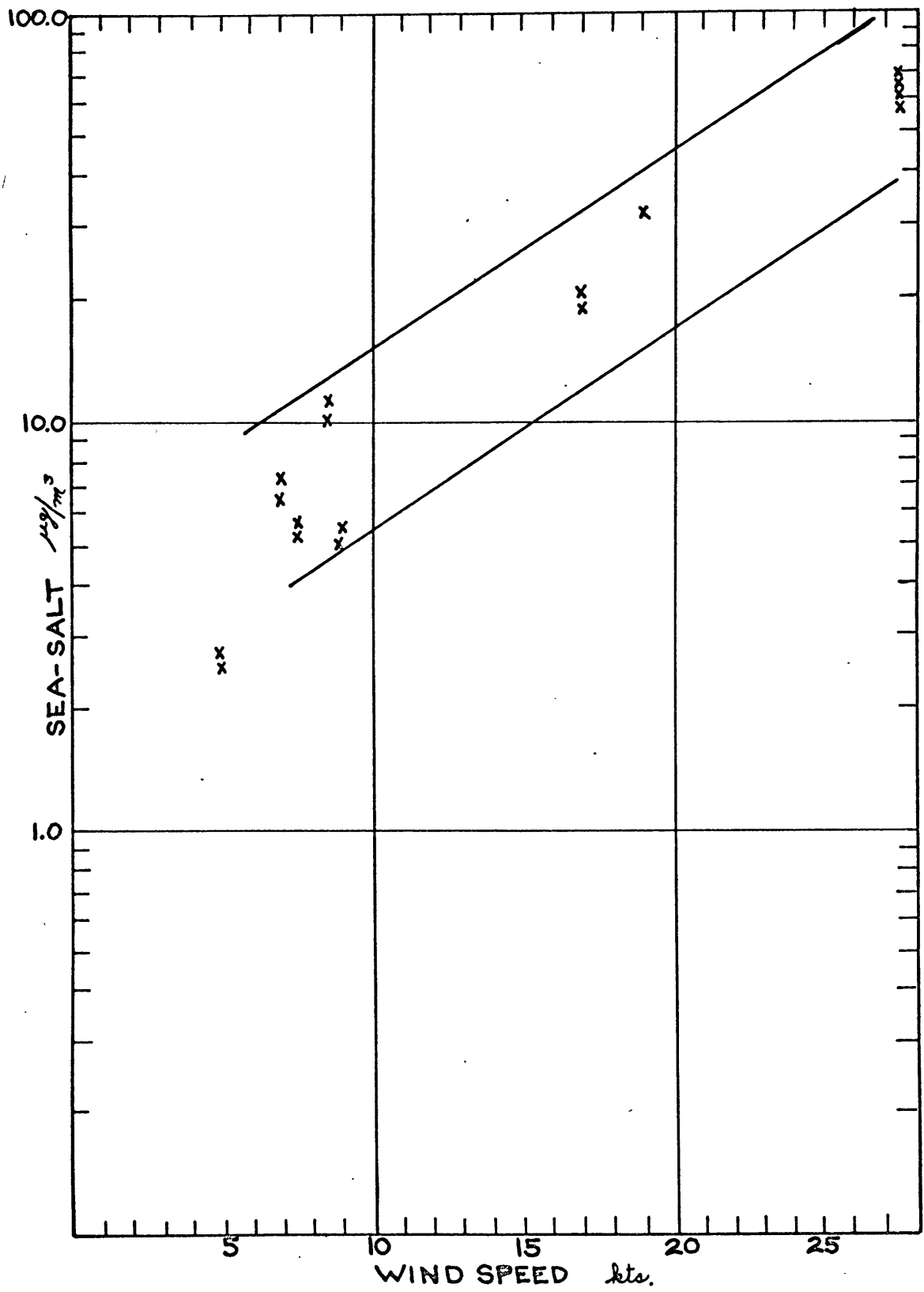
light for a winter crossing at that latitude. The baro-
meter was high (1030-1035 mb) for almost the entire crossing
and the only rain consisted of a few light showers on
several days during the middle of the passage. It appears
that a high pressure cell was drifting across the ocean at
roughly the same rate as the ship. The cloud cover was
often stratocumulous with some undeveloped cumulus and
the sea was remarkably still. The situation was the anti-
thesis of the stormy conditions expected. Notwithstanding
these exceptional conditions, all data collected with wind
above 8 kts (and some below this) fit within the range "curves"
sketched for the dry northeast monsoon and the same empiri-
cal expression appears valid.

Since there were many days of low winds, the discontinuous
nature of the data is particularly obvious in figure 15.
Below 8-10 kts the sea-salt content is not related in any
obvious way to the wind speed. At 4 kts (local wind speed)
the sea-salt content is more than an order of magnitude
higher than it is at 7 kts.

The nature of the "discontinuity" must not be misconstrued.
It is not particularly sharp and the lines drawn on the ear-
lier plots (Figs. 8-12) are meant as aids to the eye and are
suggestive rather than definitive. There is, however, no
doubt that there are two different "regimes," as it were,
in the data collected. These regimes are closely related
to the presence or absence of local production. When there
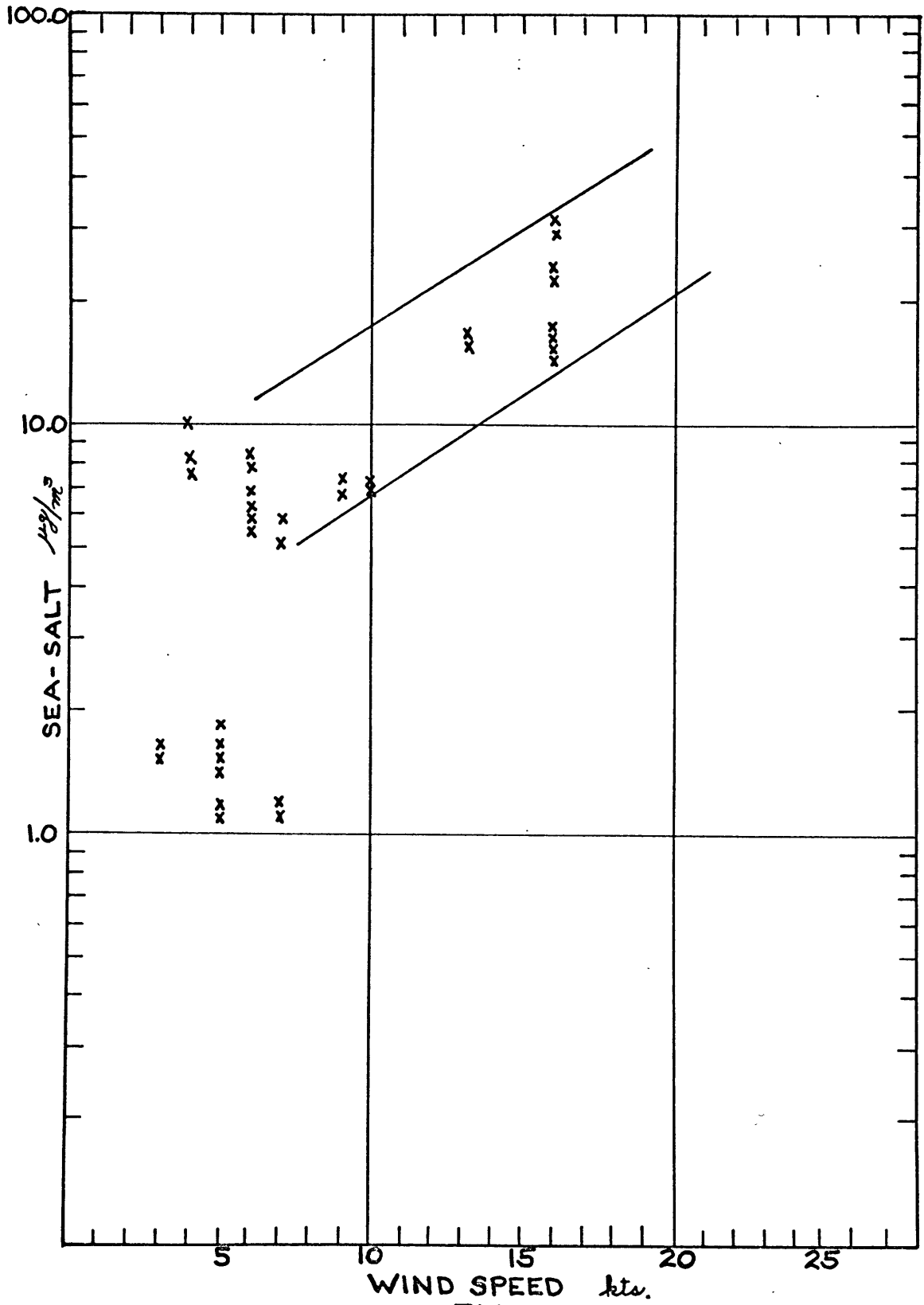
WIND SPEED *kts.*

FIG. 15

is no local production, the combined effects of advection, sedimentation, washout and instability are decisive in determining the sea-salt content of the air. Very scattered values are noted during showery weather, due no doubt to the patchy nature of the washout. During general rains I would expect the depletion of the sea-salt to be more consistent over a large area.

Advection brings in at least the remnants of aerosols formed in areas of higher production and may cause values which seem inordinate for the local wind speed. Sedimentation like washout, tends to lower the salt content, although it acts preferentially on the larger particles where the greater amount of mass is found. Instability, which is rarely considered a significant factor in reference to salt content, will be shown to have a strong influence in a following section.

As a result of the not well understood interactions of these four parameters the salt content at wind speeds below those necessary for local production is distributed chaotically with respect to wind speed. When local production begins, and this occurs when the wind reaches about 8 kts., the more random effects of the four parameters are masked and the sea-salt content becomes a fairly clear-cut function of the wind speed. This then is the nature of the discontinuity: below it several factors act in a manner which is poorly understood quantitatively and scatter the sea-salt

content; above it a single parameter, wind speed, becomes
determinative, at least when general rains are absent.

RESULTS AND DISCUSSION

b. The Relationship Between Sea Salt Content

and Low Level Instability

Over the oceans the difference between the surface tem-
perature of the water and that of the overlying air can be
conveniently used as a first-order indication of stability.
The larger the difference $(T_W - T_A)$ the greater the instabi-
lity. Negative values of the difference indicate stable
conditions. Two strong correlations were found between
the total amount of sea-salt and the degree of instability.
For light winds (Fig. 16) when there was no local produc-
tion the mass of salt in the air at the 10 m level decreased
quite rapidly with increasing instability. For strong winds
(Fig. 17) the converse proved to be the case. As the in-
stability increases, the amount of salt increases.

The higher winds consist of those over 15 kts. All data
points are included with the sole exception of those taken
on May 11, 1965 when stable conditions were recorded along
with high winds and high local production. This was one of
the very few instances on the whole cruise where stable con-
ditions were noted. For the wind speeds of 7 to 15 knots
no correlations with instability were found and the data
tended to be quite scattered. For the light winds, those
of less than 7 knots, all data points without exception
are included.

FIG. 16

FIG.17
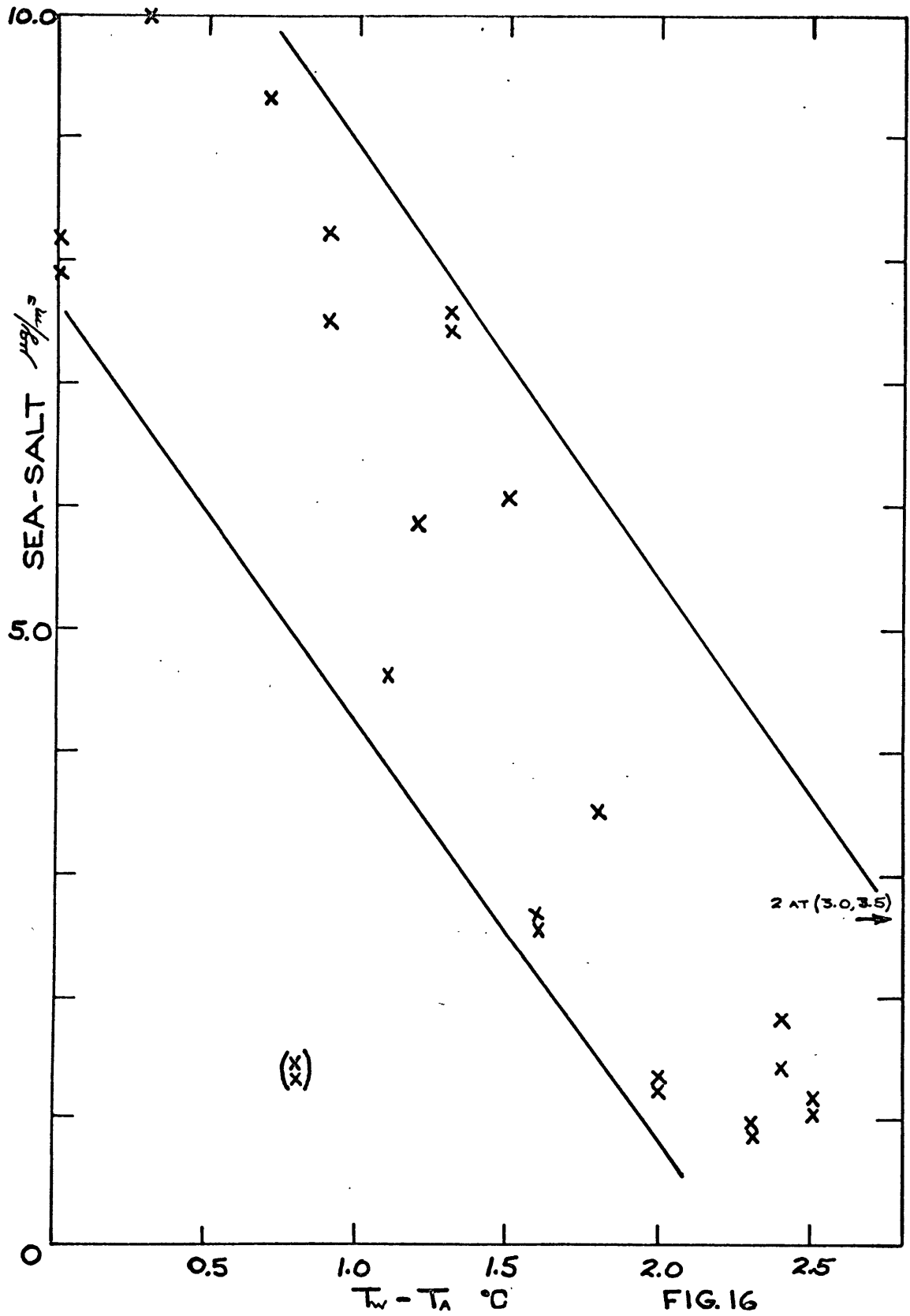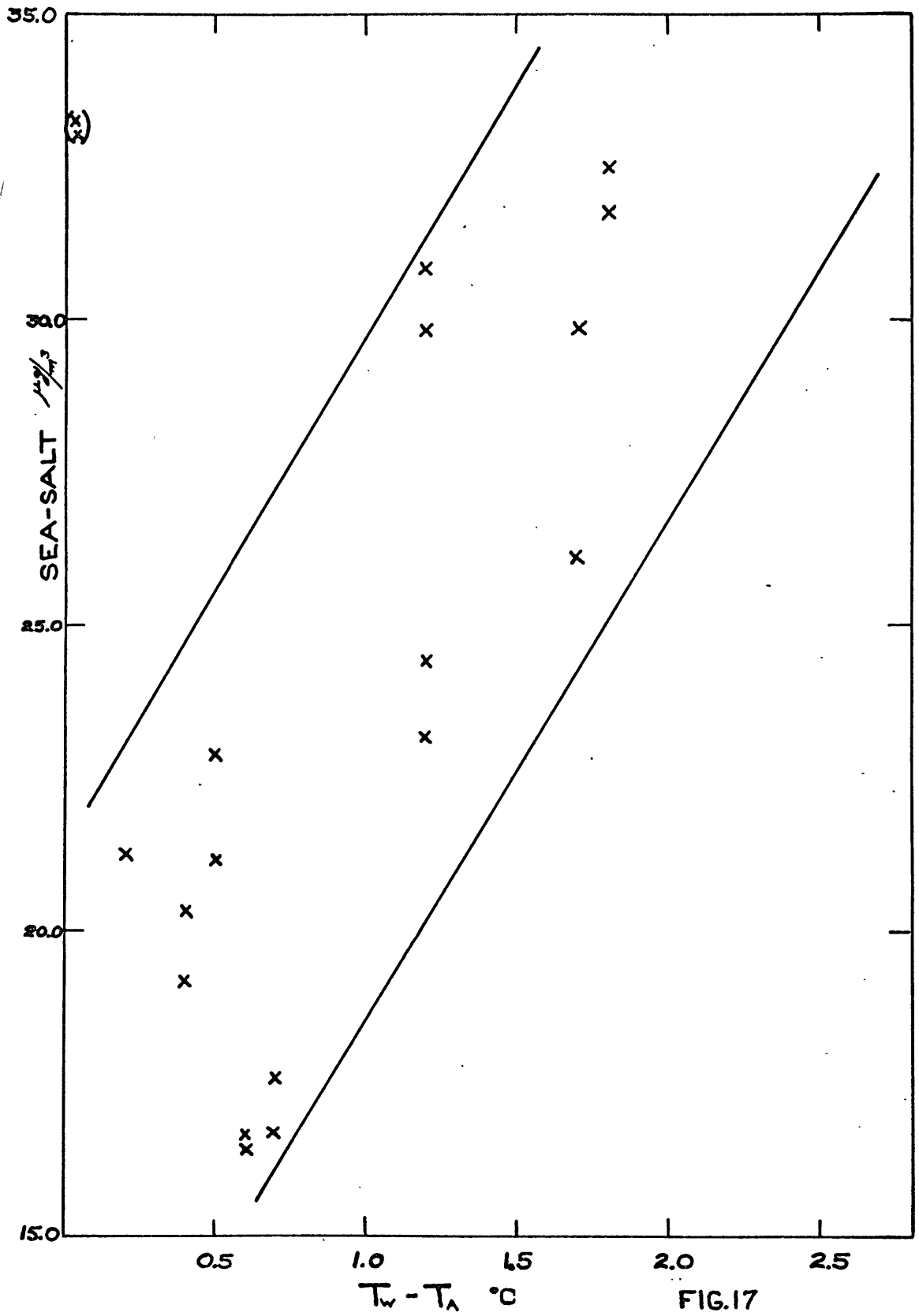
During the higher winds fairly intense local production
is taking place and the dependency of sea-salt mass on
the instability is rather straight forward. As the insta-
bility increases, the probability that parcels of air
originating immediately over the sea surface will reach·
the 10 m collecting level within a fixed time interval
also increases. Since these parcels will contain some of
those larger particles whose size generally relegates them
to the air immediately over the sea surface due to high
sedimentation rates, there will be a significant increase
in mass per cubic meter of air at the collecting level.
In this case physical intuition is closely matched by
the data. As the instability increases the larger parti-
cles are on the average lifted up higher against the set-
tling force of gravity. Even those particles with high
fall velocities were able to reach the 10 m level where
observations were taken. To avoid confusion, it should be
mentioned that the increases noted in sea-salt content due
to increased instability were in addition to those related
to increasing wind speed. For example, if two samples were
taken at 20 kts on different occassions, the higher value
would be found on the occassion with the greater instability.

The light wind case (Fig. 16) is at first somewhat less
obvious, although it too is best explained by instability
and consequent mixing. It is well documented that over
the continents the heating of the surface and the resulting
instability creates a nearly uniform distribution of sea-
salt nuclei with height, at least in the lower several kilo-
meters. (Junge, 1958). This is in sharp contrast to the
maritime situation where the distribution generally falls
off quite rapidly with increasing altitude, although cer-
tain secondary maxima may occur (Woodcock, 1953; Lodge, 1955).
Particularly with some of the larger values of $T_W - T_A$ it is
to be expected that mixing will occur from the sea surface
up to an altitude of several thousand feet (Houghton, 1968).

With no local production to complicate matters, what
occurs is a simple redistribution of the particles and
hence the mass. Instead of having greater concentrations
right over the sea surface (Woodcock and Gifford, 1949)
which fall off with height, a more nearly uniform verti-
cal distribution results from the presence of the rela-
tively deep mixed layer. This in turn will cause the
values near the sea surface to be lower as a consequence
of the approximate conservation of mass in a particular
column of air. This result was observed and the correla-
tion between low values of salt and greater instability
was quite strong. Instability is therefore another signi-
ficant factor which must be considered in the overall salt
distribution in addition to production, sedimentation, wash-
out and advection.

RESULTS AND DISCUSSION

c.   Fallout Rate and the Particle Lifetimes

On March 10 and 11, 1965, (Fig. 5) there were typical north-
east monsoon winds of approximately 15-17 knots causing
local production of sea-salt nuclei.   Quite suddenly, around
2400 h. on March 11, the wind dropped to about 6 knots.
Between that time and March 15, the winds were very light,
reaching 9 or 10 kts for several hours only and often being
under 4 knots.   During this period the wind turned from
northeast to north and remained from that direction.   Thus
there was essentially no production after 2400 h. March 11
and the direction and speed of the wind were such that no
continental influence would be felt due to advection.   Even
though the ship travelled several hundred miles, it is not
inconceivable that the same conditions prevailed over a
fairly broad area.   Keeping the limitations of the argument
in mind, it is possible to obtain at least a rough idea of
the fallout rate.   Figure 18 shows that after approximately
2 1/2 days the salt content has fallen to one-third its
value before production ceased.   This means that roughly
60-70% of the mass fell out during the interim.   Referring
to Woodcock's (1953) distribution curves, we see that for
a wind between force 4 and 5 Beaufort (about 16 kts), ap-
proximately two-thirds of the mass is found in particles
larger than 10^{-10} gm. mass. It can be concluded as a limited
approximation that those particles larger than 10^{-10} gm.
all had lifetimes of 2 1/2 days or less.   Considering the
somewhat qualitative arguments involved, this finding is
remarkably consistent with the estimates of 2.6 and 2.9
days given for particles of 10^{-10} gm. and larger by Eriksson
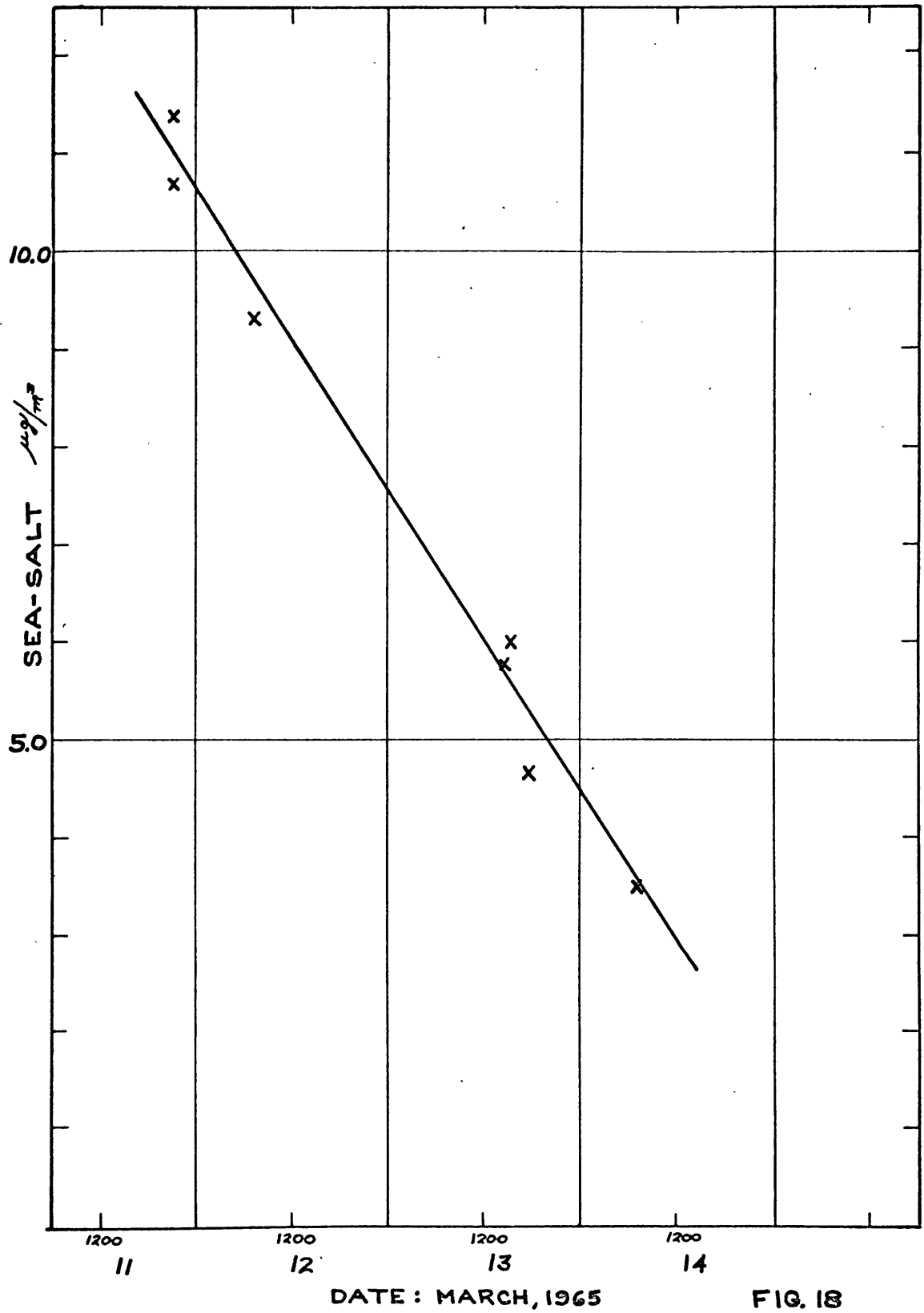(1959) and Toba (1965a) respectively.

DATE: MARCH, 1965   FIG. 18

VII. SUMMARY

(1) Sea-salt nuclei may be collected on small diameter
     wires at efficiencies of approximately 90% for those
     particles whose radius is greater than one micron.
     Almost all of the total mass of sea-salt in the marine
     atmosphere is to be found in these so-called giant
     particles.

(2) At wind speeds above 8 to 10 kts there is local pro-
     duction of sea-salt nuclei and the total sea-salt con-
     tent is a logarithmic function of the wind speed.

(3) The production rate appears unrelated to geographical
     position so long as the situation is truly maritime.

(4) At wind speeds below 8 to 10 kts the logarithmic re-
     lationship breaks down due to the highly variable effects
     of advection, sedimentation, instability, and washout.
     The last two factors qualitatively appear to be the
     most important at the sampling height of 10 meters.

(5) Even with fairly uniform conditions as during the dry
     monsoons, the salt content varies from one large par-
     cel of air to the next at the same wind speed. Values
     may differ by factors of two to three in the same day,
     all other conditions seeming equal.

(6) The effect of convection as measured by the degree of
     low-level instability is found to be quite significant.
     Vertical mixing decreases the salt content at the 10
     meter level for light winds, those less than 7 knots
     and it increases the salt content for higher winds,
     those greater than 15 knots.

(7) Based on a somewhat qualitative argument it appears that the larger particles (mass $>$ 10^{-10} gram) settle out quite rapidly when production ceases. A reasonable estimate of their lifetime is one to three days.

REFERENCES

Aitken, J., Collected Scientific Papers, Ed. C.G. Knott, Cambridge University Press, 1923.

Blanchard, D.C., Electrification of the Atmosphere in Progress in Oceanography, volume 1, Pergamon Press, 1963.

Blanchard, D.C. and A.T. Spencer, Condensation Nuclei and the Crystallization of Saline Drops, J. Atmos. Sci., 21, 182-186, 1964.

Blanchard, D.C. and A.H. Woodcock, Bubble Formation and modification in the sea and its meterological significance, Tellus, 9, 145-158, 1957.

Eriksson, E., The Yearly Circulation of Chloride and Sulfur in Nature: Meteorological, Geochemical, and Pedalogical Implications, Part I: Tellus,11, 375-403, 1959.

Fournier d'Albe, E.M., Sur les embruns marins, Bull. Inst. Oceanog, Monaco, 48, 995, 1951.

Houghton, H.G., The Size and Size Distribution of Fog Particles, Physics, 2, 467-475, 1932.

Houghton, H.G., Personal Communication, 1968.

Isono, K., Komabayosi, M., Takahoshi, T., Gonda, T., A Physical Study of Solid Precipitation From Convective Clouds Over the Sea, J. Meteorol. Soc. Japan, 44, 308-319, 1966.

Jacobs, W.C., Preliminary Report on the Study of Atmospheric Chloride, Mon. Weather Rev., 65, 147-151, 1937.

Junge, C. Die Konstitution des atmospharischen Aerosols, Ann. der Met., Beiheft, 1-55, 1952.

Junge, C.E., The Chemical Composition of Atmospheric Aerosols, I: Measurements at Round Hill field station, June-July 1953, J. Meteorol, 11, 323-333, 1954.

Junge, C.E., Recent Investigations in Air Chemistry, Tellus, 8, 127-139, 1956.

Junge, C.E., The Vertical Distribution of Aerosols Over the Ocean, in The Artificial Stimulation of Rain, Ed. A.

Weickman and W. Smith, Pergamon Press, 1957a.

Junge, C.E., Chemical Analysis of.Aerosol Particles and of Gas Traces on the Island of Hawaii,Tellus, 9, 528-537, 1957b.

Junge, C.E., Atmospheric Chemistry, in Advances in Geophysics, vol. 4, Ed. H.E. Landsberg, J. Van Mieghum, Academic Press, 1958.

Junge, C.E., Air Chemistry and Radioactivity, Academic Press, New York, 1963.

Kientzler, C.F., A.B. Arons, D.C. Blanchard, and A.H. Woodcock, Photographic Investigations of the Projection of Droplets by Bubbles Bursting at a Water Surface, Tellus, 6, 1-7, 1954.

Knelman, F. N. Dombrowski, and D.M. Newitt, Mechanism of the Bursting of Bubbles, Nature, 173, 261, 1954.

Köhler, H. The Nucleus in and the Growth of Hygroscopic Droplets, Trans, Faraday Soc., 32, 1152-1162, 1936.

Komabayasi, M., Primary Fractionation of Chemical Components in the Formation of Submicron Spray Drops from Seasalt Solution, J. Meteorol. Soc. Japan, 42, 309-316, 1964.

Langmuir, I. and K.B. Blodgett, A Mathematical Investigation of Water Drop Trajectories, Gen.Electr. Res. Lab. Tech. Report 5418 (A.T.S.C. Contract W-33-038-ac-9151), 1946.

Lodge, J.P., A Study of Sea-Salt Particles Over Puerto Rico, J. Meteorol., 12, 493-499, 1955.

Mason, B.J., The Physics of Clouds, Oxford University Press, London, 1957.

Moore, D.J., Measurements of Condensation Nuclei Over the North Atlantic, Quart. J. Royal Meteorol. Soc., 78, 596-602, 1952.

Moore, D.J., B.J. Mason, The Concentration, Size Distribution and Production Rate of Large Salt Nuclei Over the Oceans, Quart. J. Royal Meteorol. Soc., 80, 583-590, 1954.

Munk, W.H., A Critical Wind Speed for Air-Sea Boundary Processes, J. Marine Res., 6, 203-218, 1947.

Oddie, B.C.V., The Variation in Composition of Sea-Salt

Nuclei with Mode of Formation, Quart. J. Royal Soc., 86, 549-551, 1960.

Owens, J.S., Condensation of Water From the Air Upon Hygroscopic Crystals, Proc. Roy. Soc. London (A), 110, 738-752, 1926.

Roll, H.V., Physics of the Marine Atmosphere, Academic Press, New York, 1965.

Simpson, G.C., On the Formation of Cloud and Rain, Quart. J. Royal Meteorol. Soc., 67, 99-133, 1941a.

Simpson, G.C., Sea-Salt and Condensation Nuclei, Quart. J. Royal Meteorol. Soc., 67, 163-169, 1941b.

Svedrup, H.V., M.W. Johnson, and R.H. Fleming, The Oceans, Prentice-Hall, Inc., Englewood, N.J., 1942.

Svedrup, H.V., The Humidity Gradient Over the Sea Surface, J. Meteorol., 3, 1-8, 1946.

Toba, Y., I General Features of the Distribution: On the Giant Sea-Salt Particles in the Atmosphere, Tellus, 17, 131-145, 1965a.

Toba, Y., II: Theory of the Vertical Distribution in the 10-M Layer Over the Ocean: On the Giant Sea-Salt Particles in the Atmosphere, Tellus, 17, 365-382, 1965b.

Toba, Y., III: An Estimate of the Production and Distribution Over the World Ocean: On the Giant Sea-Salt Particles in the Atmosphere, Tellus, 18, 132-145, 1966.

Twomey, S., The Composition of Hygroscopic Particles in the Atmosphere, J. Meteorol, 11, 334-338, 1954.

Wilson, A.T., Surface of the Ocean as a Source of Air-Borne Nitrogenous Material and Other Plant Nutrients, Nature, 184, 99-101, 1959.

Woodcock, A.H., Convection and Soaring Over the Open Sea, J. Meteorol. Res., 248-253, 1940.

Woodcock, A.H., Sea-Salt Nuclei in a Tropical Storm, J. Meteorol. Res., 7, 397-401, 1950a.

Woodcock, A.H., Condensation Nuclei and Precipitation, J. Meteor., 7, 161-162, 1950b.

Woodcock, A.H., Atmospheric Salt Particles and Raindrops

J. Meteorol., _9_, 200-212, 1952.

Woodcock, A.H., Salt Nuclei in Marine Air as a Function
of Altitude and Wind Force, _J. Meteorol._, _10_, 362-
371, 1953.

Woodcock, A.H. and M.M. Gifford, Sampling Atmospheric
Sea-Salt Nuclei Over the Oceans, _J. Marine Res._,
_8_, 177-197, 1949.

Woodcock, A.H., D.C. Blanchard, and C.G.H. Rooth, Salt
Induced Convection and Clouds, _J. Atmos. Sci._, _20_, 159-
169, 1963.

Wright, H.L., Atmospheric Opacity at Valentia, _Quart. J._
Royal Meteorol. Soc., _66_, 66-77, 1940.