ON THE FINE STRUCTURE OF DENSITY AND CURRENT DISTRIBUTION AND ITS SHORT-TIME VARIATIONS IN DIFFERENT AREAS

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IT IS intended in this article to discuss some of the results which have been obtained by Kiel University from continuously or almost continuously recording instruments during the last few years. These instruments mainly are the *in situ* salinometer called Bathysonde, Savonius rotor current meters with cable connection to the ship, and different types of anchored current meters.

The very first results of the Bathysonde measurements attracted a special interest to the fine structure of the temperature–salinity–density layering and its short-time variations. When different recordings are put together, typical differences can be found in this structure and its time-dependence.

Before discussing this in more detail, it seems worthwhile to explain what will be meant by the expressions "fine structure" and "short-time variations". "Fine structure" is defined here, more or less arbitrarily, as the deviations from a smooth curve of various physical quantities measured at certain levels, e.g. by Nansen bottles. "Short-time variations" are the changes of these values within a time interval that normal hydrographic work will take, i.e. some minutes to a few days. It is admitted that both these definitions are somewhat uncertain, but they seem to be useful at this stage of the investigations.

The very first approach to get an idea of the character and size of the fine structure and the order of magnitude of the short-time variations was to add continuous measurements of temperature and salinity to normal hydrographic work, and to compare the values obtained during lowering and raising the instrument with Nansen bottle values. This has been done in different sea areas, and two examples will be selected from deep-water regions.

Figure 1 shows measurements which were carried out in the autumn of 1964 on R/V *Meteor* in the Mediterranean. No differences between the lowering

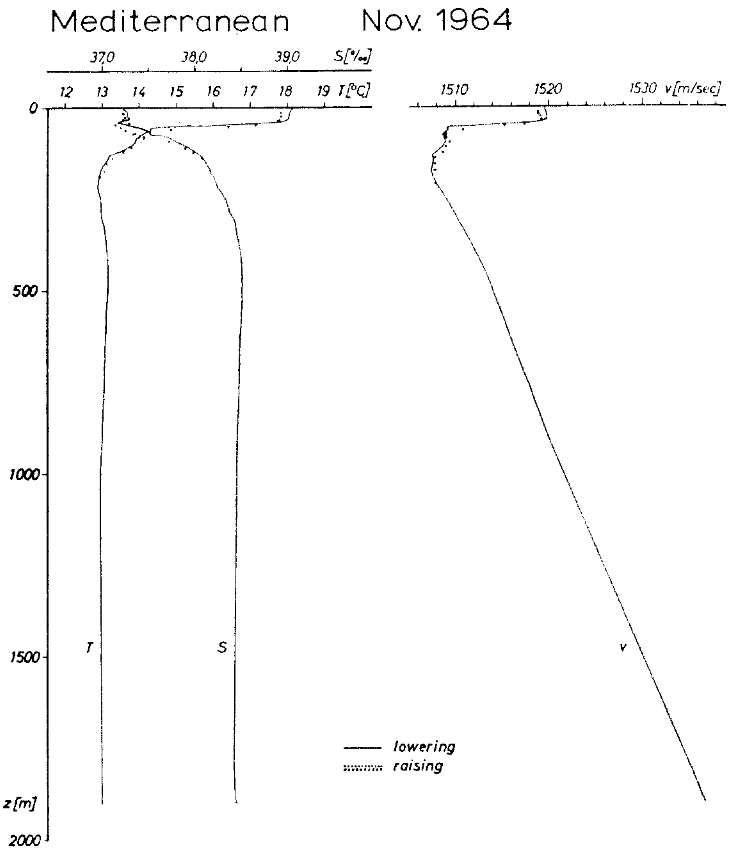

FIG. 1. Salinity, temperature and sound velocity as a function of depth. The time interval near the surface between raising and lowering was approximately 1 hr.

and the raising record can be seen in the intermediate and deep water, but small changes of the fine structure can be detected in the upper 200 or 300 m, reaching the order of 0.1°C in temperature and some 0.1‰ in salinity. The difference in time between the lowering and the raising curve near the surface is approximately 1 hr; the ship's drift is believed to have been less than one nautical mile on this station.

A completely different picture is to be seen in Fig. 2, a typical measurement from the Irminger Sea about 150 nautical miles southeast of Cape Farvel (see HOLZKAMM, KRAUSE and SIEDLER, 1964). This measurement was carried out in the spring of 1963, at the end of a long winter, and apparently demonstrated the influence of vertical mixing which is known to cause the formation of Atlantic Deep Water in that region. In the depth range 100 m

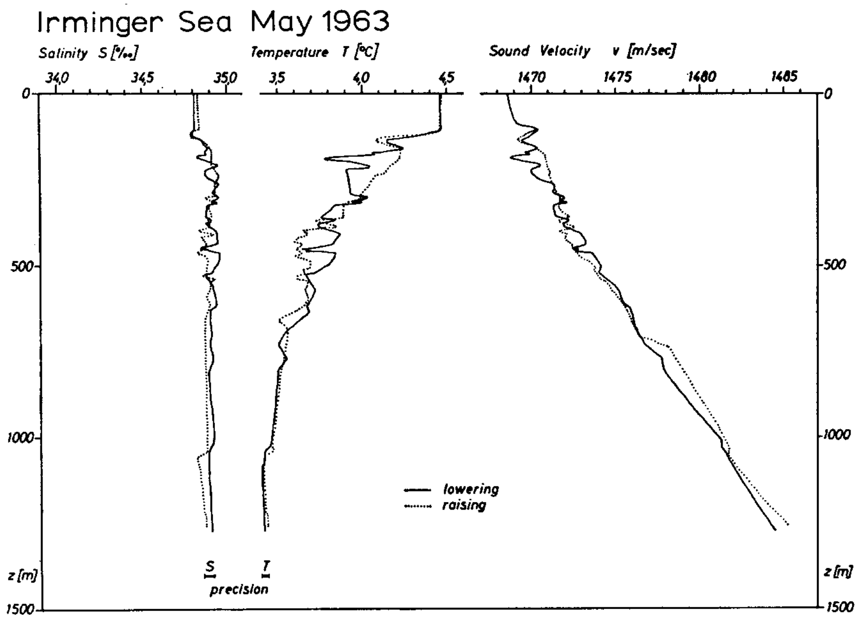

Fig. 2. Salinity, temperature and sound velocity as a function of depth.

to 800 m a remarkable fine structure is to be seen, which is combined with great differences between the lowering and raising curves, exceeding 0.5°C in temperature.

In the resulting temperature–salinity diagram (Fig. 3) there occur deviations which roughly parallel the density lines. It is believed that this type of curve is caused by the formation of water elements with different degrees of mixing and cooling. Of course this kind of measurement gives a very rough picture of the phenomena, and it turns out that the separation of the dependence on time and on space in the horizontal direction is the most difficult problem to solve during the evaluation. The next step was, therefore, to measure the variations in time only by using an anchored ship and by repeating the measurements over a longer time period.

One of the first results of that kind obtained with the Bathysonde, is shown in Fig. 4. These temperature measurements were obtained in 1960 during a characteristic summer situation in the central Baltic, with a sharp vertical gradient in the thermocline and an increase of temperature in the deeper water which contains a high percentage of North Sea water (see SIEDLER, 1961). There is much fine structure to be found in the thermocline as well as in the deeper water, and it may be noticed that a rapid change occurs in the steepness of the thermocline. Other measurements, especially those by KRAUSS

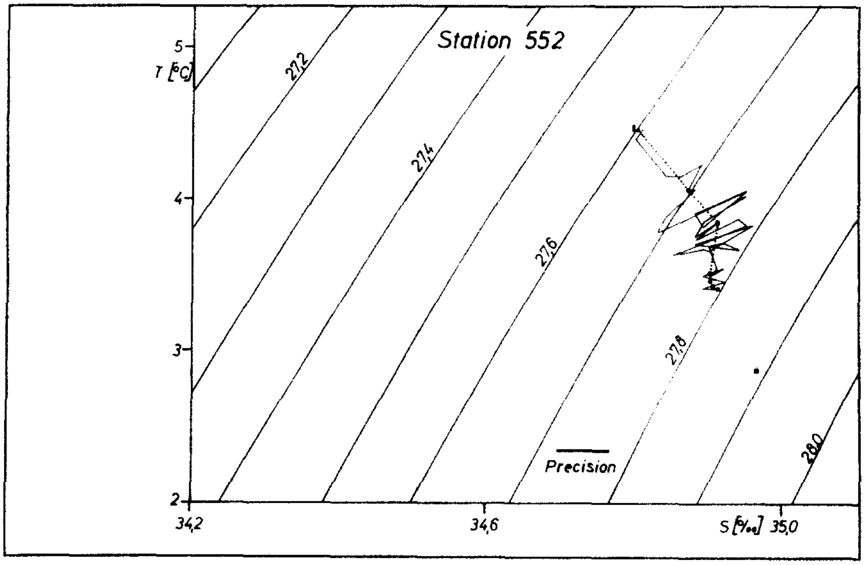

Fig. 3. *T*/*S* diagram corresponding to Fig. 2.

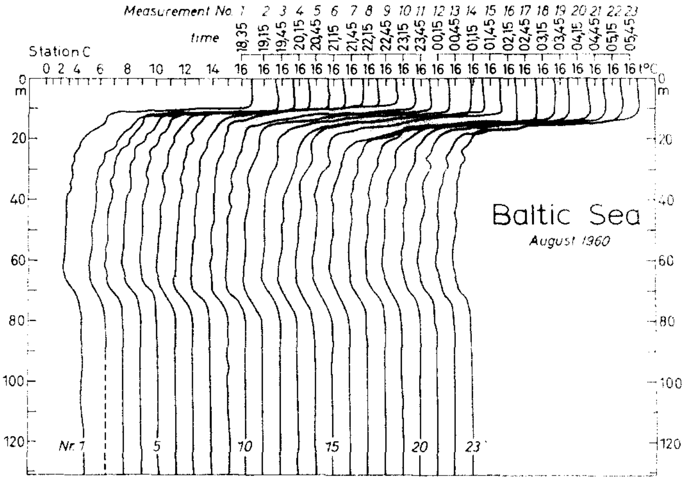

Fig. 4. Temperature versus depth and time measurements obtained with the continuously recording Bathysonde.

(1960, 1963) with observation masts, indicate that one major reason for these time changes is the existence of internal seiches in the Baltic. In addition, stability oscillations in the thermocline would cause a scattering in this kind of record.

An example of stability oscillations is given in Fig. 5 (see KRAUSE and SIEDLER, 1964). In this case a temperature follower moved by an underwater winch system measured short-time variations of a particular isotherm situated in the thermocline. The record indicates the existence of a period of less than ½ minute. One may therefore suppose that much of the fine structure variation in the recordings in a stratified shallow-water area is caused by short-period variations of that kind. On the other hand it is known from former investigations that the Baltic is strongly influenced by the wind system which determines the flow in the straits between the Baltic and the North Sea thus causing non-periodic changes in the structure of the water masses.

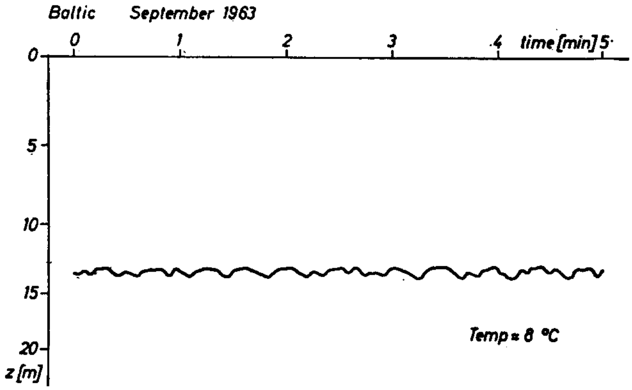

FIG. 5. The depth of the 8° isotherm as measured by a "temperature follower", as a function of time.

The next step in the investigation of the fine structure, and its variations with time, was to use continuously recording instruments from an anchored ship and to anchor self-recording instruments in the neighbourhood of the ship. This scheme has been used during the investigation of the water exchange between the Red Sea and the Indian Ocean on the Indian Ocean cruise of R/V *Meteor* in 1964/65. As the shore line and the bottom topography have a strong influence on water movements and layering in this region, it may be useful to give a short description of the positions where measurements were carried out.

Figure 6 illustrates the bottom topography of the region under investigation. In this article measurements from Anchor Station 62, from Station 32,

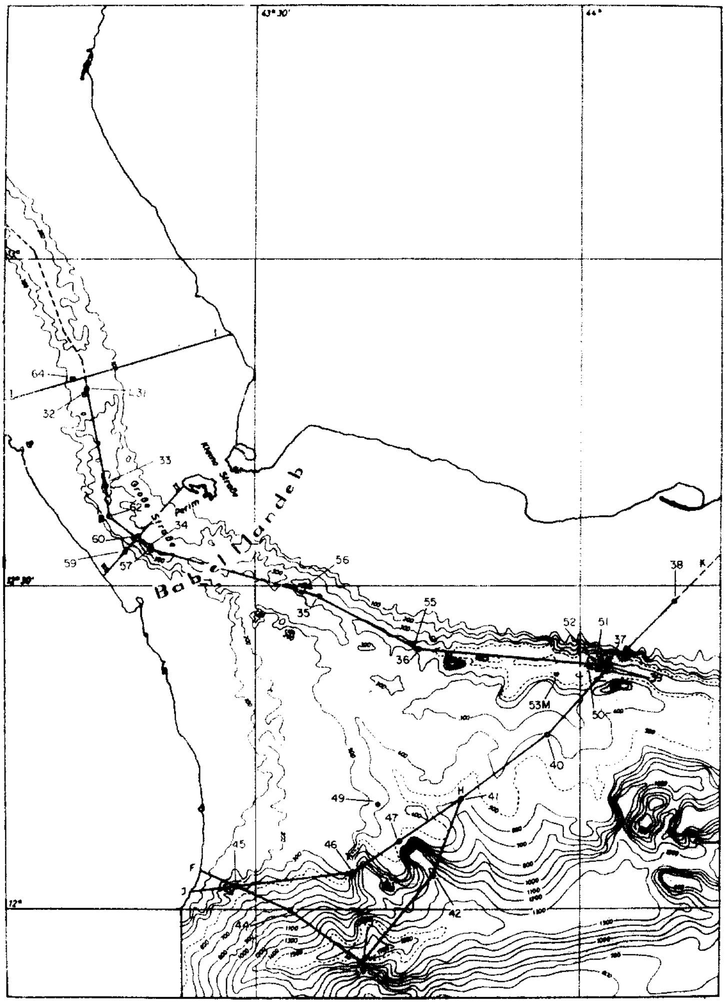

FIG. 6. Bottom topography in the region of the mouth of the Red Sea.

where two self-recording current meters were anchored, and from Hydrographic Stations 34 to 37 have been used. (The complete results of all the measurements will be described in detail in *Meteor-Forschungsergebnisse*, Reihe A.)

On Station 62 the ship was anchored for a period of 2½ days, and repeated measurements were carried out with the Bathysonde and the Savonius rotor current meter. The vertical temperature distribution, shown in Fig. 7, indicates homogeneous surface and bottom layers and an intermediate layer

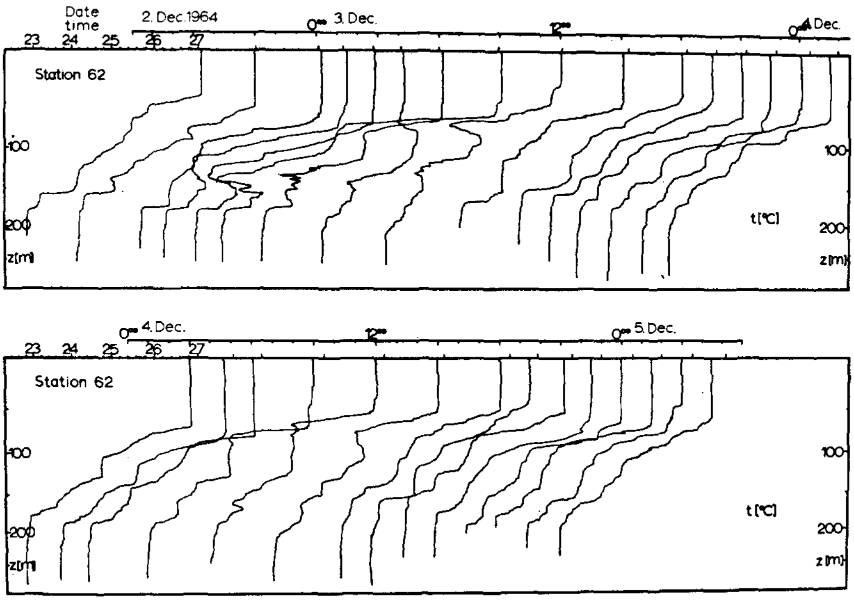

FIG. 7. Temperature as a function of depth and time at Station 62 (see Fig. 6).

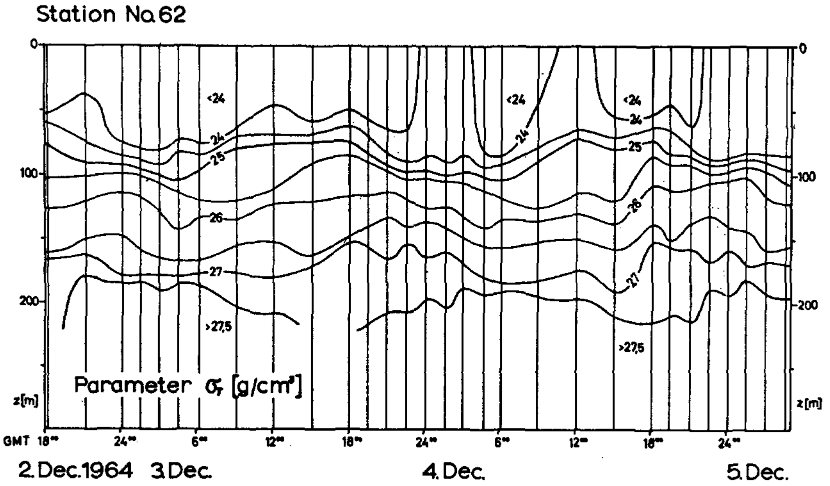

FIG. 8. Isopleths of σ_t as a function of depth and time, corresponding to Fig. 7.

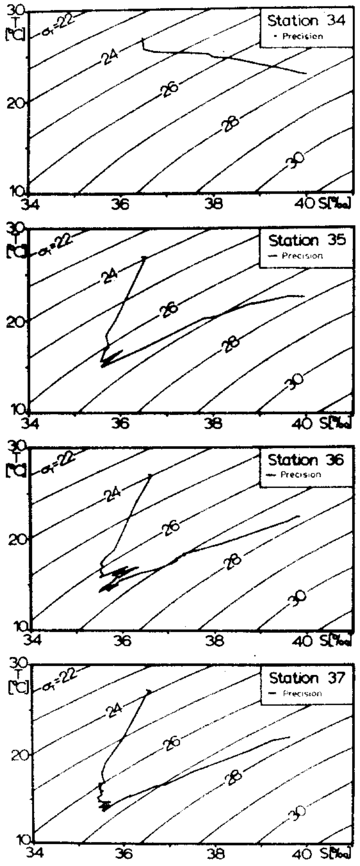

FIG. 9. *T*/*S* diagrams constructed from Bathysonde records on Stations 34–37 (see Fig. 6).

with much fine structure and very rapid changes in time. Apparently this is the effect of mixing between Red Sea water flowing into the Gulf of Aden and Indian Ocean water flowing into the Red Sea. In addition, internal diurnal tides are indicated by the vertical displacements of the boundary between surface and intermediate water. This can be seen more clearly in Fig. 8 where isolines of σ_t have been drawn from these measurements.

The comparison between *T*/*S* diagrams, constructed from the Bathysonde measurements on Stations 34 to 37 (Fig. 9), indicate that the fine structure is mainly caused by mixing processes leading to a straight line in the *T*/*S* diagram of Station 34, and to a structure similar to Fig. 3 in the diagrams for Stations 35, 36, and 37.

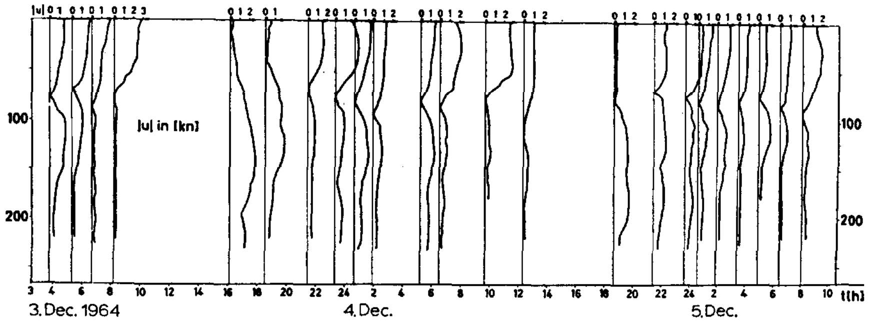

FIG. 10. Directly measured current speed as a function of depth and time at Station 62 (see Fig. 6).

In Fig. 10 profiles have been drawn of current speed measurements obtained on Anchor Station 62. The changes with time are large at every depth, and the vertical displacements of the interface between inflowing and outflowing water, as indicated by the zero points on the curves, are by far larger than the vertical displacements of the density boundary layers. This can easily be explained by an addition of movements by surface and internal tides.

By using the additional recordings from anchored current meters, more information can be obtained about the periods of short-time variations in that region. All the measured values have been analyzed by histogram and by amplitude spectral computations.

The histograms of current direction and speed values given by the current meters on Station 32 are shown in Figs. 11 and 12. A very stable northward direction of the upper current with a most frequent speed of about 70 cm/sec is to be seen. The speed distribution (Fig. 12) with two maxima is caused by passing of the current interface along the current meter.

Amplitude spectra of these current measurements are given in Figs. 13 and 14, filtered for the ranges between 4 hr and 40 hr and between 40 min and 10 hr. There exist peaks which can be explained by diurnal and semi-diurnal tides and by shallow water tides of 8 and 6 hr. The peak at 5 hr may be an indication of an internal seiche of the channel, since this period is found as the first order solution in a three-layer model calculation; it may as well be a shallow-water tide of higher order.

Summarizing the different results, it can be said that a fine structure of the temperature–salinity–density distribution can be found in many parts of the ocean. Quantitative information can be received about the periodic parts of its short-time variations, while as yet only qualitative information is available about the non-periodic parts. Short-time changes in the recordings

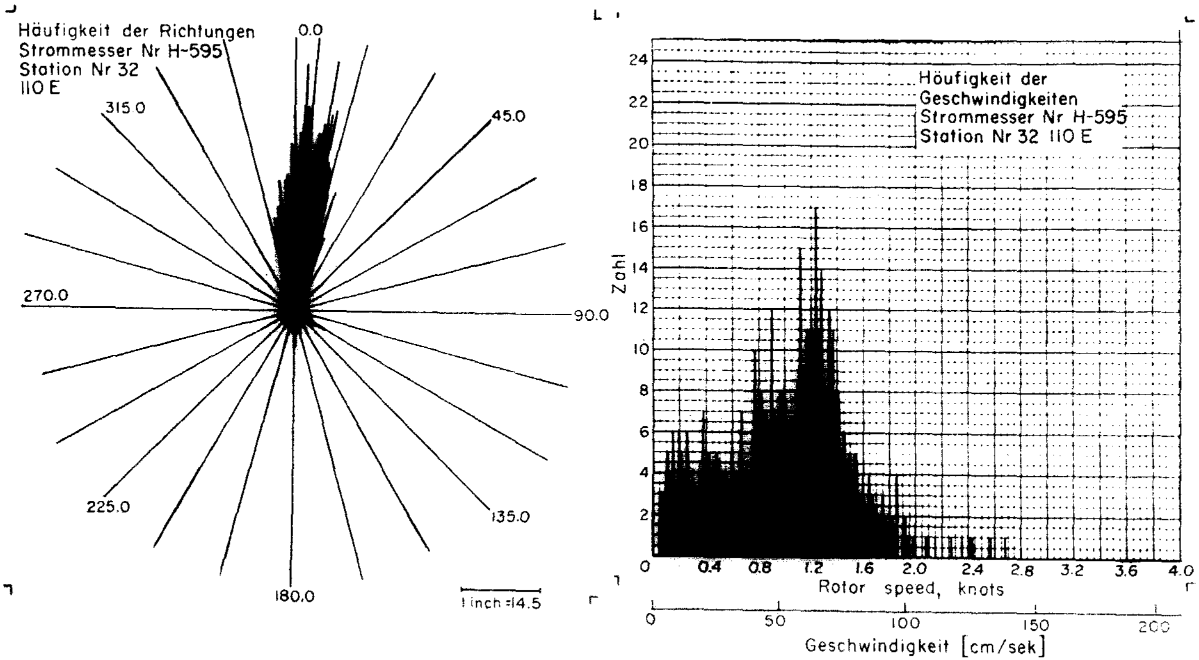

FIG. 11. Histograms of direction (*left*) and speed (*right*) of current measurements in the upper layer in the Strait of Bab el Mandeb. The height of speed histogram lines is proportional to the number of measurements.

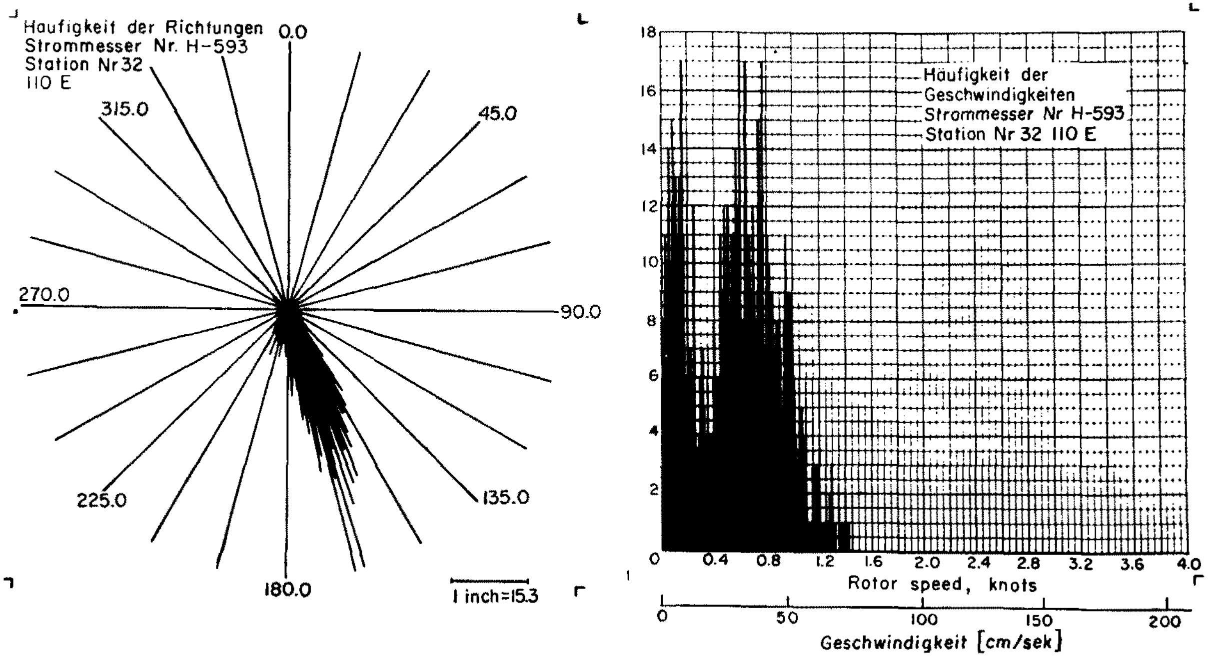

FIG. 12. Histograms of direction (*left*) and speed (*right*) of current measurements in the lower layer in the Strait of Bab el Mandeb. The height of speed histogram lines is proportional to the number of measurements.

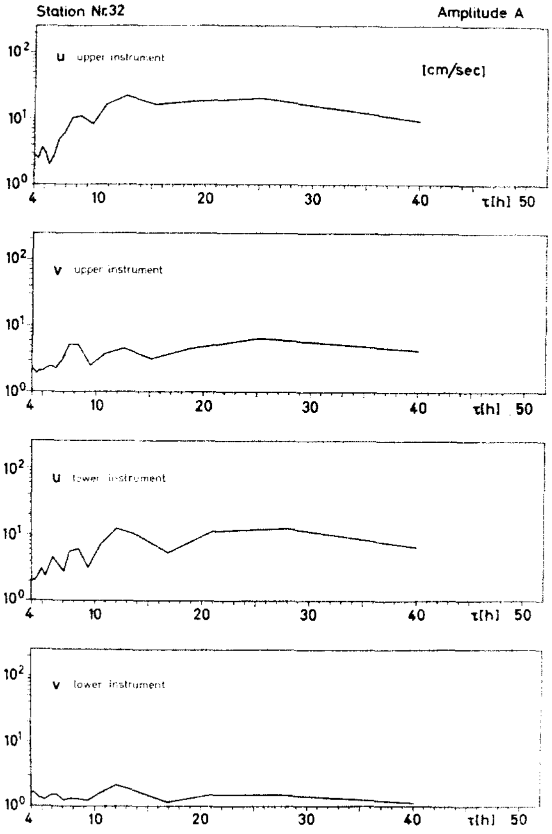

FIG. 13. Amplitude spectra of the along-channel (*u*) and the cross-channel (*v*) components of velocity. The data are filtered for the range 4 to 40 hr.

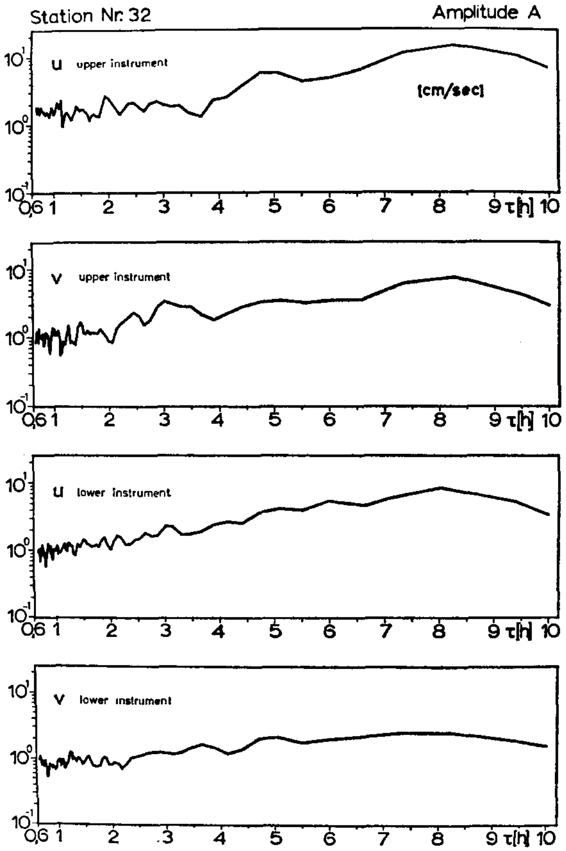

FIG. 14. Amplitude spectra of the along-channel (*u*) and the cross-channel (*v*) components of velocity. The data are filtered for the range 40 min to 10 hr.

presently available seem to be caused mainly by internal seiches, internal tides, mixing processes during vertical convection, and mixing processes caused by vertical current shear. More quantitative results will be available if it becomes possible to obtain far longer time series.

REFERENCES

HOLZKAMM, F., KRAUSE, G. and SIEDLER G. (1964) On the processes of renewal of the North Atlantic deep water in the Irminger Sea. *Deep-Sea Res.*, **11**, 881–890.

KRAUSE, G. and SIEDLER, G. (1964) Ein System zur kontinuierlichen Messung physikalischer Größen im Meere. *Kieler Meeresforsch.* **20**, (2), 130–135.

KRAUSS, W. (1960) Hydrographische Messungen mit einem Beobachtungsmast in der Ostsee. *Kieler Meeresforsch.* **16**, (1), 13–27.

KRAUSS, W. (1963) Zum System der internen Seiches der Ostsee. *Kieler Meeresforsch.* **19**, (2), 119–132.

SIEDLER, G. (1961) Über die kurzfristige Veränderlichkeit von Temperatur- und Salzgehaltsschichtung in der östlichen und mittleren Ostsee in Sommer 1960. *Kieler Meeresforsch.* **17**, (2), 148–153.