Some observations of temperature fluctuations in the coastal region of the Baltic

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ABSTRACT

Two months of almost daily observations of temperature variations on a section through the coastal region of the Baltic are presented. The results are found to be compatible with theoretical expectations (Walin, 1972; Csanady, 1968). In particular, we have observed large amplitude temperature variations confined within a region extending 5–10 km from the coast. Although this is not finally proved, these perturbations seem to propagate as internal Kelvin waves along the coast.

I. Introduction

In a theoretical study of the transient response of the Baltic to meteorological forcing (Walin, 1972) it has been demonstrated that we can expect large amplitude temperature fluctuations within a region extending 5–10 km from the coast. It has also been shown that these "trapped internal waves" should have a tendency to propagate along the coast as internal Kelvin waves (i.e. southwards on the Swedish east coast). Similar results have also been obtained by Csanady (1968) in work mainly related to the Great Lakes.

Hydrographical observations clarifying the relative importance of these phenomena in the Baltic seem to be almost completely missing. The empirical knowledge collected in the Great Lakes is considerably larger (e.g. Mortimer, 1963 and 1971) but, even there, the character and relative importance of the coastal internal motions are poorly known. The measurements presented in this paper represent a first small effort to fill this gap in our empirical knowledge of the Baltic.

Though we do not consider the material presented here substantial enough for quantitative interpretation, we nevertheless hope that certain qualitative conclusions can be drawn which may be helpful in the planning of future efforts.

[1] *Contribution No. 244.*

2. Description of the measurements

The observations were made during July and August, 1968. The measuring section was located in the southern Baltic as illustrated in Fig. 1. As seen, the coastline in the neighbourhood of the section is relatively smooth, which was considered to be favourable.

The bulk of the observational data obtained consists of temperature-depth soundings taken at different distances from the coast. In addition to the temperature soundings the surface layer temperature at the coast was continuously recorded as a function of time. The wind transport calculations were based on routine wind observations from the Lighthouse Sandhammaren (see Fig. 1) kindly made available by the Swedish Meteorological and Hydrological Institute.

2.1. *Measuring equipment*

The observations were taken from a 33 feet fishing vessel by the author alone. This made it necessary to arrange the measurement procedure in such a way that no manoeuvering of the boat was required during the soundings. Most important, a modest drift of the boat has to be tolerated while measuring. This problem was satisfactorily solved as discussed below. The most serious limitation on the measuring capability was found to be the low speed of the boat (<7 knots), particularly against strong winds.

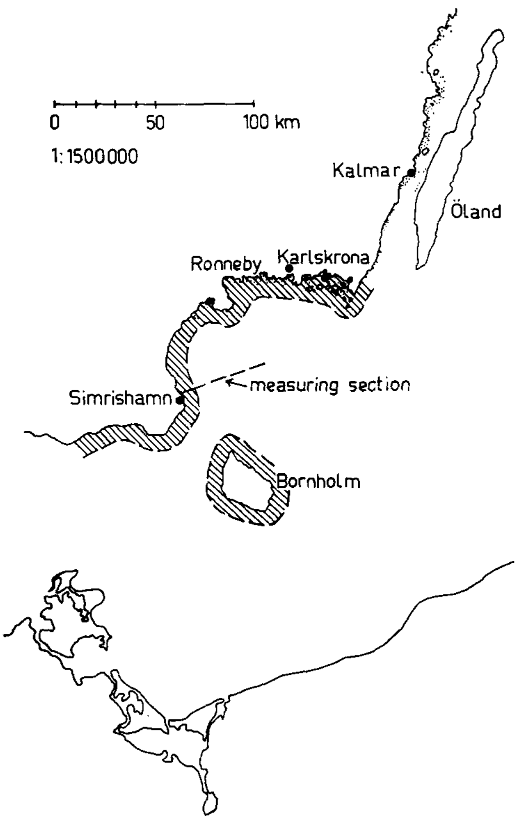


Fig. 1. Map of southern Baltic showing position of measuring section. The coastal region, where we expect strong internal movements to occur, is indicated with light shadow.

The sounding device consisted of a temperature-sensitive resistor (thermistor) and a pressure gauge, at the end of a slender cable connected, via some simple electronics, to an $x-y$-recorder on which temperature was plotted against pressure (i.e. depth). The weight of the sonde was adjusted to give it a speed of free fall through the water of 0.5–1.0 m/s. To obtain a temperature profile the cable and sonde were simply thrown overboard and the temperature recorded while the sonde was sinking through the water. If the boat drifted with the same speed as the sonde was sinking (~ 1–2 knots) the maximum depth reached by the sonde was approximately 70 % of the cable length. Observe that if it is required to keep the sonde at constant depth for some time while the boat is drifting (even much more slowly than 1 knot) it is necessary to make the sonde much heavier. This in turn, necessitates the use of a winch (with rotating contacts) and a stronger cable (and also, presumably, continuous manoeuvering of the boat).

The temperature of the surface layer at the coast was measured with the aid of 600 m standard, two-part electric cable stretched on the bottom from the shore to a depth of about 10 m. The resistance of the loop formed by the two parts of the cable, which was recorded as a function of time, provided a rough vertical mean value of the surface layer temperature at the coast.

3. Information treatment

Primarily, information was collected in the form of temperature-depth profiles such as those shown in Fig. 3*a–c*. The separation of the soundings was 1–2 km within 10 km from the coast and 2–5 km further away from the coast. However, since it was very time-consuming to go further out from the coast, and since the coastal region was considered to be of primary interest, most of the observations were taken within 10 km (see Fig. 2).

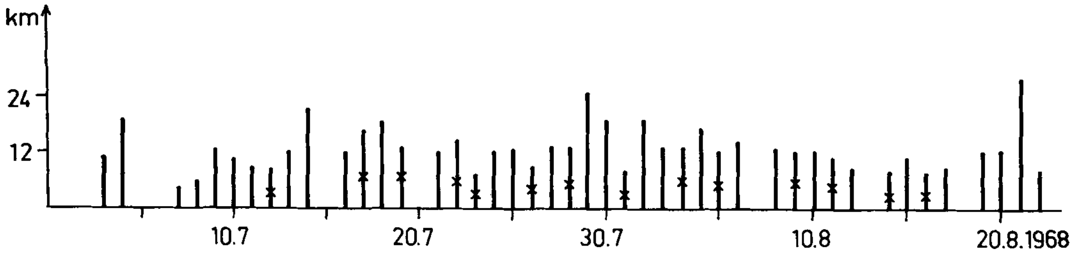
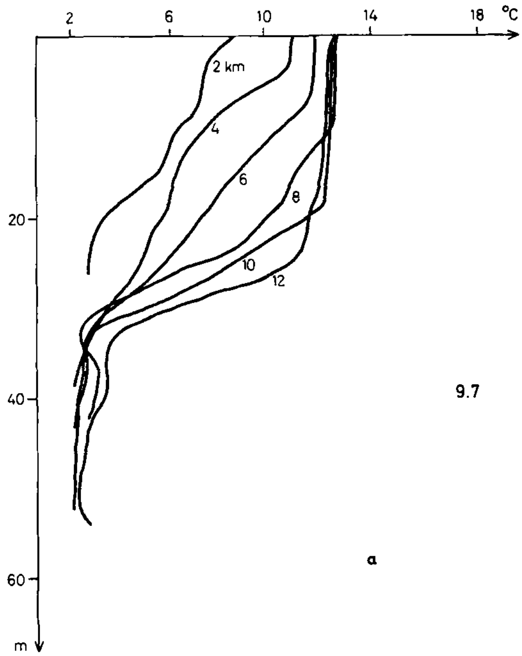
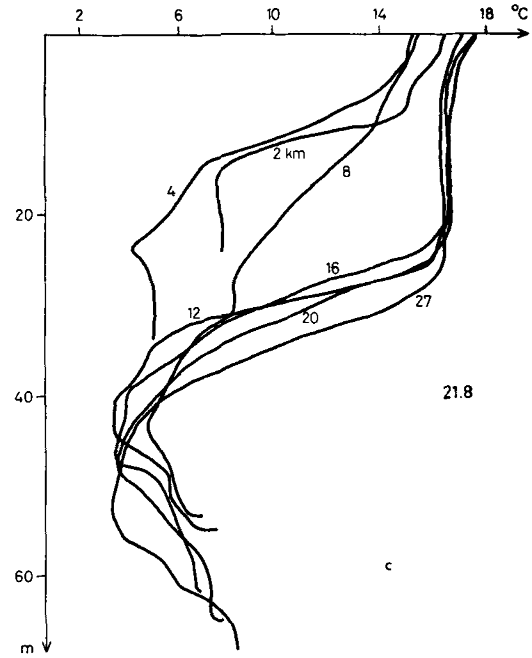


Fig. 2. Illustration of the number of temperature soundings obtained. The days on which soundings were taken are indicated with a vertical line, the length of which indicates how far from the coast measurements were taken the corresponding day. Days which have not been included in Fig. 5 have been indicated by a cross.





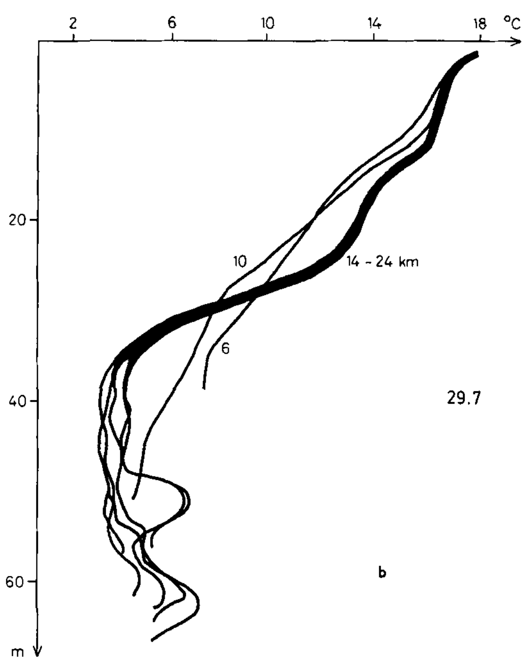


Fig. 3a–c. Examples of temperature soundings. Date of sounding and distance from the coast are given in the Figs. Fig. 3*a* shows clearly how the temperature profile approaches a "well behaved" summer thermocline at a distance of roughly 10 km from the coast. Fig. 3*b* illustrates the situation during a period with relatively weak and irregular winds. Outside the coastal region the temperature field is horizontally very homogeneous. Approaching the coast, the step-like character of the thermocline typically becomes less pronounced, very likely as a result of the near-shore mixing. Note also the "whiggles" on the temperature curves, close to the bottom, associated with salinity variations. Fig. 3*c* demonstrates that the thermocline is relatively unperturbed at distances from the coast larger than, or of order, 10 km despite the unusually vigorous internal variations in the coastal region.

Fig. 4*a* is intended to represent the "off shore temperature structure" as a function of time. It is based on all the soundings taken 10 km or more from the coast. We have interpolated over the days with no such observations and taken horizontal mean values when more than one sounding were available. We have thus implicitly assumed that no large amplitude, short time scale, temperature variations are present outside the coastal region; an assumption which is consistent with all the observations available, but perhaps not yet completely justified.

The temperature sections in Fig. 5, based on the main part of our measurements, have all been extended to the same distance from the coast in order to make visual interpretation easier. The isotherms have thus been extrapolated (the dotted part of the isotherms) when

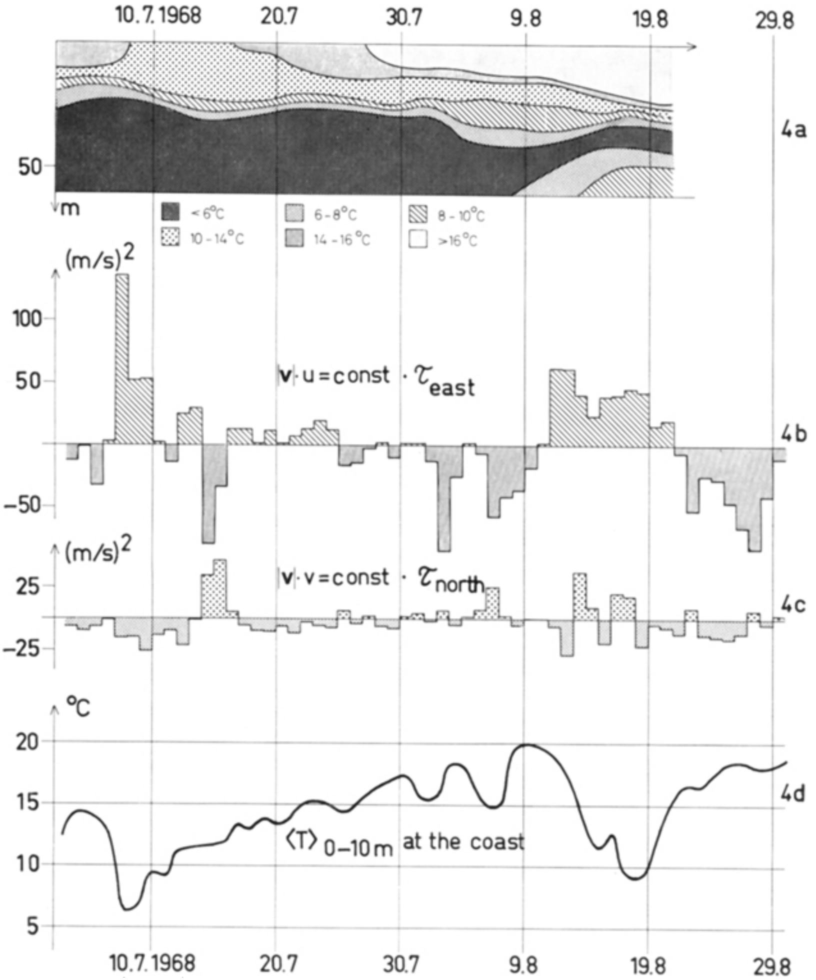


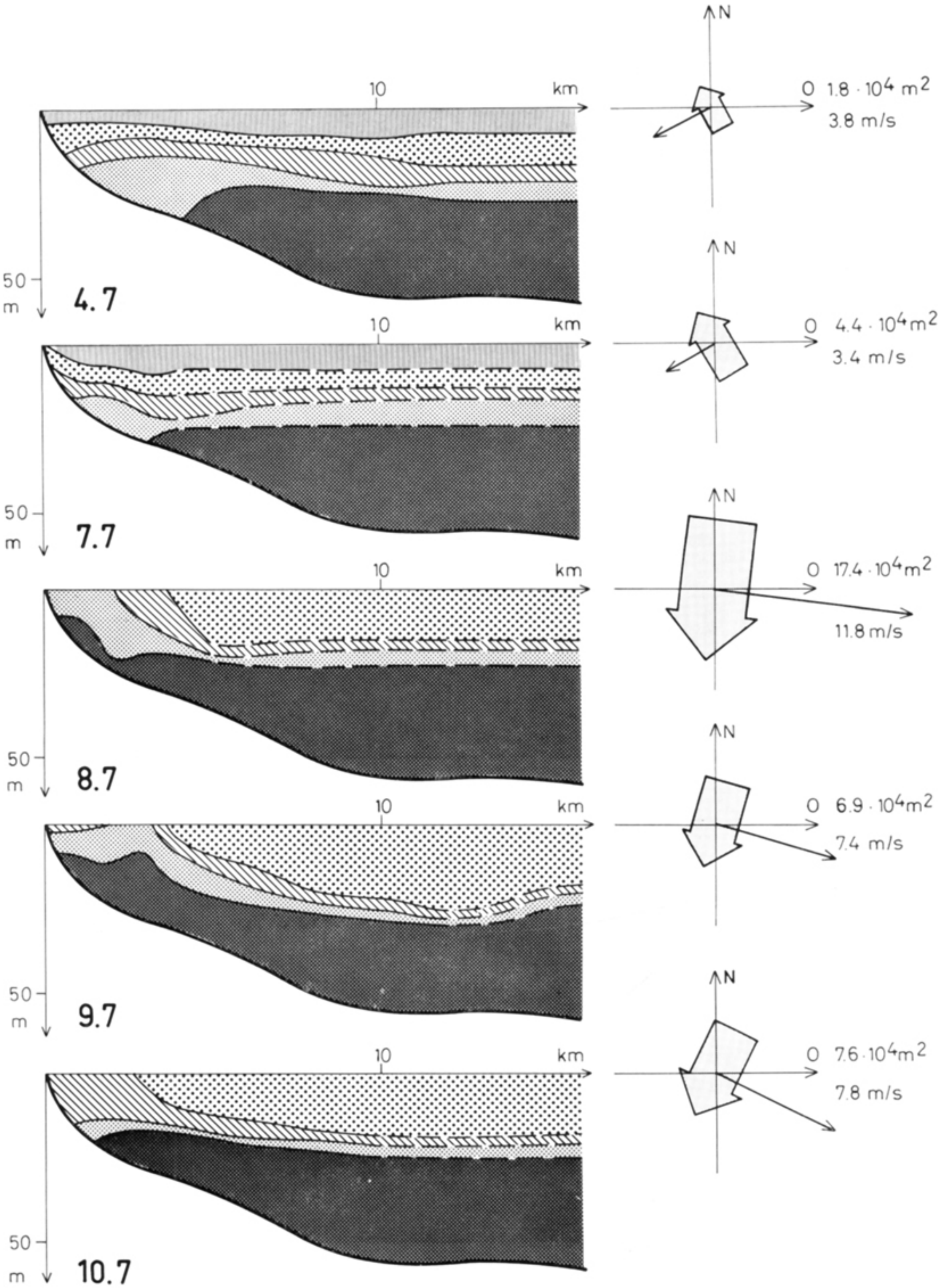
Fig. 4a–d. The "off-shore" temperature structure as obtained from measurements 10 km or more from the coast (see text). Figs. 4*b* and *c* show daily mean values of $|\mathbf{v}|\cdot u$ and $|\mathbf{v}|\cdot v$, where $\mathbf{v}$ is the wind vector, u the wind component towards east and v the component towards north. Within a square law relationship for the windstress, Fig. 4*b* and *c* thus give the time-dependence of the windstress components on a relative scale. Fig. 4*d* shows the temperature of the surface layer (vertical mean value between 0 and 10 m depth) at the coast.

necessary to fit smoothly with the "off shore temperature structure" given by Fig. 4*a*.

The wind observations at Sandhammaren were available from every third hour except for a nine-hour gap during nights. For the computation of the windstress we have used the assumption

$$\boldsymbol{\tau} = \alpha\varrho\,|\mathbf{v}|\,\mathbf{v} \tag{1}$$

Fig. 5 a–f. The major part of the temperature measurements displayed as isotherms on vertical sections. To the right of each section the wind forcing between the time of observation of this section and the foregoing one is illustrated. The broad arrow thus illustrates the direction and magnitude of the wind transport, integrated from the time of measurement of the foregoing temperature section. (Upwards (to the right) in the diagram means flow towards north (east).) The magnitude of this transport (having the dimension of an area) is given numerically in the diagrams. The thin arrow illustrates the equivalent constant wind that would give rise to the same integrated wind transport. The strength of this wind is also given numerically.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O 1.8 · 10⁴ m²
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km
O 17.4 · 10⁴ m²
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Fig 5 a

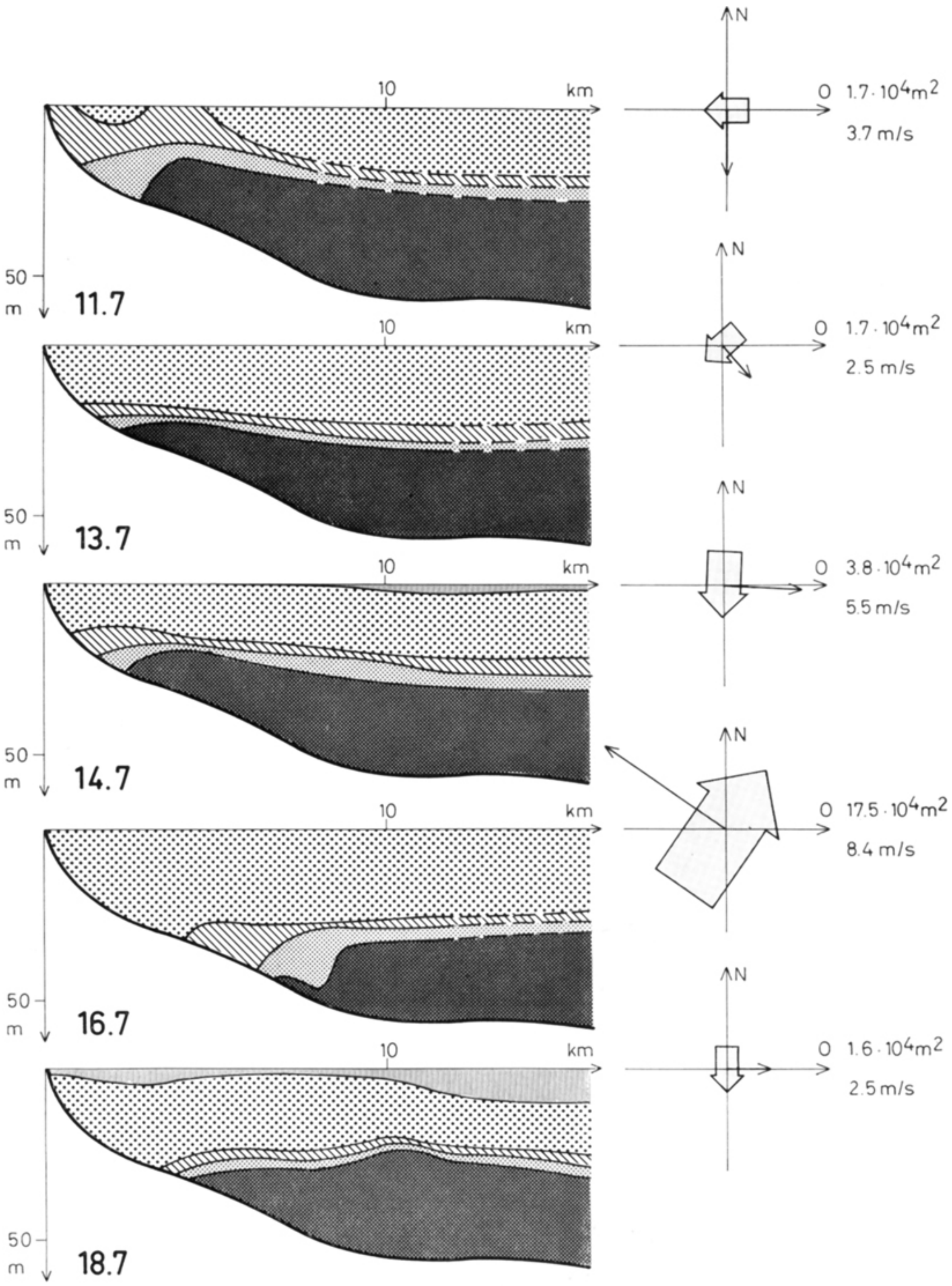
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Fig. 5b

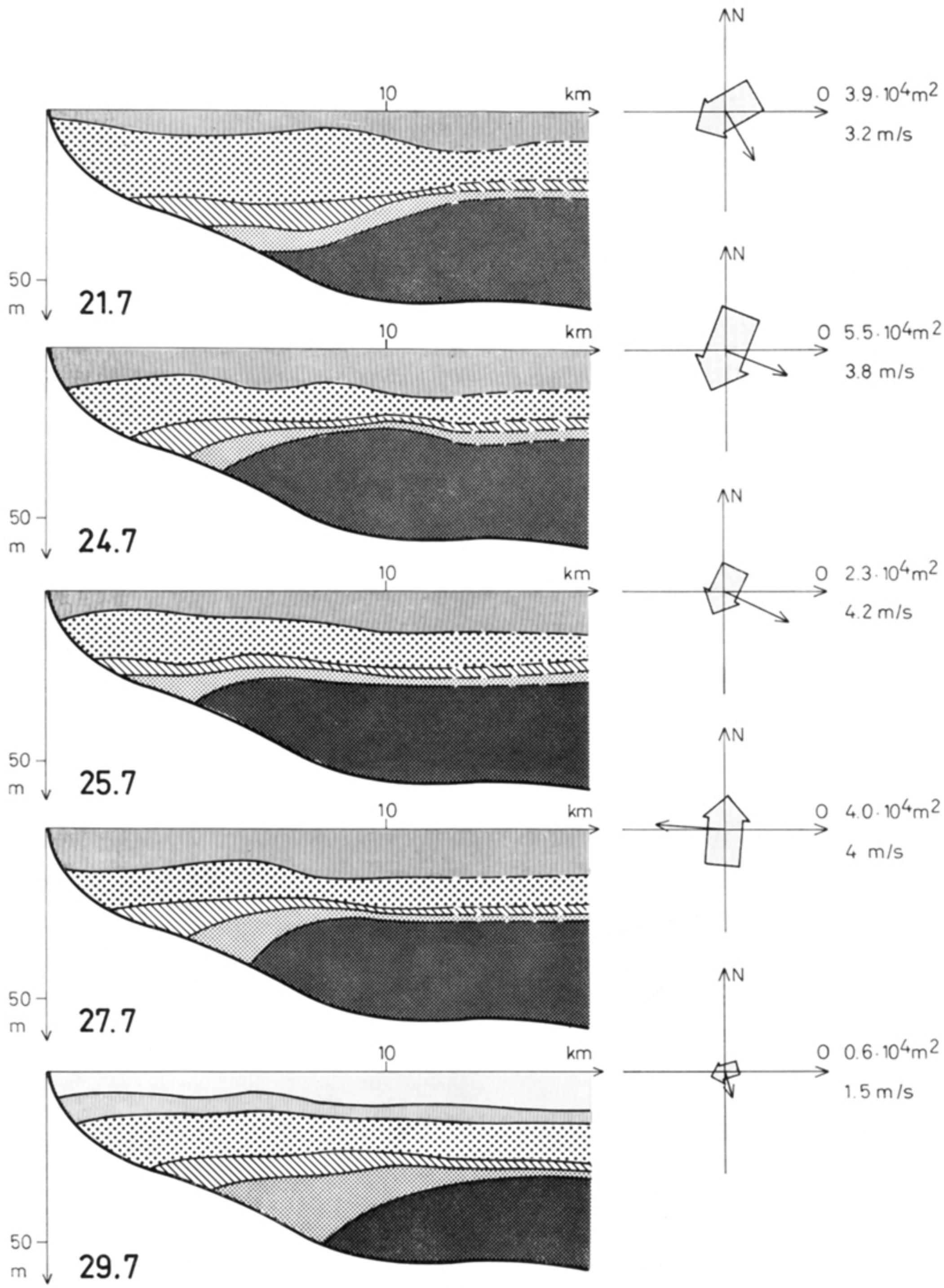

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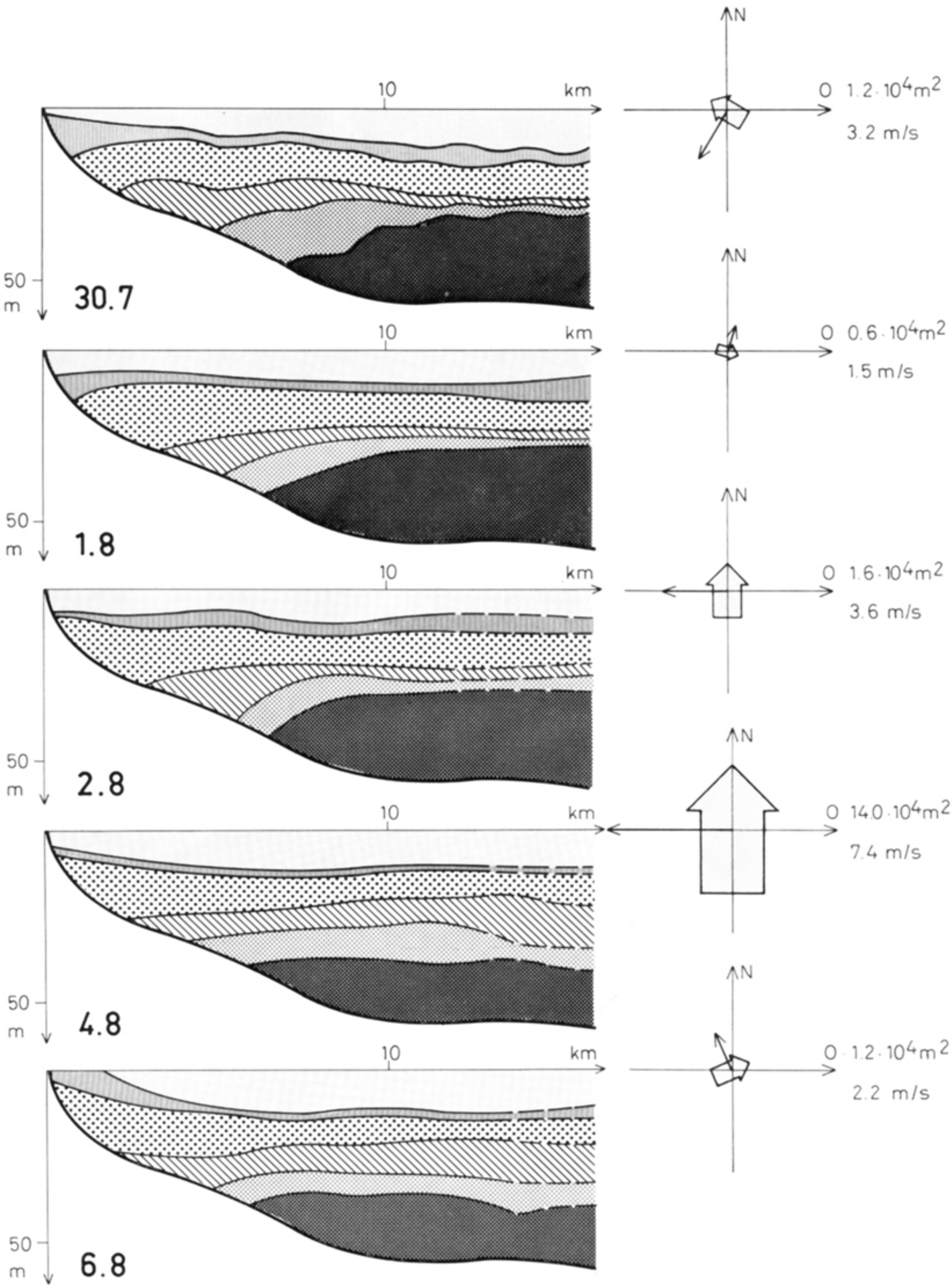
Fig. 5 c



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O 14.0·10⁴m²
7.4 m/s
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m
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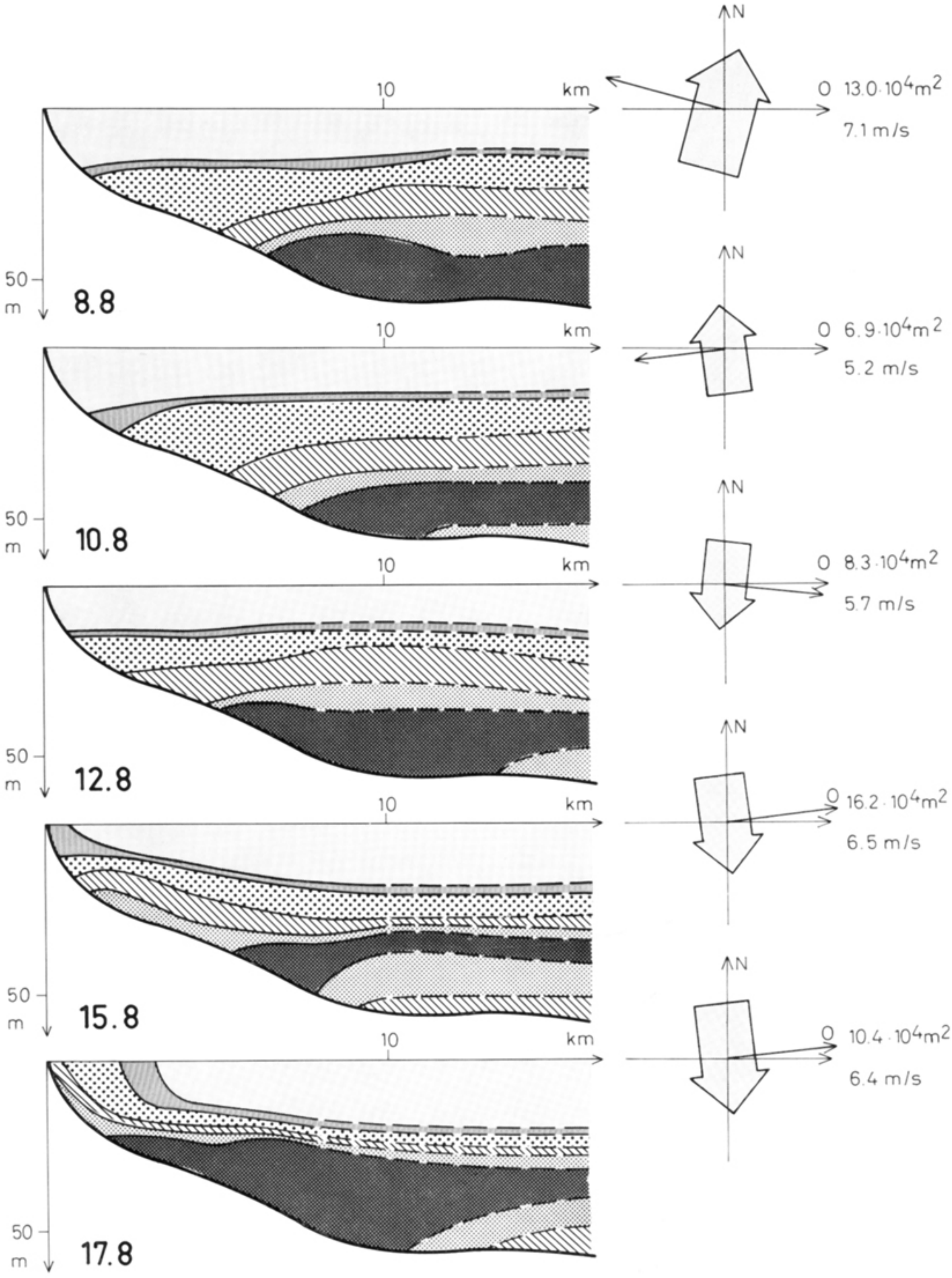
Fig. 5 d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5.7 m/s
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6.5 m/s
15.8
O 10.4·10⁴m²
6.4 m/s
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Fig. 5e

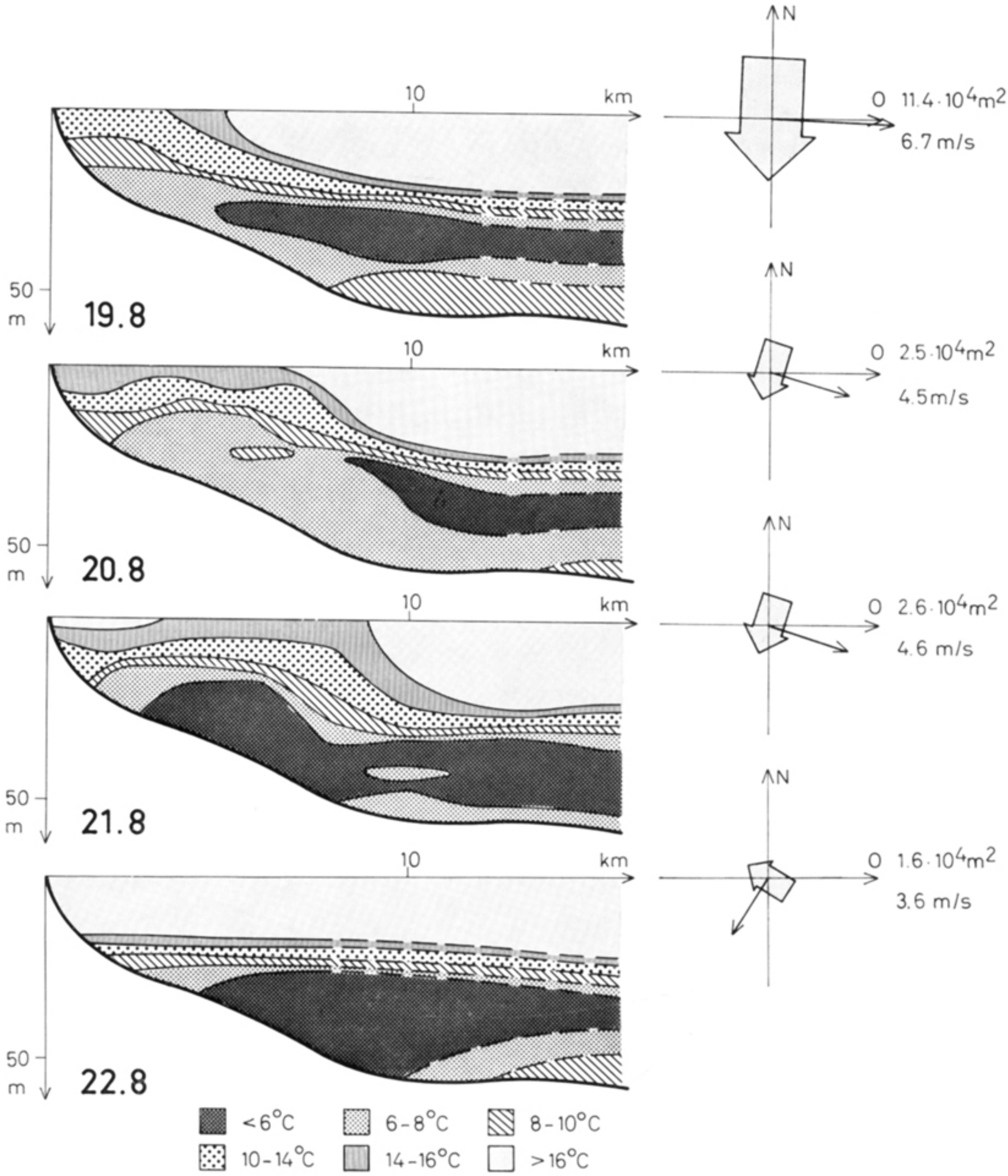

Fig. 5 f

where $\boldsymbol{\tau}$ is the windstress, $\mathbf{v}$ the wind vector, ϱ the density of sea water and α a non-dimensional constant approximately equal to $1.75 \cdot 10^{-6}$ (Svansson, 1966).

According to Ekman theory (Ekman, 1905) we have

$$\mathbf{M} = (f\varrho)^{-1}\boldsymbol{\tau} \times \mathbf{k} \tag{2}$$

where $\mathbf{M}$ is the wind-transport (volume/unit length and time), f is the coriolis parameter ($f \simeq 1.2 \times 10^{-4}$ sec^{-1} in the southern Baltic) and $\mathbf{k}$ is a vertical unit vector. From (1) and (2) we obtain an expression for the total transport during a certain time, $T = t_2 - t_1$,

$$\int_{t_1}^{t_2} \mathbf{M}\, dt = \alpha T f^{-1} \left| \mathbf{v}_T \right| \mathbf{v}_T \times \mathbf{k} \tag{3}$$

where $$|\mathbf{v}_T|\,\mathbf{v}_T = \frac{1}{T}\int_{t_1}^{t_2} |\mathbf{v}|\,\mathbf{v}\,dt$$

The magnitudes and directions of this integrated transport, calculated for the time intervals between consecutive temperature sections, are presented in Fig. 5 (see caption also). For example, the broad arrow to the right of the section dated the 16.7 represents the transport integrated between the 14.7 and the 16.7. The magnitude of this integrated transport is proportional to the area of the arrow and the scale-factor has been chosen to make it easy to estimate from the size of the arrow the possible effect on the temperature structure. Thus, 1 cm^2 of the arrow represents roughly 10^5 m^2 while 1 cm^2 in the section corresponds to 0.5×10^5 m^2. The wind-vector represented by the thin arrow is the "equivalent constant wind speed" $\mathbf{v}_T$ (see equation 3).

The development of the daily mean windstress components are given by Figs. 4*b* and *c*.

4. Discussion of observations

4.1. *The "off shore" thermocline*

During the measuring period the "off shore" thermocline changed slowly, as illustrated in Fig. 4*a*, essentially becoming deeper and stronger. In the beginning of the period the effect of the strong wind around the 8.7 can be seen, mixing the surface layer and thus temporarily lowering the surface temperature. At the end of the measuring period a reversal of the temperature gradient develops below the main thermocline. This phenomenon, of course, is associated with the development of a vertical salinity gradient and may be understood as follows: A slow mixing of the water in the layer (0–50 m) with more saline and warmer (i.e. warmer than the lower part of the layer 0–50 m) water from levels below 50–60 m depth is going on continuously in the Baltic. During winter conditions this water is quickly mixed with the whole surface layer. This is no longer the case, however, with a protecting thermal stratification on the top of the system, as in summer conditions. We thus expect a stable salinity gradient and a reversed temperature gradient to build up below the thermocline towards the end of the summer.

4.2. *The coastal temperature perturbations*

It is thought that the following qualitative conclusions may be drawn from the observations presented in Figs. 4 and 5.

(i) The temperature fluctuations are generally an order of magnitude stronger closer to the coast than further out. The length scale characterizing the decay with distance from the coast is roughly 5 km.

(ii) These coastal temperature fluctuations are driven by the surface transports associated with variable winds.

(iii) The coastal temperature variations are essentially modified by Kelvin-type internal wave motion along the shoreline.

(iv) The near shore (or bottom) mixing associated with the vigorous internal activity along the coast may be of primary importance for the whole hydrographic system.

We will discuss the above conclusions only briefly, hoping that the reader will make his own independent evaluation of the observational material.

The conclusion (i) is not strictly a consequence of Fig. 5 since many of the temperature sections have, in fact, been extrapolated on the basis of an assumption equivalent to (i). However, many more observations of the "off shore" temperature variations have been made, during this measuring period as well as on other occasions, and none of these show temperature variation amplitudes comparable with those observed in the coastal region.

With regard to conclusion (ii) we may compare the amplitude of the coastal temperature variations with the amplitude of the windstress in a number of reasonable ways. (For example, the area swept by an intermediate-depth isotherm may be compared with the integrated wind transports perpendicular to the coast.) Such considerations show that the amplitude of the coastal internal perturbations have a strength which may be accounted for by windstress forcing and, furthermore, that strong temperature variations occur simultaneously with strong winds.

(iii) A preliminary inspection of Figs. 4 and 5 suggests that the coastal response is best correlated with Ekman transports parallel to the coast; i.e. with winds perpendicular to the coast. For example, the periods of "upwelling" around the 8.7 and 19.8 are both associated with offshore winds. This seems to indicate that the

Ekman theory is not even qualitatively useful for predictions of the wind drift. Such a result is indeed hard to accept.

We recall, however, that according to Walin (1972) we can expect perturbations in the coastal region to move southwards along the coast with the internal wave speed (0.5 m/s). This means that a perturbation created outside Ronneby, for example, (see Fig. 1) will reach the measuring location within approximately two days—a time which is not long compared with the time scale of the weather systems. If transport of information along the shore is taken into account, therefore, we find, from a second inspection of Figs. 4 and 5, that our observations are qualitatively compatible with Ekman theory. For example, the cold surface water observed during the period of strong westerly winds from the 15–21.8 may be thought of as "created" in the neighbourhood of Ronneby where the "Ekman wind drift" was roughly perpendicular to the coastline.

We may also point out here that the resonance conditions for the internal Kelvin waves, $L/T \sim C_i$ (Walin, 1972), where C_i is the internal wave speed, T the meteorological time scale and L the length scale of the coastline, requires $T \sim 3$ days if L is chosen as the distance along the coast between "Utklippan" and "Sandhammaren" (see Fig. 1). We can see that the natural time and length scales may frequently satisfy the resonance condition. Thus we have good reasons to suggest that Kelvin type wave motion along the coast is of primary importance for the local internal response.

(iv) It is a dominating feature of almost all the temperature sections in Fig. 5 that the spacing between the isotherms become larger when approaching the coast. This means that water of intermediate densities are more abundant in the near shore region. This is precisely the most likely qualitative result of intense, near-shore vertical mixing, since any type of mixing is bound to produce water of an intermediate density. The relative importance of this coastal mixing as compared with other types of vertical exchange is still an open issue, however.

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НЕКОТОРЫЕ НАБЛЮДЕНИЯ ФЛУКТУАЦИЙ ТЕМПЕРАТУРЫ В ПРИБЕРЖНОЙ ОБЛАСТИ БАЛТИЙСКОГО МОРЯ

Представлены результаты двухмесячных почти ежедневных наблюдений изменений температуры в прибрежной части Балтийского моря. Найдено, что результаты согласуются с теоретическими предсказаниями (Валин, 1972, Чанади, 1968). В частности, мы наблюдали изменения температуры большой амплитуды в области, простирающейся от берега на 5–10 *км*. Хотя это окончательно не доказано, представляется, что эти возмущения распространяются вдоль берега как внутренняя волна Кельвина.