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AN EXAMPLE OF A VELOCITY JUMP ACROSS THE SUMMER THERMOCLINE

by

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Abstract

Vertical gradient of horizontal velocity across the summer thermocline in the Bothnian Sea is estimated from observations of horizontal velocities in the upper and lower layers of a seasonally stratified sea. Vertical gradient of horizontal velocity of about $3 \cdot 10^{-2} s^{-1}$ was observed in normal summer weather conditions.

1. *Introduction*

During the summer strong seasonal thermocline, which is also a pycnocline, develops in the Bothnian Sea. This forms also a more or less two layer situation in the density stratification. The thermocline forms a strong velocity shear layer, where horizontal velocity suddenly drops with increasing depth. Knowledge of the shear is important for the mixed layer deepening problems. When the shear is large enough, Richardson number $Ri = (g/\rho)(\partial\rho/\partial z)/((\partial u/\partial z)^2)$ drops under the value 0.25 and instability can occur and internal waves break. Shear flow instabilities are reported to be occasionally present in the seasonal thermocline (EVANS 1982, KRAUSS 1981).

Real observations of velocity profiles are needed for verification of numerical two-layer models, as well as also if one-layer models are used for crude estimations of currents. Profiling velocity sondes make it easy to measure the velocity profiles throughout the whole water column. In our study, however, such instruments are not used. Our observations are indirect in the sense, that they are derived from a single moored current meter, which was in the thermocline region and recorded part of the time upper layer velocity field and part of the time lower layer velocity field.

2. *The experiment*

The observations used here are a by-product of a Nordic cooperation project EROS (Erosion and sedimentation study) in the Bothnian Sean (which is a part of the Baltic Sea). The purpose of the experiment was to study the turbidity layer, which exists in the deep layers in the Bothnian Sea. Current measurements were done by Aanderaa RCM-4 recording current meters at two sites about 25 km out off the west coast of Finland. Also two thermistor chain sites were in use. The sampling interval of all of the moored instruments was 10 minutes. CTD-ĉasts were done from R/V Aranda in the area during the experiment.

The moored instruments were operating from 19th of July to 3rd of August 1978. The observations analysed in this study are from 23rd of July. The thermocline was above the uppermost current meter, which was at 13 m depth, from midnight to 6.50 am, then the thermocline suddenly sank within half an hour below the current meter for 5.5 hours and rose then back again (Fig. 1). During this event the current meter at 13 m depth registrated thus two different current fields, which are interpreted to be the upper layer and lower layer current fields.

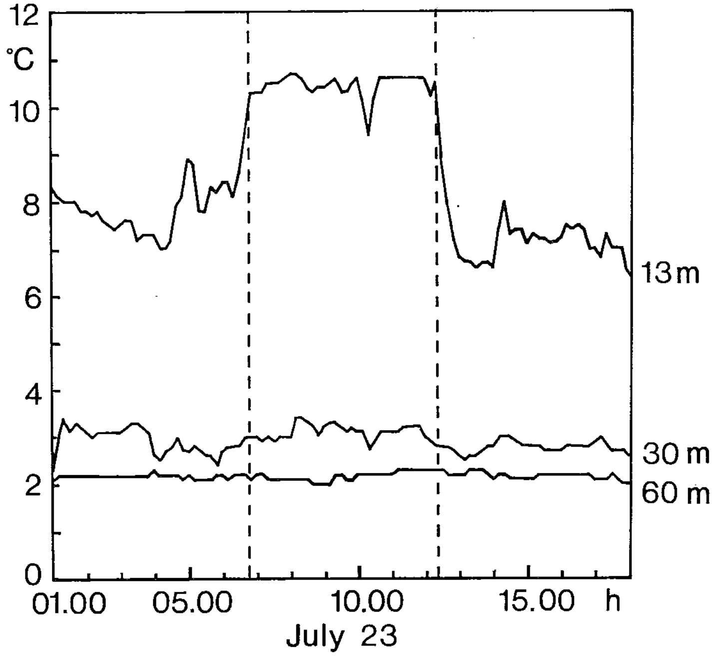

Fig.1. Temperatures registrated by the current meter thermistors at 13, 30, and 60 m depth. The upper layer situation is marked with dashed vertical lines.

Other two current meters at the same vertical were at 30 m and 60 m depths. We analyse here the observations of the one vertical where this phenomena was more clearly seen. This site is located at 61°19′N, 20°54′E.

3. *Meteorological and hydrographic conditions during the study*

Meteorological data, that is only wind speed and direction, are from the Mantyluoto pilot station at the coast of Finland. Standard meteorological observation

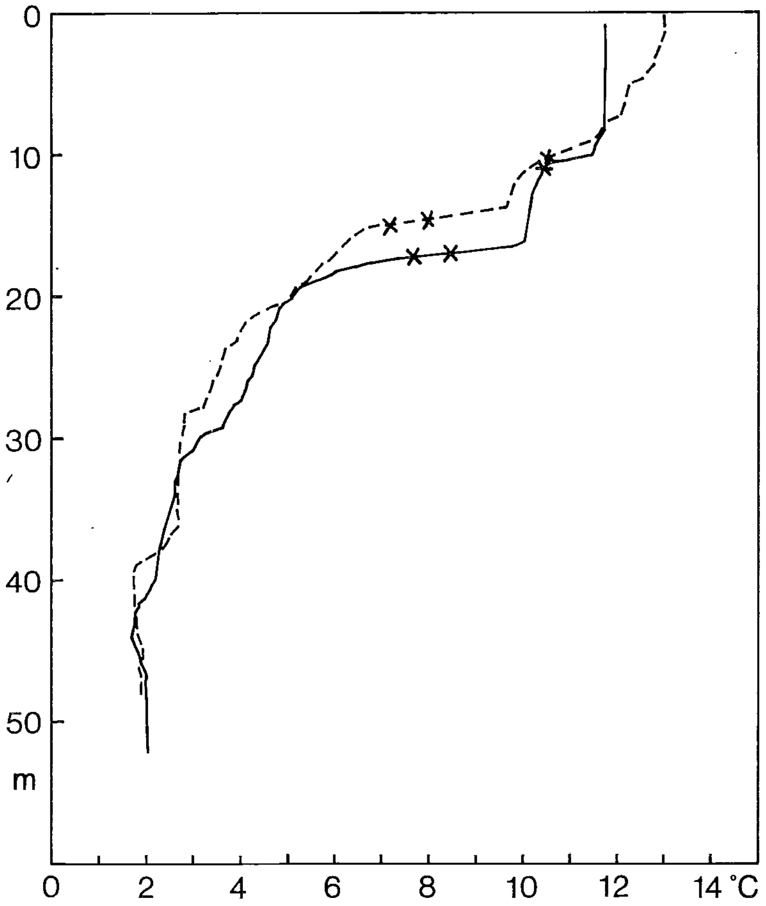

Fig. 2. Temperature profiles near the current meter site at July 20 (dashed line) and 24 (continuous line). The stars at the profiles indicate mean temperatures of the 5.5 hour observation periods.

times were used. The winds were moderate during the days before the event. The wind blowed from south-east and wind speed was about 10 m/s during July 21 and 22. The wind direction changed during the night and morning of July 23 to south-south-west and at noon back to south-east.

A lot of CTD-casts were done during the EROS-experiment, but unfortunately not at the most interesting day of this study, the 23rd of July, because of the week end, when the ship had a port-call. To increase our unluck (and decrease the accuracy of this analysis) considerable changes had occurred in the hydrography between the dates of CTD-casts near the current meter site (these dates are July 20 and 24). At July 20 the thermocline depth was 15 m (Fig. 2), but the temperature decreased almost continuously from 13 °C at the surface to 10 °C at 15 m depth and to 5 °C at 20 m depth. Stronger winds during July 21 and 22 caused strong mixing and the shape of the thermocline sharpened. A secondary thermocline was formed above the main thermocline. At July 24 the surface temperature was 11.7 °C and the upper layer till 10 m depth was homogeneous. At 10 m depth the temperature dropped to 10.25 °C and was constant to about 16 m depth, where the main thermocline was. The lower layer temperatures remained unchanged. The temperature structure determined wholly the density stratification in the upper 50 m deep layer which was isohaline.

4. *Current velocity observations*

The temperature records of the current meter at 13 m depth clearly showed when the thermocline (or rather a part of it) passed by the current meter (Fig. 1). The thermocline sank and rose quite rapidly (in 10–30 minutes) to a new stable position at both ends of our »upper layer» observation period. This could be waited for due to the very two-layer nature of the stratification.

Inertial oscillations were present during the whole EROS-experiment, but the strong winds during July 21 and 22 lasted suitably long to damp somewhat the amplitude of these oscillations. During the day of this analysis, July 23, quite strong mean current to south-south-west was present, but the current speed was decelerating slowly during the day. Current speeds at 13, 30 and 60 m depths are shown in Figure 3.

The strong vertical component of velocity, which made possible this analysis is probably associated to these strong inertial oscillations. As pointed out by KRAUSS (1981) in a study from the southern Baltic Sea, the vertical component of velocity must exist in such areas due to the boundary condition $w = u(\partial H/\partial x)$ at the bottom $z = H(x)$. In our case $\partial H/\partial x \sim 10^{-3}$, $u \sim 15$ cm/s and thus $w \sim 15 \cdot 10^{-3}$ cm/s corresponding vertical displacements of about 3.5 m during half an inertial period.

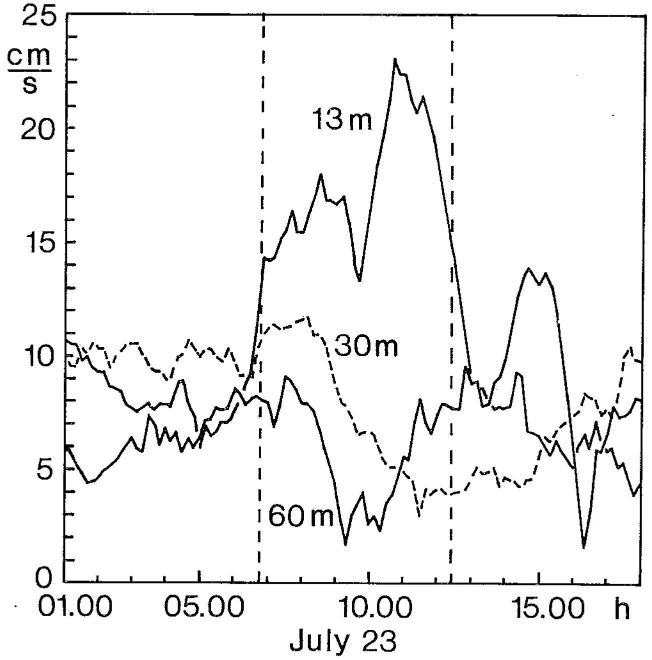

Fig. 3. Current speed at 13, 30 and 60 m depths at July 23, 1978. The upper layer situation is marked with dashed vertical lines.

Observations with quite similar two-layer fluid situation with inertial oscillations are reported also by Millot and Crépon (1981) from the Mediterranean, from Gulf of Lions. The vertical component of inertial oscillations in the Bothnian Sea was estimated by the author (Alenius, 1982).

The observation period of the 23rd of July was divided to three equally long 5.5 h parts. The first and third of these parts represent the »lower layer» currents and the part in the middle represents the »upper layer» current field. This upper layer is at least part of the time actually the layer between the main and secondary thermoclines. The current speeds during the first and third parts are reasonably similar to each other (Table 1) showing quite stationary lower layer. The speed was considerably higher during the middle part, although it was not as stationary as during the first and third parts.

The velocity jump across the thermocline is estimated by using the mean values of the 5.5 h long observation periods (from Table 1). The standard deviations (Table 2) of the speed during the different »periods» indicate quite stationary conditions which gives justification for the use of mean values. The current vectors

Table 1. Mean temperature, speed and velocity components and velocity vector during the 5.5 h long study periods.

Period	t °C	speed	u cm/s	v	$\lvert\vec{v}\rvert$	ϕ
1	7,86	8,29	0,22	–6,96	6,96	178
2	10,44	17,51	–2,82	–14,88	15,14	191
3	7,17	7,14	–6,12	–0,58	6,15	265
all	8,49	10,98	–2,91	–7,48	8,03	201

Table 2. Standard deviations of temperature, speed and velocity components during the study.

Period	t	speed	u cm/s	v
1	0,55	1,22	4,47	1,52
2	0,24	2,75	8,78	3,12
3	0,45	2,22	2,09	3,76
all	1,48	5,13	6,32	6,57

are decomposed to components u to the east and v to the north.

The change in current direction with inertial oscillations is seen in the velocity components. In order to estimate the vertical gradient of the horizontal velocity we must have some vertical separation of the observations. Because the current meter was whole the time at a constant depth, the vertical separations of the observations must be estimated from the temperature profiles of the CTD-casts at July 20 and 24. We can also bear in mind the vertical displacement 3.5 m estimated from the vertical velocity estimate. The mean temperature of the observation periods 1–3 are converted to »quasi» depths with the temperature profiles. Thus from the profile of July 20 we get an estimate 2–3 m and from the profile of July 24 about 5–6 m for the vertical separation of the upper and lower layer current observations. These together with the former estimate 3.5 m fall all in the same range. These estimates are of course quite inaccurate, but give still correct insight to the situation because of the very steep thermocline (Fig. 2).

To get a lower limit estimate for the velocity gradient we take the smallest velocity (speed) difference ($\Delta|\vec{v}| = 9.22$ cm/s) and largest vertical separation estimate ($\Delta z = 6$ m), and similarly for the upper limit estimate the largest velocity difference ($\Delta|\vec{v}| = 10.37$ cm/s) and smallest vertical separation estimate ($\Delta z = 2$ m). Thus we get

$$1.5 \cdot 10^{-2}\,\mathrm{s}^{-1} \leqslant \Delta|\vec{v}|/\Delta z \leqslant 5.2 \cdot 10^{-2}\,\mathrm{s}^{-1}$$

and for the velocity components

$$0.5 \cdot 10^{-2}\,\mathrm{s}^{-1} \leqslant \Delta u/\Delta z \leqslant 1.7 \cdot 10^{-2}\,\mathrm{s}^{-1}$$

$$1.6 \cdot 10^{-2}\,\mathrm{s}^{-1} \leqslant \Delta v/\Delta z \leqslant 7.2 \cdot 10^{-2}\,\mathrm{s}^{-1}$$

Using the data from current meters at 13, 30 and 60 m depths as such, we get at most (between 13 and 30 m depths) $\Delta|\vec{v}|/\Delta z = 0.6 \cdot 10^{-2}\,\mathrm{s}^{-1}$ and on the average $\Delta|\vec{v}|/\Delta z = 0.2 \cdot 10^{-2}\,\mathrm{s}^{-1}$. Between 30 and 60 m depths the figures are $\leqslant 0{,}1 \cdot 10^{-2}\,\mathrm{s}^{-1}$ at most and $\leqslant 0.1 \cdot 10^{-2}\,\mathrm{s}^{-1}$ on the average. Thus we see that vertical gradient of horizontal velocity through the thermocline is an order of magnitude greater than in the lower layer. This is also confirmed by observations with the simple pendulum current meters. Thus the velocity drops 1.5–5.2 cm/s/m across the thermocline region and only less than 0.1 cm/s/m in the lower layer.

Using our velocity gradient estimates, we see that the Richardson-number is near to 1. The calculations of EVANS (1982) show, that the value $Ri = 1$ is a preferred value, which is confined in vertical extent <4 m, which is also our case.

5. *Discussion*

Vertical gradient of horizontal velocity was estimated quite grudely by using the observations of a single moored current meter. There are several sources of inaccuracies in this estimation. For example, the temperature profiles used in the estimation of the vertical separation of the current observations were even not from the same place and day than current observations. The estimation procedure was possible only because the current meter happened to be at a »right» depth and the thermocline oscillated due to strong inertial oscillations near the coast. In spite of the inaccuracies we still feel, that this kind of estimate is interesting in describing the clear two-layer nature of the currents during summer stratification. It can also be helpfull in interpretation of the results of one- and two-layer numerical model experiments. The data set analysed in this study is too limited for estimating the existence of instabilities and erosion of the thermocline for example.

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