

Horizontal Advection of Temperature in the Seasonal Thermocline during JASIN 1978

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ABSTRACT

The temporal changes in the low-frequency thermal structure during a two-week period in August–September 1978 are discussed from moored data collected during the JASIN experiment. While some changes in the thermal structure appear to be related to local winds, the dominant low-frequency variability in the seasonal thermocline can be explained as horizontal advection of a spatially varying temperature field, and associated thermal wind, by geostrophic currents with little vertical motion or mixing required.

1. Introduction

The International Joint Air-Sea Interaction study (JASIN 1978) took place north of the Rockall Trough about 450 km northwest of Scotland (Fig. 1). Nine nations joined for the field experiment from July to September, 1978. During two intensive observation phases up to 14 research ships and 4 research aircraft became involved. A comprehensive summary of the field phases has been made by Pollard (1978). Siedler and Zenk (1980) discuss the contributions from the Federal Republic of Germany. These include three research ships, one aircraft and three moorings consisting of self-recording current meters, thermistor chains and meteorological sensors. The intermediate mooring K1 with the uppermost instrument at 70 m depth covered the whole experiment from 9 July to 6 September. Mooring K2, a twofold tethered spar buoy with five Vector Averaging Current Meters (VACM) down to 110 m, together with mooring K3 carrying two vertical thermistor chains, recorded only during the second field phase (25 August–6 September). The two surface moorings K2, K3 were also equipped with Aanderaa wind recorders. Below we will use phase II data from three of the VACM's on K2 which were at 20, 60, and 110 m depth as well as the upper 14 temperature sensors on the "B" chain of K3 (see Fig. 2). The data have been filtered to remove internal wave oscillations. While some changes in the thermal structure in the upper 80 m appear to be related to local winds, the dominant process responsible for low-frequency variability of temperature in the seasonal thermocline below the

mixed layer can be identified as horizontal advection of a spatially varying temperature field.

2. Horizontal advection of temperature

In a technique similar to that applied to deep ocean data by Bryden (1976), we will now examine the effect of horizontal advection of temperature due to geostrophically balanced currents. Thus

$$\dot{T} + uT_x + vT_y = -\epsilon, \quad (1)$$

$$\left. \begin{aligned} \rho f u_z &= g \rho_y \approx -g \rho \alpha T_y \\ -\rho f v_z &= g \rho_x \approx -g \rho \alpha T_x \end{aligned} \right\}, \quad (2)$$

$$(u, v) = S(\sin \theta, \cos \theta), \quad (3)$$

where ϵ represents non-modeled terms due to local heating, vertical advection and mixing. We have assumed a proportionality between temperature and density gradients. If the salinity were constant the coefficient α in (2) would be $0.17 \text{ (}^\circ\text{C)}^{-1}$ for the seasonal thermocline in JASIN. An analysis of the slope of the T/S curves yields a value of $0.20 \text{ (}^\circ\text{C)}^{-1}$. This agrees with an independent estimate made for JASIN by McComas and Briscoe (1979). This approximation occasionally breaks down because of salinity-compensated intrusions and will be a source of error to be considered later.

Using the above set of equations we can obtain a relationship between the veering in the direction θ of horizontal currents with depth and the temporal changes in temperature:

$$S^2 \theta_z = g \alpha f^{-1} (\dot{T} + \epsilon). \quad (4)$$

This relationship will now be used to predict changes in temperature in the seasonal thermocline and compare them with those observed during the second phase of JASIN 1978.

3. Low-passed thermistor chain, wind and current data

The time series from mooring K3 have been filtered and are shown in Fig. 3. The deepest mixed layer occurred on 23 and 24 August and can be seen as a coalescing of the temperature series at the surface on 24 August. After the wind event this mixed layer was capped by another one but can still be traced through 28 August. Other examples of new deepening events due to wind increases (e.g., 5 September) can be seen in the records.

The most striking feature in the thermocline is the oscillation in the temperature records from 28 August through 1 September. This can be traced from the deepest instrument up to 36 m but has no obvious surface expression. We will show that this increase on 28 August followed by a rapid decrease on 30 August is due to advection of a "front" through the moorings K2, K3.

The low-frequency currents from K2 during phase 2 are shown in Fig. 4 in the form of a progressive vector diagram. During this period the currents at 20 and 110 m are largely to the southwest and parallel at both levels with the exception of 28 August when the deeper instrument veers to the left of the shallower and on 30 August when it veers to the right. One can also see that during this latter period the vertical shear is predominantly in the east-west direction.

4. Comparison of model and data

To illustrate the relationship in (4) we have used low-passed VACM data from K2 from 20, 60 and 110 m depth. The crudest approximation of (4) has been used in which the veering of the current has been estimated by differencing directions between the 20 and 110 m instruments, while using the speed and temperature from the 60 m level. This is formally valid if (4) is integrated vertically assuming speed and T to be independent of depth. Our knowledge of current variations is rather limited with only three instruments, one of which is at the base of the mixed layer and may be affected by frictional, Ekman-like dynamics. The thermistor chain could be used to integrate the thermal field down to 75 m but not below. Reference to Fig. 4 will show that temperature changes in the seasonal thermocline are often in phase at all depths below 30 m with a notable exception on 1 September when temperatures are increasing below 45 m and decreasing above. One might anticipate our crude approximation of (4) to be violated here.

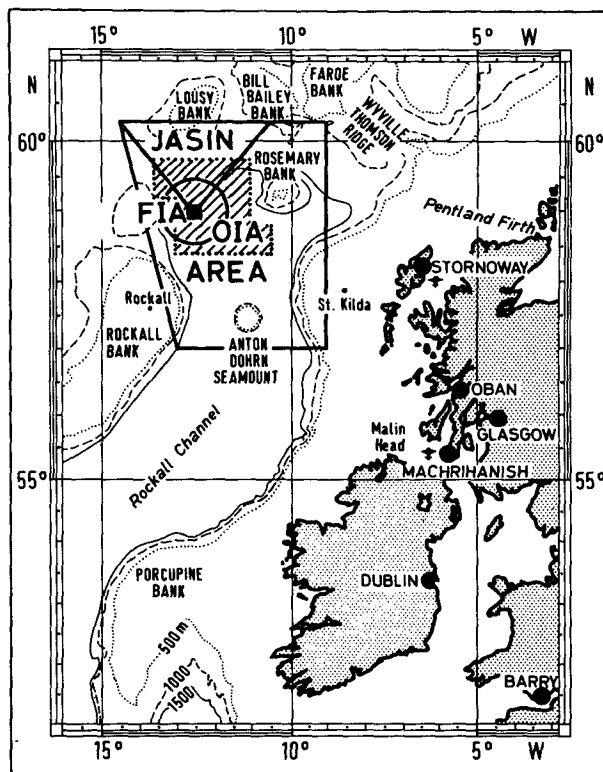


FIG. 1. Location of JASIN 1978. OIA = oceanographic intensive array, FIA = fixed intensive array. The experiment took place between 9 July and 6 September 1978.

In Fig. 5 we show the smoothed current and temperature time series from the 60 m level. The temperature reaches a maximum value the day of 29 August coinciding with the time when the current begins to swing from the south toward the southwest. A comparison of the 60 m temperatures in Figs. 3 and 5 will show a high degree of visual correlation with no phase lag; the two moorings were separated by only 1.5 km with an east-west orientation. The time at which the 60 m current swings from the south to the southwest and back is also associated with a large turning of the current with depth and a larger-than-average magnitude of the vertical shear. This latter quantity reaches a maximum of about $1.2 \times 10^{-3} \text{ s}^{-1}$ (Fig. 5, lowest panel) on 30 August. The observed and predicted rates of temperature change agree quite well during this event but diverge on 1 September. The overall correlation coefficient for these two series is 0.63, which is barely significant at the 90% level.

5. Discussion

In trying to interpret the degree of correlation between horizontal advection of temperature and the observed temperature changes at a point it must be mentioned that a perfect correlation was not

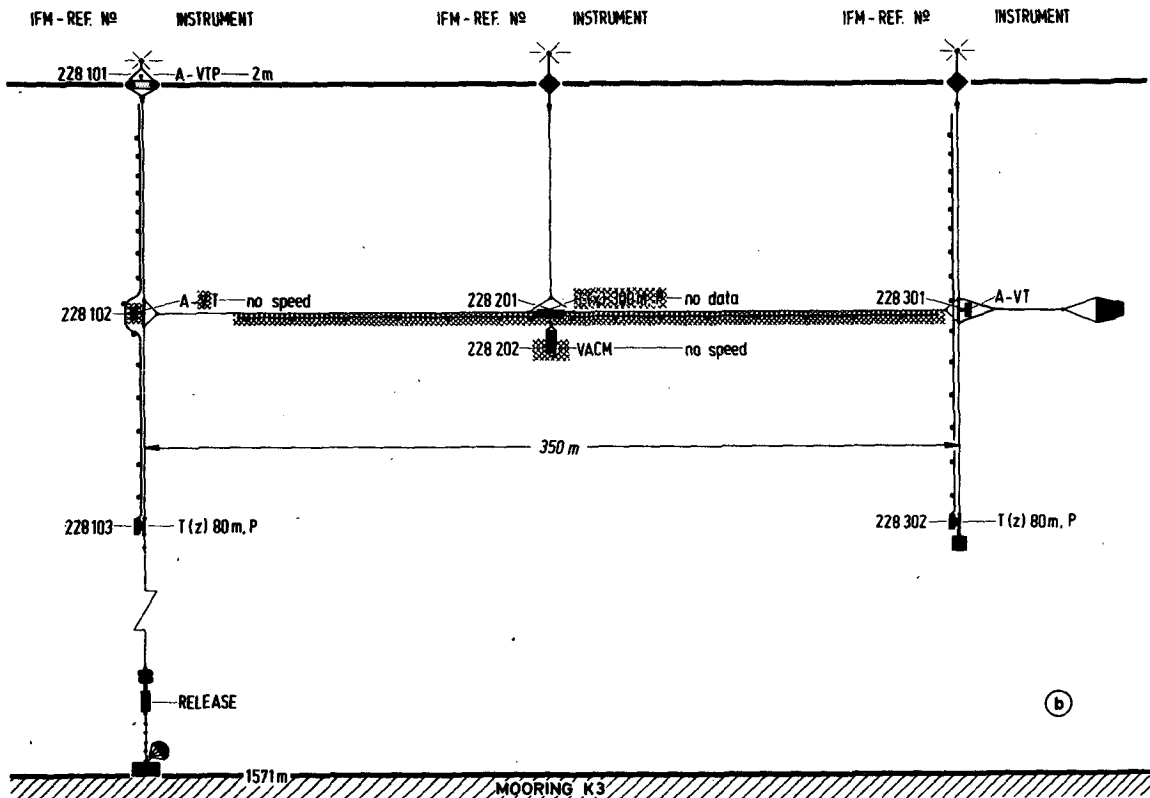
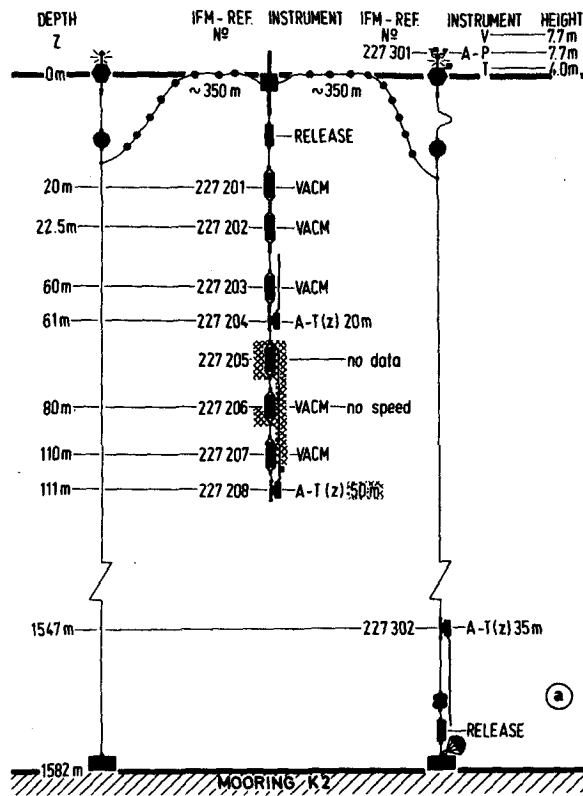


FIG. 2. JASIN moorings K2 (a) and K3 (b), two ingredients of the Fixed Intensive Array at 59°N, 12°30'W. At K2 a 17 m long spar buoy served as a platform for 5 VACM's. Temperature changes at the 60 m level together with current shear and veering between 20 and 110 m are discussed in the text. The low-passed time series of the meteorological recorder on the toroid of K3 are shown in Fig. 4. The distance between the two vertical legs was 350 m. The K2 spar buoy and the moored leg of K3 nominally were separated by 1.5 km.

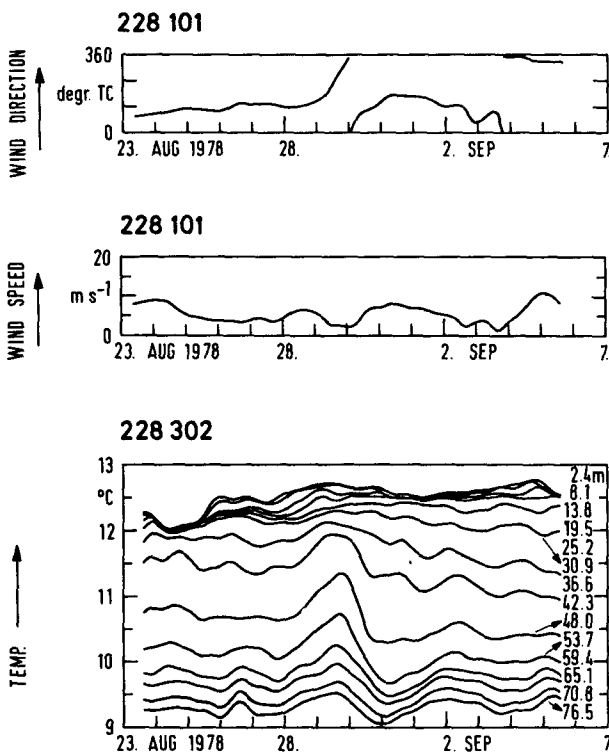


FIG. 3. Low-passed time series from mooring K3 during JASIN Phase II. Wind direction is shown in oceanographic notation (i.e., direction is that toward which wind blows).

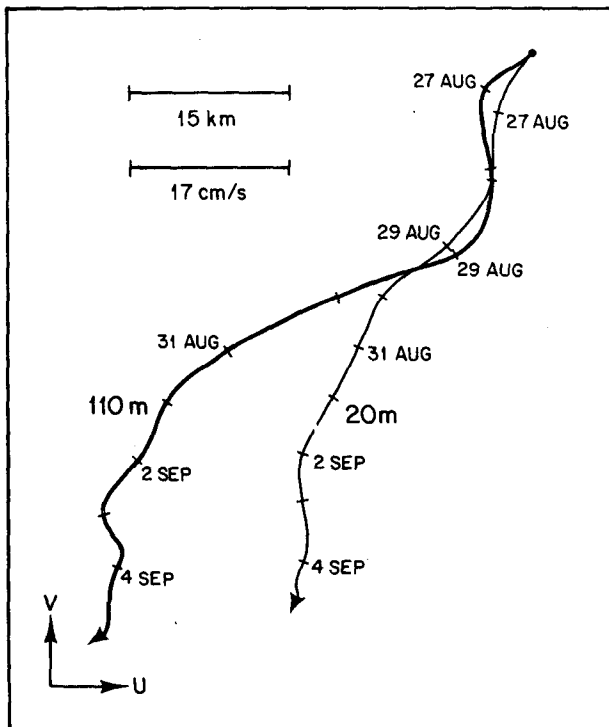


FIG. 4. Progressive vector diagram of low frequency currents at 20 and 110 m depth on K2.

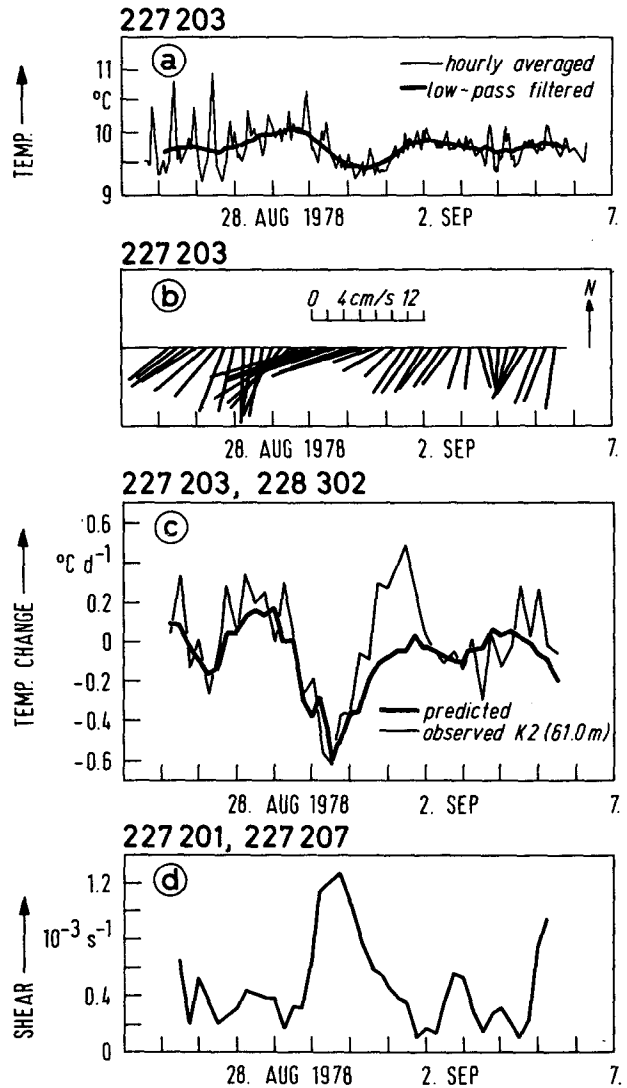


FIG. 5. Time series of VACM data from mooring K2, at 60 m, during JASIN Phase II. From top to bottom: (a) temperature, (b) low-passed current vectors, (c) observed and predicted (see text) temperature changes, and (d) magnitude of vertical shear between 20 and 110 m.

expected. One of the non-modeled terms is due to vertical advection. From the time-mean temperature profile obtained from the thermistor chain data (Fig. 3), we estimate a vertical temperature gradient of $\sim 0.04^\circ\text{C m}^{-1}$. In order to account for all of the difference between the observed and predicted temperature change in Fig. 5 on 1 September of $0.4^\circ\text{C day}^{-1}$, the vertical velocity would have to be 10 m day^{-1} . Preliminary estimates of wind stress curl over a JASIN meteorological triangle, 200 km on a side, yield vertical Ekman velocities of order 1 m day^{-1} (Trevor Guymer, personal communication) and therefore appear inadequate to explain all of the 1 September discrepancy.

A combination of shipboard CTD surveys and

moored data from an Aanderaa current meter with conductivity and pressure sensors at a depth of 70 m on K1, 1.5 km to the north of mooring K2, suggests that on 1 September a sub-surface intrusion was advected by K1. This intrusion was such that the effect of salinity variation on density nearly cancelled that of temperature, thereby violating our constant proportionality factor α in (4). We noted earlier that the 1 September interval was suspect because the deeper levels (Fig. 3) showed an increase in temperature, while above 45 m depth the temperature continued to decrease.

In order to improve quantitatively our ability to analyze the residual in (4) in terms of intrusions or vertical velocity, either the intrusions need to be averaged out by a vertical integration of (4) over a suitable depth interval or conductivity sensors must be added to moored instrumentation in the upper ocean. Nevertheless, the present data show that in the upper ocean horizontal advection of temperature is important and accounts for over 60% of the observed temperature changes during JASIN, phase 2.

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