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# Correcting false thermistor string data

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**Abstract**—In order to monitor the temperature variability over the total water column in a stratified shallow sea, a thermistor string was suspended from a moored loosely tethered surface buoy. Some of the temperature data manifested strong first tidal harmonic variability and unrealistic thermocline deepening. It is shown that the string lifted under the action of horizontal buoy displacement. Although the data may be corrected by using additional pressure or tilt sensors, a method is given to detect and correct them using current data, some simple arguments for buoy displacement under drag force and cross-spectral information from the first harmonic tidal band. The method proves adequate, as has been verified using temperature data measured at a nearby sub-surface mooring and some CTD information. Copyright © 1996 Elsevier Science Ltd.

## 1. INTRODUCTION

In a seasonally stratified shelf sea, the temperature variability may look like Fig. 1(a), which was obtained from thermistor strings moored in the central North Sea. A wind mixed surface layer is separated from a tidally mixed near-bottom layer by a strong thermocline. Typical characteristics of the vertical displacements of isotherms are obvious, such as the deepening of the main thermocline during intensified wind mixing in late summer and the broadening and shallowing of it after the passage of a front (e.g. near day 235). This synoptic scale variability is strewn with variations at tidal frequencies, which may indicate internal wave motions or a manifestation of the advection of fronts (Haren and Maas, 1987).

The occurrence of increased higher harmonic tidal variability ($\sim M_4$, between days 238 and 244 and between 248 and 257) raises some doubts about the correctness in physical terms of parts of the measurements. Although one could imagine mechanisms driving higher tidal harmonics to resonance (wave–wave interaction or non-linear forcing), the data are more likely an image of advective properties, not only in the horizontal plane but also, artificially, in the vertical plane. The latter is possible for data obtained from a thermistor string suspended from a loosely tethered surface buoy as opposed to those from a well-designed taut wire sub-surface mooring.

As the mooring is subject to drag forces imposed by currents, its horizontal displacement may result in thermistor string lifting. This type of suspended mooring configuration was used (although somewhat improperly, as will become clear later) to obtain the data shown,

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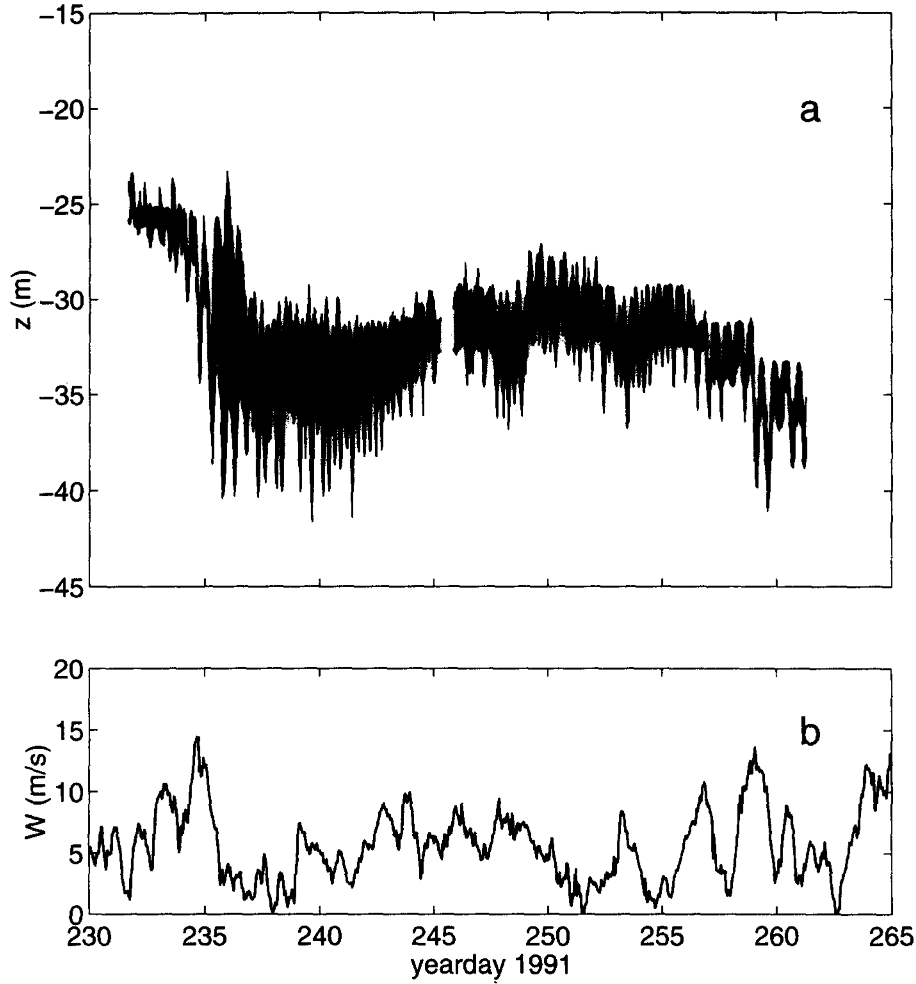


Fig. 1. Thermocline depth variations as a function of time obtained from thermistor strings suspended from a surface buoy in the central North Sea (54°25'N 04°02'E) during late summer 1991. Day 243 = September 1. (a) The shaded area represents the thickness of the thermocline between 13 and 16°C. The data gap at day 245 is due to mooring servicing. (b) Wind speed measured at a stable platform (K13) located approximately 100 km to the southwest of the moorings.

as it was the only means to monitor the water column from surface to bottom and at the same time minimizing the risk of mooring loss due to surface wave action. Due to the impact of the latter, taut wire moorings can not be used safely within a distance of about 10 m from the surface, thus disabling the monitoring of a substantial part of the water column in continental-shelf seas.

This note is an account of the discrimination between physically realistic and 'false' temperature records, and suggestions will be made for repairment of the latter, specifically for the data shown in Fig. 1. As the exact motions of the individual sensors relative to a fixed position in the water column are irretrievable, emphasis will be on the most successful but simplest means of correction. In any case, at least one additional set of data is required (pressure, current or fixed depth temperature).

## 2. DATA ACQUISITION AND ENVIRONMENTAL CHARACTERISTICS

Monitoring thermal structure variability is a vital element of the Integrated North Sea Project (INP) on the study of diapycnal fluxes under atmospheric and tidal forcing. Focus is on the synoptic variations with time of the potential energy content as they reflect mixing events induced by such forcing, using temperature as tracer, as opposed to internal (wave) breaking. Hence, loss of data from thermistor strings should be avoided by all, realistic, means. During INP, several moorings holding different types of instrumentation were maintained at a single site in the central North Sea at 54°25′N, 04°02′E, where the water depth is 45 m.

The location was chosen to be, at least on average, well within a part of the North Sea that becomes thermally stratified in the summer, but fronts separating the stratified from well-mixed waters approach the site occasionally (Aken *et al.*, 1987). The major tidal component is semi-diurnal ($M_2$) and tidal current amplitudes are typically 0.3 m $s^{-1}$. Away from frictional boundaries the current ellipse is almost rectilinear and the major axis is aligned in the E–W direction. Surface elevations due to tides have a typical amplitude of about 0.5 m. Of the total data set collected during the summers of 1991–1993 and the full year of 1994, mainly those obtained in 1991 will be discussed, as the thermistor string mooring configuration was changed after that.

Two standard Aanderaa 20-m thermistor strings, each holding 11 thermistors at intervals of 2 m, were coupled, thus monitoring between 2 and 43 m depth. This string was suspended from a surface buoy, which was fixed to an anchor using a 7-mm coated steel line of 60 m length approximately, to provide sufficient slack to allow for surface wave action. The thermistor string was kept suspended by its weight of about 30 kg and, in retrospect erroneously, by attaching the string to the mooring line using nylon fixations ('tie-wraps'). A diamond shaped cylindrical 'spar' buoy was used, 3 m in length (without the mast) and between 0.4 and 0.6 m in diameter. A balancing 150 kg weight made the buoy sink by about 1.3 m below sea level.

A second mooring was located approximately 300 m away and included two standard NBA current meters, carrying temperature sensors, at about 11 and 36 m depth. This sub-surface mooring was designed for minimal deflection upon the action of prevailing currents, and a conservative estimate of the maximum vertical displacement is 0.1 m during periods of moderately strong winds. The accuracy of the temperature sensors from both types of instrumentation was typically 0.1°C. The sampling intervals were 7.5 and 15 min for current meters and thermistor strings, respectively. Hence, scales larger than fine structure were adequately resolved. The sensors were calibrated against CTD observations, which were made during the bi-weekly cruises for instrument inspection and redeployment of the moorings.

## 3. DETECTION AND CORRECTION OF ARTIFICIAL THERMISTOR STRING DATA

In this section attention will be focused on the period between days 235 and 242, during which the thermocline seems to cover the depth of the lowest current meter (at 36.5 ± 0.5

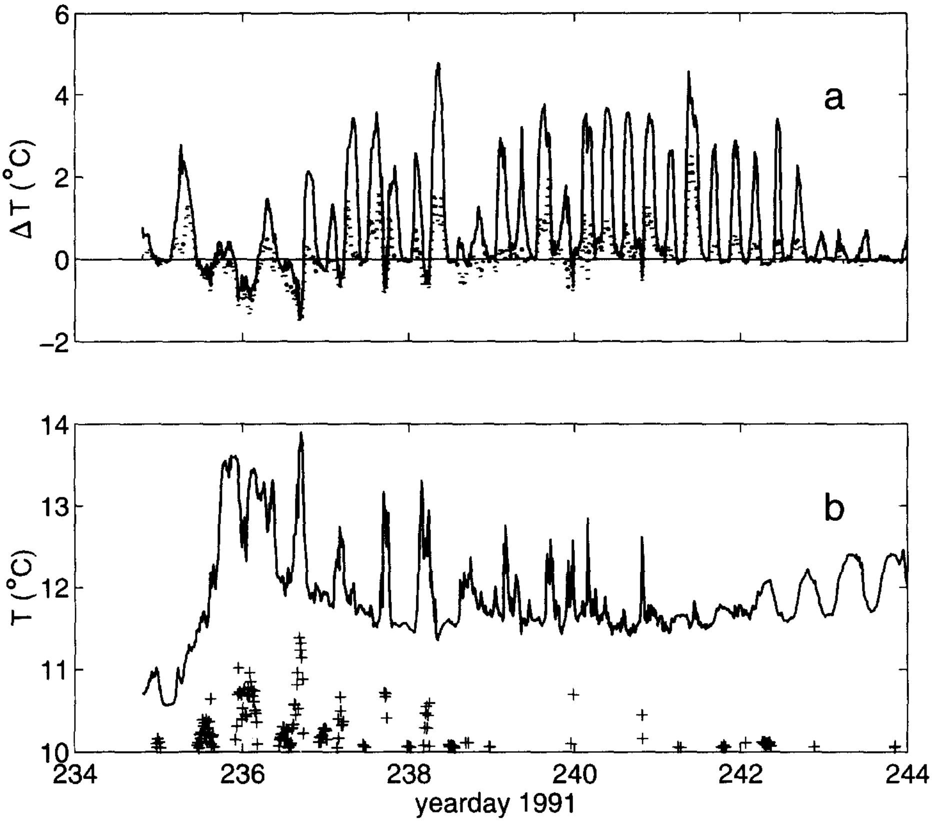


Fig. 2. (a) Temperature difference between the current meter sensor and the associated thermistor string sensor at 36 m depth, before (solid line) and after (dotted line) correction (cf. section 3). (b) Temperature measured at the current meter (solid line) and data points (+) for which the temperature measured at the current meter was larger than at the corresponding thermistor. The scale for the latter is offset by 10°C.

m) and hence an additional, differently moored, sensor is available for comparison [Fig. 1(a)]. Prior to analysis the fixed depth of the current meter was transposed into a record of depth variations with time using a record of sea-level variations to match the 'free floating' thermistor string sensors. For the area and period of study this correction was generally small as even during periods of stronger winds sea level variations about their mean were never larger than 0.8 m. It may be necessary, however, in other regions. The horizontal distance between the two moorings is of no relevance in the subsequent analysis, as will become clear shortly.

In comparison with the current meter temperature sensor, the corresponding thermistor string sensor generally shows higher temperatures, up to a difference of 5°C (Fig. 2). Such large values are unrealistic when translated into a horizontal temperature gradient, using the mooring distance, and associated vertical current shears of O(0.1) $s^{-1}$ were not observed. Hence, the possibility of frontal advection is ruled out for explanation, even though it is important to second order, as is clear from the current meter temperature record which shows tidal variations of 0.3–1.0°C amplitude, notably near day 236. Except

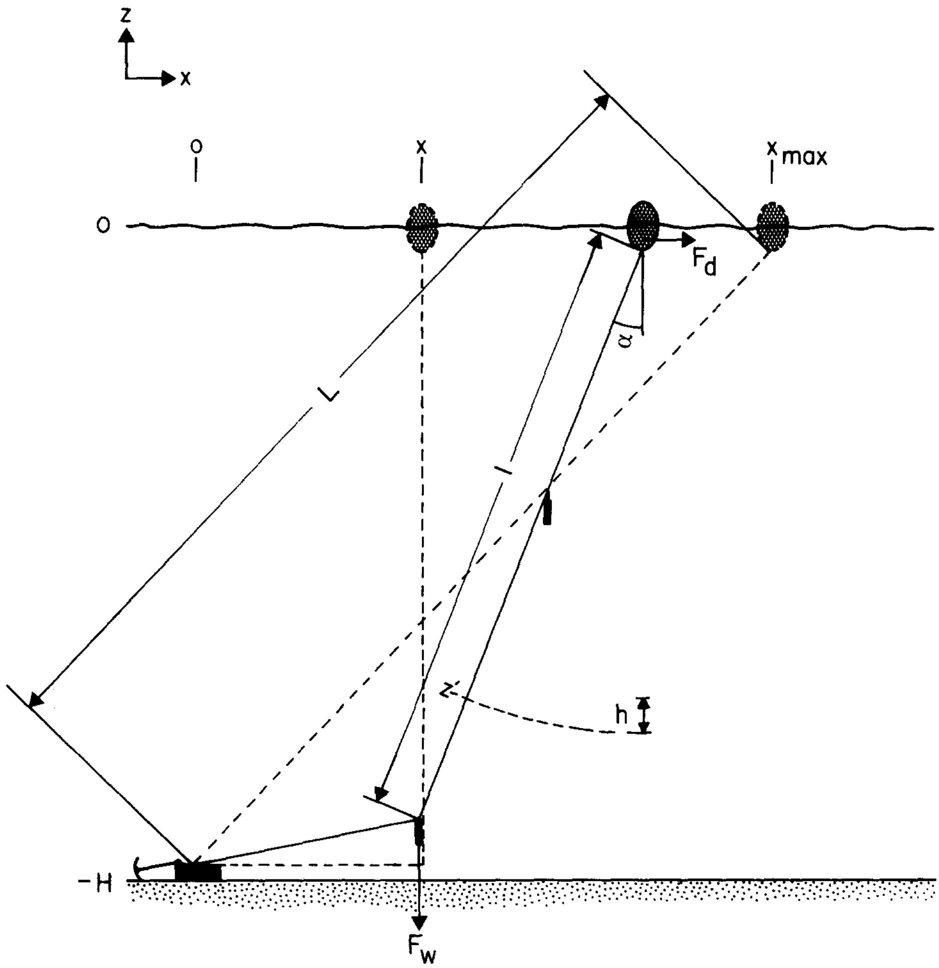


Fig. 3. Impression of the movement of a moored loosely tethered surface buoy and attached thermistor string under the action of currents (see text for symbol explanation).

during this period of frontal advection the positive definite temperature difference between two sensors at the same depth merely points to thermistor string uplift, caused by buoy displacement, in the presence of a vertical temperature gradient, which is modelled as follows.

Consider the surface buoy moving horizontally from its position above the anchor. The thermistor string will be suspended vertically by its weight until the buoy is displaced to distance $x$, beyond which the string will be rotated to first order by angle $\alpha$, when the drag force $F_d$ imposed on the mooring is sufficient to overcome the weight of the string $F_w$ (Fig. 3). The implicit assumption that the string may be considered as a stiff rod upon rotation is the simplest model available without further knowledge about its exact movement. Then the apparent temperature $T_{z'}$ measured at a certain position $z'$ along the string at time $t$ will read

$$T_{z'} = h\, \partial T/\partial z + T_0 \qquad (1)$$

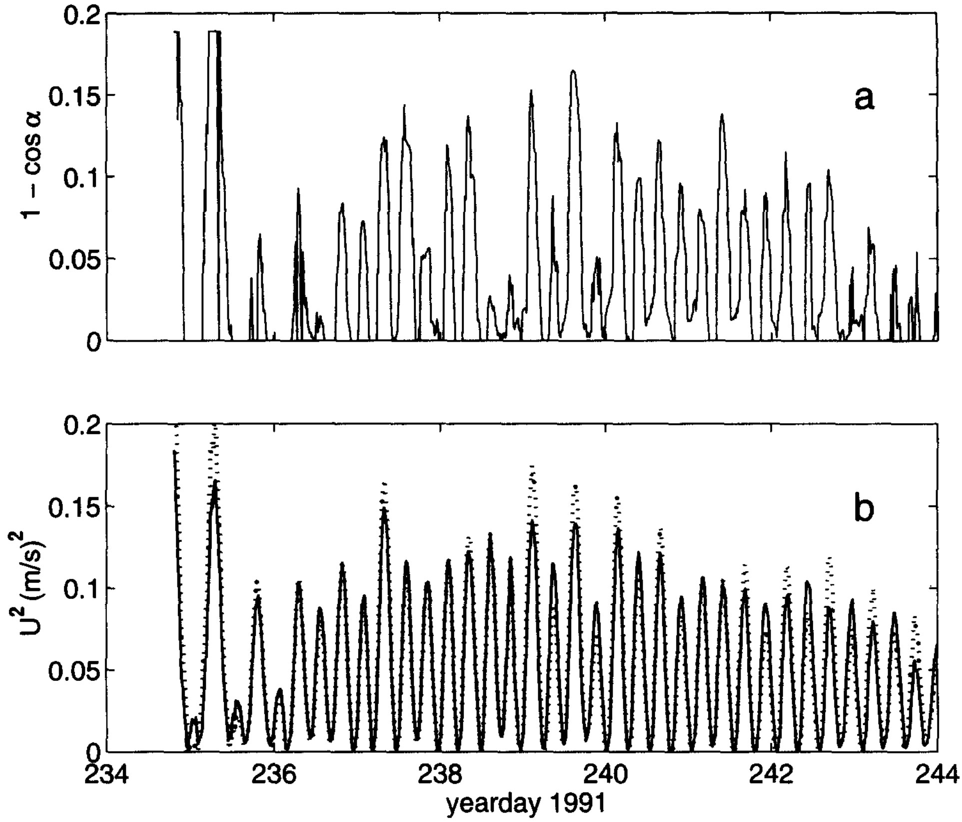


Fig. 4. (a) The amount of thermistor string uplift according to equation (1) using equation (2), and scaled with the length of the string. (b) The amplitude squared of the currents measured at 11 m depth (solid line) and those including a correction for wind effects (dotted line).

where

$$h = z'\,(1 - \cos\alpha)$$

denotes the uplift. The unknown local vertical temperature gradient is given by $\partial T/\partial z$ and $T_0$ denotes the temperature measured properly at the vertical position $z = z'$ ($\alpha(t) = 0$) and is governed by all processes other than artificial vertical advection. The key is to find the uplift $h$, or $\alpha$, as a function of time.

When a temperature record measured at a fixed depth $z = d_0$ is available, one may find the unknown uplift by searching for the matching (interpolated) temperature value $T_i$ along the string at position $d_i$, for which

$$\Delta T_i = |T_i - T_0| \to 0$$

so that

$$\cos\alpha = d_0/d_i. \tag{2}$$

We used data from a well-moored current meter, where relative depth $d_0$ is a (weak) function of time to correct for the sea-level variations. For the period shown in Fig. 4(a) the displacements reach up to the maximum detectable, when $(\cos\alpha)_{min} = d_0/d_1 \approx 0.81$ when the lowest thermistor (index $i = 1$) was higher than the current meter. Other possibilities for correction are to use data from a pressure sensor or a tilt meter, but no such sensors were attached to the string at the time.

Alternatively, current data may be used. The strong occurrence of the first tidal harmonic ($M_4$) in the temperature record and the apparent spring/neap cycle point to a resemblance with the amplitude of the horizontal current (Fig. 4). Physically, this resemblance is modelled in a simple manner as the instantaneous (static) balance between the drag force $F_d$ acting on the buoy and wire and the weight $F_w$ of the thermistor string

$$F_w \tan\alpha = F_d = CU^2 \quad (3)$$

where $U$ is the current amplitude acting on the underwater part of the mooring and the constant $C$ contains the cross-sectional area exposed to the current and drag coefficients. Model (3) is more generally applicable than equation (2) to calculate the uplift magnitude, due to the relative inaccuracy of the temperature sensors when located in well-mixed water layers [e.g. during most of the second period in Fig. 1(a)]. The expected dependency of the (false) temperature record on the current magnitude varies with the amount of uplift. Combining equations (3) and (1) one finds

$$T_{z'} - T_0 \propto 1 - \cos(\tan^{-1}(U^2C/F_w)) \quad (4)$$

which is approximated to

$$T_{z'} - T_0 \propto U^4 \quad \text{for} \quad \alpha \approx 0$$

and

$$T_{z'} - T_0 \propto U^2 \quad \text{for} \quad \alpha \approx \pi/6$$

as may be inferred from Taylor expansions of the trigonometric functions around the given values for $\alpha$.

Ideally, one wants knowledge on a well-resolved vertical current profile to model (3) acting on the mooring. This is seldom the case as it is for the present data. For the period between days 235 and 242 when the fixed depth temperature sensor was situated in the apparent thermocline, the validity of equation (3) was verified, using equation (2) to find $\alpha(t)$ and for $U(t)$, initially, currents measured at 11 m depth, which was well outside the frictional influence of near-bottom and internal layers and approximately in the middle of the near surface Ekman layer. The data from this depth are chosen (out of two possibilities) to represent the currents responsible for drag on the mooring, of which about half were acting on the submerged part of the buoy.

A tendency towards a linear relationship was found between $\tan\alpha$ and the squared amplitude of the horizontal current (Fig. 5). Prior to the production of this figure some minor noise treatment was invoked by omitting data when $d_0/d_i > 0.999$ and using a relaxed criterion of $\Delta T_i \leq 0.1°C$, which reflect the accuracies of the sensors and their depth determination. The latter (in)accuracy, estimated to be no better known than $\pm 0.5$ m, in combination with the 2-m intervals between the thermistors, caused trouble in finding the proper off-set (zero temperature difference when no displacement of the mooring took place). When the lowest thermistor temperature was higher than the value measured at the current meter, data were excluded too. In total, about 30% of the data were thus not used in the subsequent analysis.

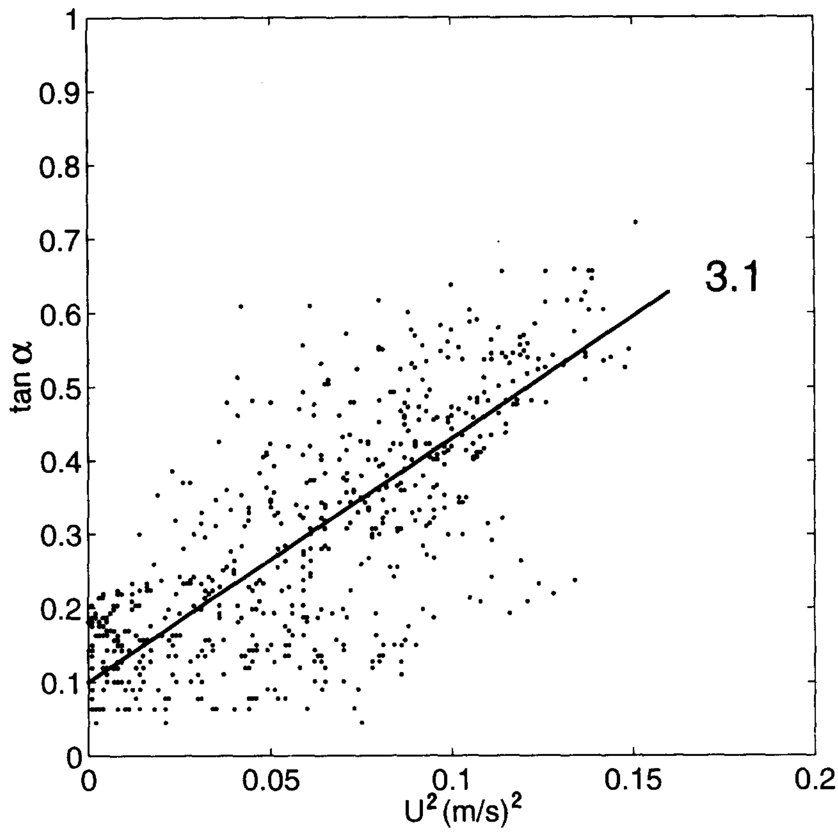


Fig. 5. Verification of model (3) for buoy displacement for the period between days 235 and 242, using the current data measured at 11 m depth and the temperature sensor at 36 m depth to find the uplift, represented by $\alpha$. The data which passed the criteria (see text) are given by the dots, and the line of linear best fit has slope $m = 3.1$.

The root-mean-square deviation with respect to the fixed temperature sensor at 36 m depth reduced from 2.0 to 0.8°C, while the mean deviation decreased from 1.5 to 0.5°C, when

$$\tan\alpha(t) = 3.1U^2(t) + 0.1 \quad (5)$$

was used. Relationship (5) was found after a linear least squares fit between the two time series, and the correlation coefficient between them amounted to $0.74 \pm 0.02$ and lent some confidence to the concept proposed in equation (3). The non-zero offset reflects the inadequacy of the adopted model (2) at low current speeds. Apart from this uncertainty the amount of scatter is quite large and represents irregularities of the string movements [like near day 238.7, Fig. 4(a)], the finite vertical resolution of the temperature data and any misinterpretation by assuming the currents measured at 11 m depth represent those acting on the mooring, neglecting wind and surface wave effects and the influence of friction on the vertical structure on currents.

In an attempt to reduce the scatter and hence the temperature difference, nearby measured wind data were used to transfer the current data at 11 m to those near the surface using a simple Ekman (spiral) model [Fig. 4(b)]. The direct impact of the wind was incorporated by including a wind drag coefficient and an estimate of the buoy's surface above the sea surface. Although some details improved others did not and, surprisingly, no substantial improvement was obtained, using the overall root-mean-square deviation as guidance. Probably the unknown more complex string and buoy movements, for instance induced by waves, dominate the scatter found.

The acceptability of correcting method (3), with respect to equation (2), may be inferred from Fig. 6. The improvement of especially the larger-scale features is fair despite the scatter shown in Fig. 5, as nearly all of the $M_4$ tidal harmonics are removed and the mean isothermal depth is nearly constant during the quiet weather period, beyond day 237 [compare Figs 6(b) and 6(c)]. The data corrected using model (3) [Fig. 6(b)] differ from corrections made using (2) [Fig. 6(c)] in some details, like at frequencies higher than tidal and in the exact amplitude of isotherm displacements at tidal frequencies, which may have become distorted when resulting from tidal advection.

Although not initially noticeable from Fig. 1, a considerable portion of the apparent semi-diurnal tidal signal is a result of artificial vertical thermistor string motions, which may be explained as an effect of combined tidal and wind induced currents (cf. the reduction of the semi-diurnal tidal peak in Fig. 7). Note that the spectral shape of smaller scale processes (at frequencies higher than $M_4$) remained similar after correction using equation (5).

Data from the corrected record [Fig. 6(b)] have been checked against CTD profiles from days 234 and 245. In general the improvements were in accordance with the independently obtained data, but no other information was available during the more interesting period in between, which contained the largest modifications. The most conspicuous observation in the record, between days 234 and 237, probably represents the partial advection of a tidal front, where the apparent splitting of isotherms is due to enlarged tidal mixing and, in a later stage, to a (baroclinic) geostrophic balance (Aken *et al.*, 1987). The total heat content is raised by 5%, on average, after correction. Synoptic scale variations in potential energy content differ by about 10%, including shifts in time up to half a day of events such as between days 234 and 237. The correction method (3) also preserves, by its nature, the thermocline thickness, which occasionally shows a second mode tidal variability with time between days 235 and 242 that is either due to internal wave interaction or frontal advection.

## 4. DISCUSSION

Data obtained from a thermistor string suspended from a floating surface buoy may become contaminated due to the movement of the buoy. This is easily avoided by suspending the string freely down from the buoy, including sufficient weight at its bottom end. In that case data contamination may not be completely removed, as the suspended string may still entangle with the mooring line. Additional information is still preferred, and now some of our thermistor strings carry a pressure sensor at the end cap, where a tilt sensor would be equally welcome.

When no such precautions are taken or additional sensor data are not available, contaminated temperature data are detectable and may be corrected using simultaneously measured current data, while taking advantage of some knowledge of the prevailing physical models. In thermally stratified tidal areas infested with fronts, as frequently occur

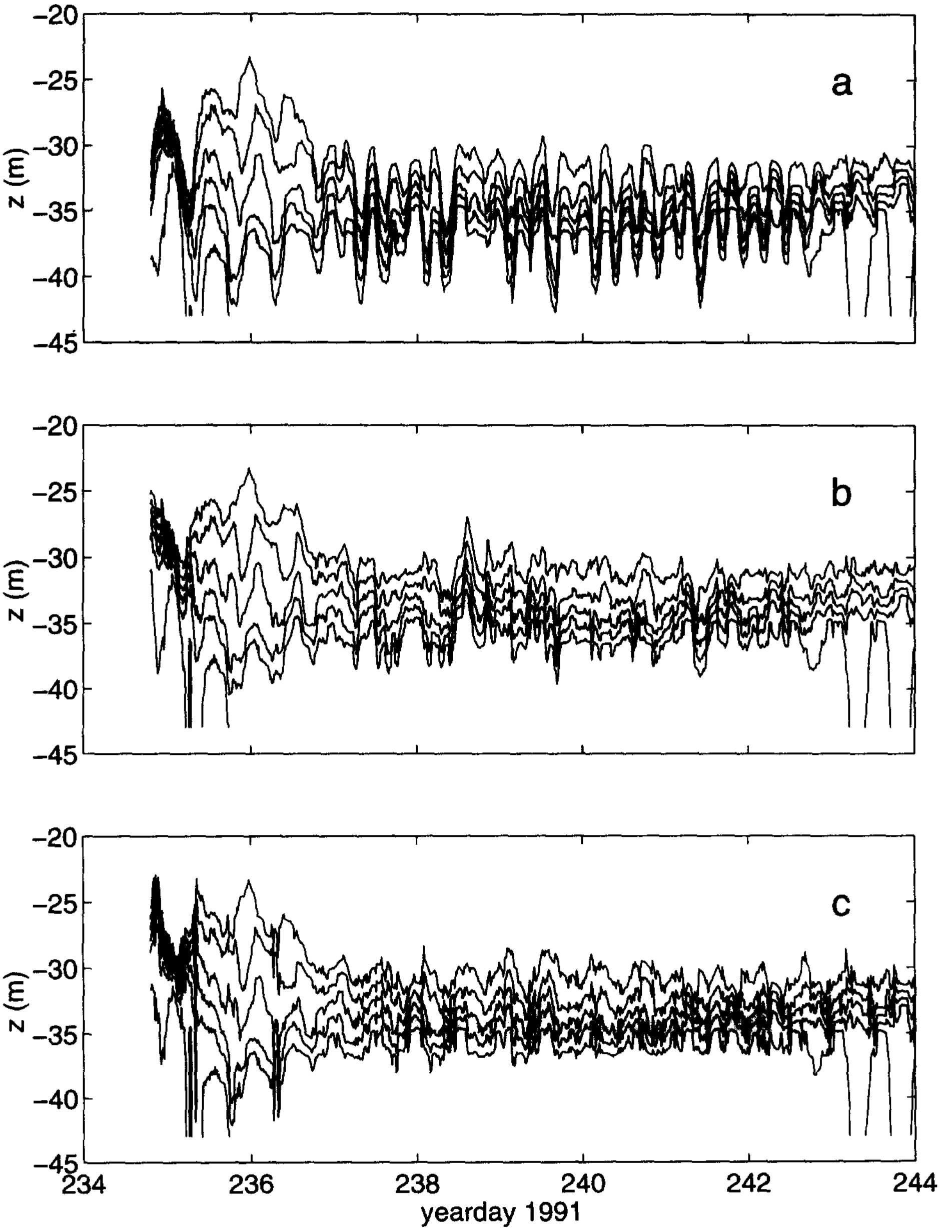


Fig. 6. (a) Isotherm displacements as a function of time, as inferred from uncorrected thermistor string data. Isotherms are drawn every 1°C, between 11 and 16°C. (b) As (a), but for temperature records that have been corrected using current data as in equation (3). (c) As (a), but for temperature records that have been corrected using temperature data as in equation (2).

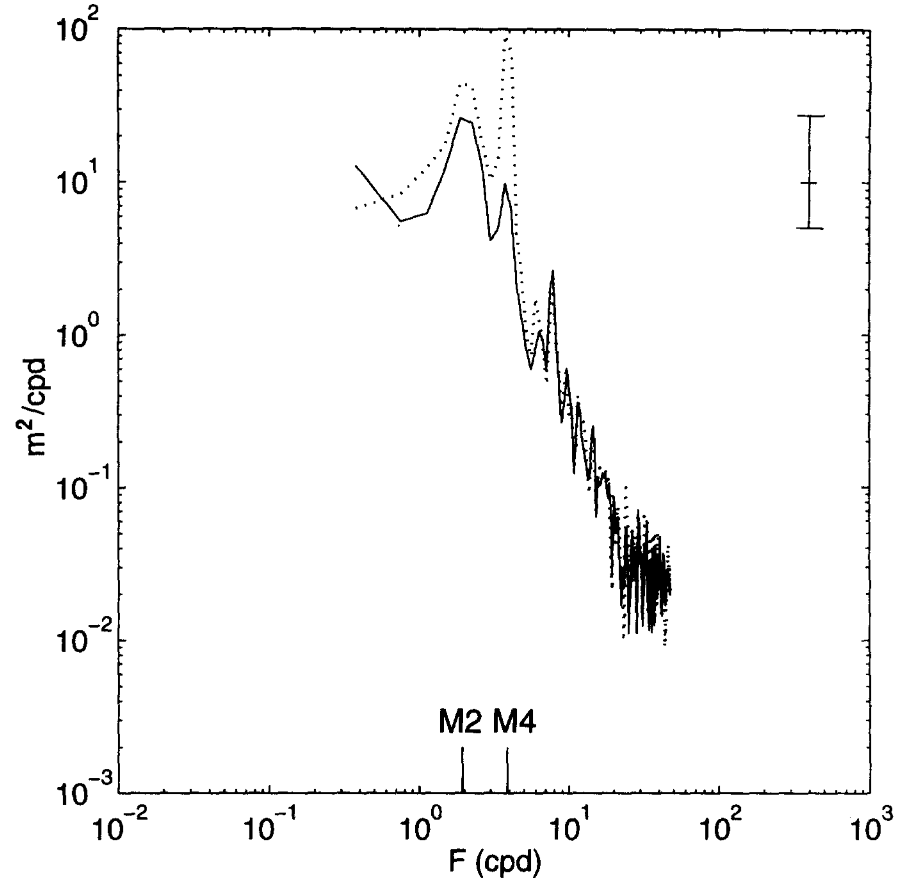


Fig. 7. Isotherm (14°C) displacement amplitude spectra from the uncorrected record (dotted line) and after correction using current data as in equation (3) (solid line).

in shelf seas, the phase and amplitude relationships at tidal frequencies may reveal data contributions from non-linear processes, (free) internal tides and tidal advection. A sufficient test for physical credibility of the temperature data would be the investigation of their cross-spectral information in the tidal and its first harmonic bands when combined with both horizontal current components and with the current amplitude.

In case of contamination the first tidal harmonic band ($M_4$) should contain significant coherent information at zero phase lag between the temperature data and the current amplitude (squared), following equation (4). Tidal advection, on the other hand, is downplayed by coherent information at phase lags of $\pm 90°$ between temperature and one (or both) current components in, at least, the dominating tidal band. This may result in significant coherence in the first harmonic tidal band between temperature and the horizontal current amplitude, but at a non-zero phase lag (more likely near $\pm 90°$). These coherency tests are easily performed and may be used for finding the correction relationship following equation (3), when one assumes that smaller scale (non-linear) processes only weakly appear in the temperature data and that the information at frequencies higher

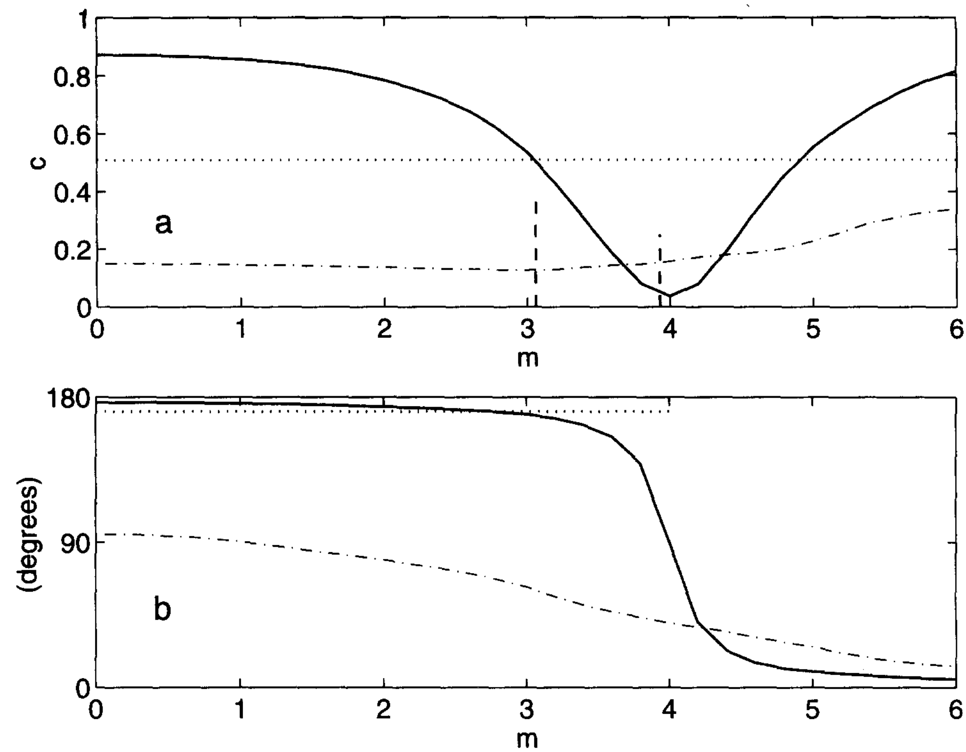


Fig. 8. Coherency method to find the region of valid temperature corrections, using cross-spectral information in the $M_4$ frequency band from the (near surface) current amplitude squared with a particular isotherm. The isotherms are determined as a function of increasing correction according to equation (1), using equation (3): $\tan\alpha = mU^2 + 0.0$, while varying $m$. The solid lines represent results for the period between days 235 and 242 in 1991 and the dashed-dotted lines those for a period between days 190 and 220 in 1994, when the mooring configuration was improved. (a) Coherency vs $m$ with the dotted line representing the 95% significance level computed according to Thompson (1979). The large vertical dashed bar indicates the solution (5) found separately in section 3, and the small dashed bar indicates this solution while including in the analysis unveryfiable data from well-mixed waters and during strong uplift. (b) Phase as a function of $m$. The approximate 95% significance levels amount 7° for a coherency of 0.9 and is indicated half-sided near 180° by the dotted line.

than tidal is of less importance. In the case of contamination the proper correction is found when the current amplitude and the corrected temperature data decorrelate.

This is shown in Fig. 8, where the coherency and phase from the $M_4$-band have been plotted for the current amplitude squared with isotherm displacements from the period between days 235 and 242, as a function of values of the slope $m$ representing the amount of correction following the linear relationship (3). A particular isotherm is used rather than temperature at a fixed depth to resolve the entire period properly. For weak correction (small $m$) a phase difference of 180° (equivalent to 0° for temperature) is found at statistically significant coherency, indicating contamination due to vertical advection. At about $m = 3.1$ the coherency drops below its 95% significance level and beyond $m = 4.9$ the two records are found coherent again, but indicating 'over-correction', as may be inferred from the phase difference of about 0°. Optimal correction would be at the minimum value of correspondence, which in this case means $m \approx 4.0$ ([3.1,4.9]). The value of $m = 3.1$, found earlier, lies just within the region of statistically non-significant coherency values. This may seem puzzling, but reflects the inadequacy of equation (2) at low current speeds and in well-mixed waters [recall the non-zero intercept in equation (5)]. When the 30% of the data that were omitted from analysis in section 3 were included by setting $\alpha = 0$ when $\Delta T_i \leqslant 0.1°C$ and $\cos\alpha = (\cos\alpha)_{min}$ when the lowest thermistor was higher than the current meter, $m = 3.9$ and a negligible intercept were found.

As an example of the more general applicability of the result (5), the temperature data obtained between days 245 and 263 (cf. Fig. 1) were submitted to the coherency method given above. A lower slope of $m \approx 3.2$, [2.3,4.0] was found at minimal correspondence. The difference in values for $m$ found may be attributable to inaccuracies in depth determination of the sensors or a change in mooring configuration. The cables were refreshed during servicing between the two periods. The period between days 245 and 263 showed stronger tidal variations than between days 235 and 242, which appeared due to advection, as was inferred from cross-spectral information, but this affected only slightly the information obtained from the coherency method.

Hence, the method underlying Fig. 8 may be used to determine the range of correction magnitude. For the period between days 245 and 263 the correction thus obtained effectively removed the large $M_4$ variations between days 250 and 257 and the corrected record compares well with the current meter data for the short period of overlap (days 259 and 262). The method clearly distinguishes between thermistor string data due to 'false' vertical advection and those due to horizontal advection. An example of the latter is included in Fig. 8, where the dash-dotted lines have been computed from a data set from a properly moored thermistor string. This method is also applicable to test the correctness of temperature data from taut wire moorings which are little or more, when buoyancy elements break down, deflected from the vertical upon current drag.

Temperature (gradient) data are still an important feature in oceanography, not to be lost. This is reflected in recent literature showing (renewed) interest for studies on diapycnal mixing, for example near bottom boundary layers above (continental) slopes. The advent of improved experimental equipment, such as ADCP and fast response thermistor strings, also allows for directly estimating vertical buoyancy (and momentum) fluxes from the high frequency part of the internal wave band and its impact on mixing.

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