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THE REDUCTION IN FINESTRUCTURE CONTAMINATION OF INTERNAL WAVE ESTIMATES FROM A TOWED THERMISTOR CHAIN

Estimates of internal wave displacements based on towed thermistor array data have historically suffered badly from finestructure contamination. It is hypothesized that a substantial amount of such contamination may be removed by sampling the ocean with thermistors spaced in a close vertical pattern and by using appropriate internal wave displacement estimation techniques. Such a technique is described, and preliminary results based on data from a 5-centimeter vertical resolution chain are presented that indicate that a substantial reduction of finestructure contamination is achievable.

INTRODUCTION

Calculation of fluid motion from oceanic temperature measurements has always been difficult; each of the two commonly used measurement systems, towed thermistor chains and dropped thermistors (thermistors are temperature-sensitive resistors), has an inherent limit to the accuracy of fluid motion estimates that can be produced from their respective data. In the case of dropped thermistor-type instruments, the horizontal and vertical wavenumber range over which fluid motion may be estimated is severely limited by the vertical drop rate and the attainable drop repetition rate. Consequently, such instruments are of limited value for estimating fluid displacements over a broad range of horizontal and vertical length scales. Towed thermistor chains do not suffer from such mechanical limitations, although there is a maximum depth to which they can be deployed. Rather, the limits to accurate fluid motion estimates are due mainly to the degree to which such estimates are contaminated by small-scale vertical temperature structures. This effect, known as finestructure contamination, has been discussed extensively in the oceanographic literature[1-6] and was also described in a previous Ocean Science issue of the *Johns Hopkins APL Technical Digest*.[7] The impact of this contamination on the accuracy of chain-based fluid displacement estimates is shown to be decreased by using proper processing techniques and adequate vertical resolution.

FINESTRUCTURE MODEL

Any successful processing technique for reducing finestructure contamination must be based on an accurate model of the underlying oceanic processes. One such model is the passive finestructure model, which states that small-scale vertical temperature features are advected passively by the background internal wavefield (very little or no active mixing occurs) so that a horizontally towed thermistor then not only measures the underlying fluid displacements but also aliases into this measurement all the short-wavelength temperature variability contained in the vertical profile. (These temperature features are formed by a variety of mechanisms, many of which are discussed in Ref. 8.)

Modeling of finestructure contamination in this manner is quite common in the literature. The temperature field is given by

$$T(\bar{x},t) = T_0[z + \zeta(\bar{x},t)] \quad ,$$

where ζ is the internal wave displacement field, explicitly a function of $\bar{x}$ and time, z is vertical position, T_0 is the undisturbed vertical temperature profile, and $\bar{x}$ is the horizontal position at fixed depth. No horizontal space or time variation is included in the model, and all the small-scale vertical variability is contained in the undisturbed temperature profile. Actual oceanic finestructure should, of course, have a space and time dependence that is not entirely attributable to the space and time variations of the internal wavefield; but, for the purposes of this analysis, it is assumed that the space and time dependence of $T_0(z)$ can be ignored.[3] It is difficult to estimate exactly the amount of a towed thermistor temperature signal that is due to passive finestructure contamination and the amount that is due to actual, irreversible mixing events. It does seem highly likely, however, that the passive finestructure hypothesis is valid over some vertical and horizontal scales. The determination of the scales was the objective of the work described in this article.

Past simulation and modeling results have indicated that vertical fine- and microstructures can be resolved, and their effects on the measurement of the internal wave displacement field reduced, if the temperature profile is sampled at high enough vertical resolution. Accurate computation of the underlying internal wavefield is then possible by tracking specific, identifiable profile features for long time intervals. These profile features may, for a monotonic profile, be simply specific temperatures, i.e., isotherms. Assuming that the passive finestructure model is correct over the scales appropriate to such towed measurements (i.e., a few meters to a few hundred meters in the horizontal), isothermal displacements in these wavebands should exactly track the underlying internal wave displacements.

If the character of the internal wave displacement field at these scales in the upper ocean were known independently, an evaluation of the performance of the above scheme for reducing the effects of fine- and microstructure contamination on towed chain measurements would be straightforward. However, due to measurement difficulties, no such independent knowledge is currently available. Therefore, the approach taken here is to hypothesize the simplest possible character for this field and to test the degree to which the internal wave displacement field derived from the measurements matches the hypothesis. Specifically, it is assumed that the true upper-ocean internal wavefield may be described as a piecewise stationary, homogeneous, gaussian random field for horizontal scales of a few to a few hundred meters and is vertically homogeneous for vertical scales of a few centimeters to a few tens of meters. It should be noted that at longer horizontal scales (several hundreds of meters), these assumptions have been shown in general to hold.[9]

With the above hypothesis, the gaussianity of the internal wave estimates is a measure of how accurately the fluid motion has been reproduced. This measure will be assessed by examining the high-order moment structure of the displacement estimates and will be described more fully in the Results section.

CALIBRATION

The practical aspects of calculating isotherms are more tedious than the theory. One such aspect is that of thermistor calibration. Accurate estimates of local temperature gradients are necessary to compute isotherms. Since such estimates involve using adjacent thermistor temperature differences in the method used in the analysis, accurate interthermistor calibration is required. Typical predeployment thermistor offset accuracy is on the order of 20 to 50 millidegrees celsius. Since it is necessary to estimate locations of isotherms to within a few centimeters, it is obvious that a relative accuracy between thermistors of greater than 20 millidegrees celsius is not adequate to resolve the typical thermocline temperature gradients of 50 millidegrees celsius per meter. Sufficient accuracy can only be obtained by in situ calibration.

The in situ calibration algorithm applied to the thermistor data used in the analysis estimated only an offset correction for each thermistor. Any gain errors in the data were corrected by forcing the vertical temperature variance profile of the thermistors to be smooth, a technique that is effective only if the original thermistor-gain values were more or less accurate and if only the occasional thermistor requires correction.

The specific in situ interthermistor calibration algorithm actually used is known variously as the average gradient method or the depth-temperature cross-correlation method. The conceptual basis for the method is simple: The ocean is believed to consist, to a large degree, of a series of layers of nearly isothermal water where the vertical-to-horizontal length-scale ratio is of the order 10^{-2}. If a vertical array of closely spaced thermistors is pulled horizontally through the water while being raised and lowered by approximately the vertical separation distance of the thermistors every few seconds, the differences in temperatures sensed by each thermistor from the top to the bottom of its path should allow calculation of a temperature gradient for that layer of water, for each thermistor. Many such gradient estimates are computed over, say, half an hour of data, and the least-squares estimate of the average gradient seen by each thermistor is calculated. These gradients are vertically integrated from top to bottom, thus constructing an estimate of the average temperature profile unbiased by calibration offset errors for that time segment. The profile is then compared to the temperature profile produced by simply averaging the temperature values of each thermistor. The thermistor-by-thermistor differences between these two profiles represent the bias corrections for each thermistor. It is easy to see that this method is independent of initial bias errors in both temperature and depth.

Figure 1 demonstrates the effectiveness of the intercalibration algorithm in correcting an average profile from an unreasonable curve to one that is more physically plausible. There is no known way to estimate the true residual calibration error, but estimates from the variation of the corrected average profile indicate

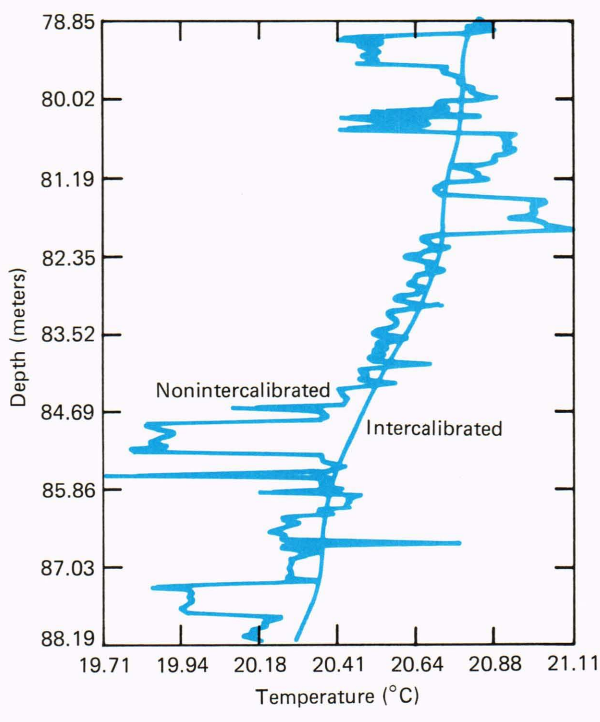

Figure 1—Vertical profile of temperature averaged over 50 meters horizontally. The smooth curve represents a calibrated profile.

that the maximum residual error is something on the order of 1 millidegree celsius or less.

The frequency with which the data need to be intercalibrated is a function primarily of the stability of the thermistor system electronics. In the case described here, the thermistors were intercalibrated every half hour.

ISOTHERMS

Conceptually, the process of calculating isotherms is simple: A temperature value is selected that falls within the range of temperatures measured by the array, and its location in depth is calculated by linearly interpolating between thermistors (the isotherm's temperature value will not, in general, be one of those exactly measured by any thermistor). However, there are problems with this simple method. The local temperature profile is not always monotonic; regions occur where the gradient changes sign. These are called temperature inversions. Wherever the thermistor array encounters an inversion, there may be several locations where a given temperature may occur. A simple isotherm algorithm will typically scan the chain to locate a given temperature and select the first position where that temperature can be located. The process gives rise to the sort of behavior exhibited in Fig. 2; note the clearly unphysical step-like structures in the lower isotherms.

One way to alleviate the problem is to calculate all locations for each isotherm and then select the one closest in depth to the previous position. This is called the minimum displacement method. However, inversions are not all of the same type since they are products of a variety of mechanisms such as salt fingering, wave breaking, and double diffusion; consequently, this procedure does not eliminate all unphysical behavior. The problem must be approached from a more global point of view.

In general, the problem may be stated as: What should be done in regions in which the passive finestructure model is clearly not an accurate description of the physics?

From the point of view of internal wave displacement processing, an adequate answer to that question is that some regions of temperature inversion are generated by nonreversible, active processes, and the passive finestructure model clearly does not apply in those areas. Since internal wave displacement estimates are meaningless in regions of turbulent mixing, such regions should be avoided in the estimation process, i.e., isotherms should not be tracked through regions of temperature inversion.

To be effective, the inversion-avoiding algorithm implemented for this analysis relies on the statistical behavior of the small-scale oceanic turbulence. In particular, the rate of incidence and the vertical extent of temperature inversions are such that it is extremely unlikely that a situation will occur in which most of the array is inverted.[10] It is possible, then, to calculate many isotherms over short time intervals and then select a subset of them based on the frequency of occurrence of inversions encountered by individual isotherms. At each new short time interval, a completely new set of isotherms is selected. Each of these short intervals (or data windows) is selected to overlap the previous one by 50 percent. In the overlap regions, the subset of selected isotherms is merged from the two windows with a triangular smoothing filter. The result is smooth, inversion-avoiding, composite isotherms that will behave essentially as true isotherms over all physically significant scales. These series have been descriptively named modified inversion-avoiding composite isothermal displacements (MIACID).

It will not always be possible to choose isotherms that encounter no inversions at all. In these cases, the pair of thermistors yielding the negative gradient is

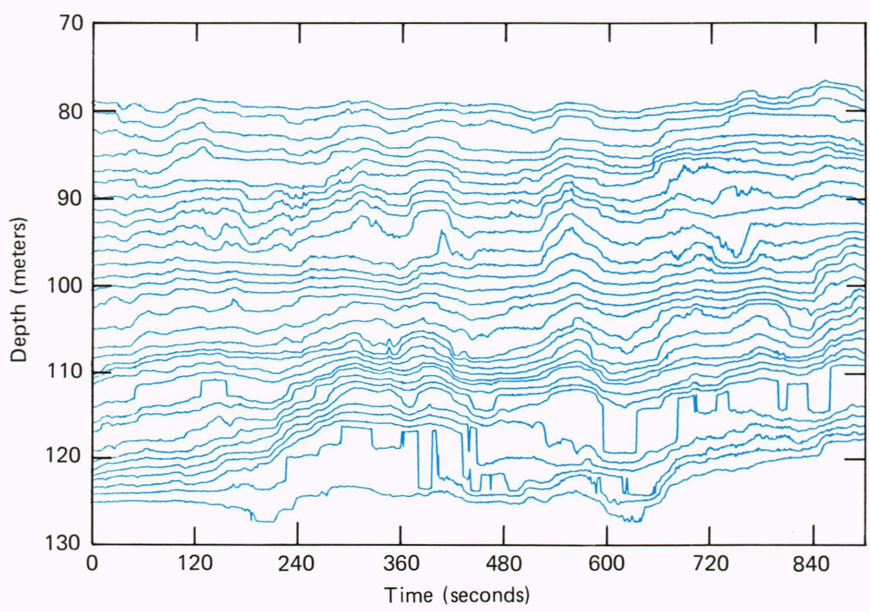

Figure 2—Simple isotherms. Note the step-like structures in the lower isotherms.

eliminated from consideration and the next wider pair that show a positive gradient is used for the interpolation.

Figure 3 is a plot of some representative MIACIDs that can be usefully compared with Fig. 2. Note the complete absence of the step-like structures observed in Fig. 2 and the well-behaved nature of the time series. These particular MIACIDs were selected to track through no inverted regions at all, a condition that will not be possible overall because an average MIACID will encounter about 20 unavoidable inverted points in the course of about 5 kilometers of data. However, the MIACIDs should still be better estimates of internal wave displacements than simple isotherms since a simple isotherm will typically track through many hundreds of inversions in the same time period. The number of inversions encountered in approximately 5 kilometers of Sargasso Sea data during our investigations was 633 using simple isotherms (about 8 percent of the approximately 8000 measurements) versus 20 using MIACID (about 0.2 percent).

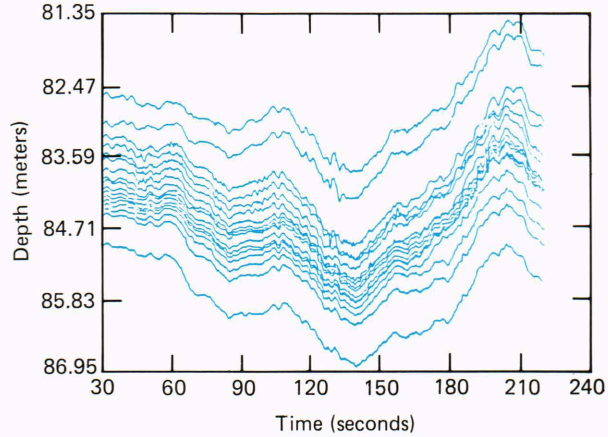

Figure 3—Modified inversion-avoiding composite isothermal displacements (MIACID). Note the lack of step-like structures.

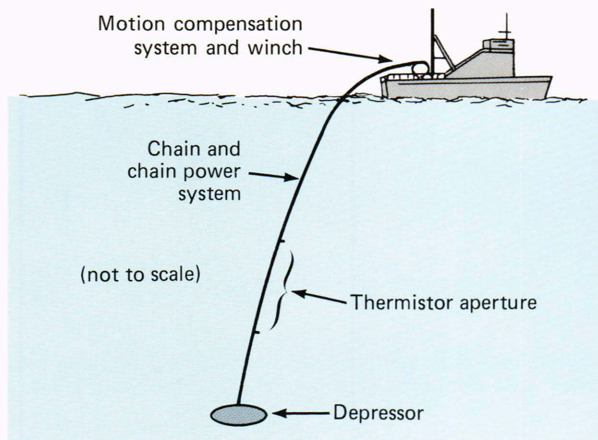

Figure 4—A schematic of the APL high-density towed thermistor chain used to acquire these data.

DATA CHARACTERISTICS

Our results are based on data acquired in the seasonal thermocline in November in the Sargasso Sea with an APL low-drag thermistor chain.[11] The chain used to gather these data has a vertical thermistor aperture of 10 meters with thermistors spaced nominally at 5 centimeters in the vertical (see Fig. 4). A tow speed of 6 knots and a data rate of 5 hertz (after decimation) yield a Nyquist wavelength of 1.2 meters. Relative change in chain depth was calculated from the average of 11 Entran pressure transducers. Chain motion caused by wave-induced ship motion was reduced by using the APL-developed passive motion compensation system,[12] yielding a root-mean-square vertical motion of about 5 centimeters over the primary wavelength band of surface waves (i.e., 10 to 30 meters). Figure 5 gives a representative segment of intercalibrated temperature data; Fig. 6 indicates the average spectral levels for two temperature channels and a noise resistor. Autospectral density plots such as Fig. 6 provide information about the relative contributions to the overall signal power from the various spectral components of the signal. Oceanic temperature spectra typically exhibit slopes of k^{-2}, where k is the wavenumber. The noise resistor spectrum characterizes the instrument noise floor power levels. The temperature signal should be (and is) well above the noise floor across the entire frequency band if the sensor is measuring the ocean and not its own self-noise. These data have been preprocessed to remove wild points and electronics drift. All results presented are based on ensemble averages taken over about 75 kilometers of horizontal tow.

RESULTS

Figure 3 showed a representative sample of MIACID; note again the behavior of these series relative to the simple isotherms shown in Fig. 2, namely, the lack of step-like structures and the generally more regular appearance. Qualitatively, the estimates of internal wave displacement certainly appear superior to the simple isotherms and, obviously, to temperature displacements (normalized temperature). Figure 7 is an autospectral plot of both MIACID and the normalized temperature (the temperature has been scaled by the local average temperature gradient so as to yield displacements in units consistent with the MIACID). The spectral slope for the MIACID is −2, as would be expected since the typically observed internal wave spectrum (in these bands) has a slope of k^{-2} and the spectral level is lower than for temperature, as would also be expected if an actual reduction in noise power variance were achieved. In other words, the spectral slope of the MIACID is consistent with other, uncontaminated estimates of internal wave slope, and the spectral levels show that some of the power in the temperature series (presumably attributable to finestructure contamination) has been removed by the MIACID.

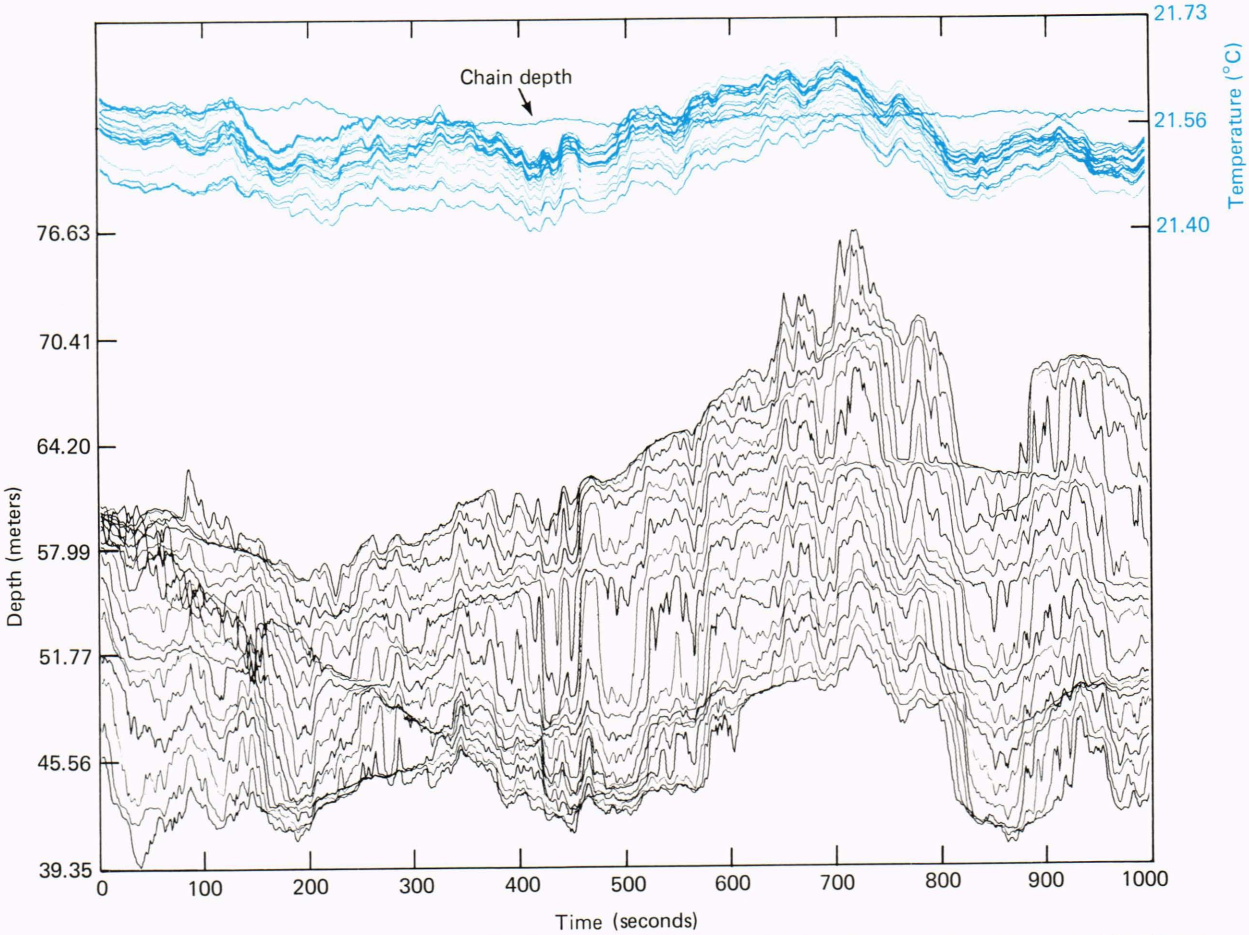

Figure 5—A representative segment of intercalibrated temperatures, plotted on the bottom half of the figure, and isotherms calculated from those temperatures, plotted on the top.

A quantitative measure of finestructure contamination reduction is now required. One such measure is the lagged flatness factor, $\beta(L)$, which directly reflects the gaussianity and independence of a time series. It is defined as

$$\beta(L) = \frac{\langle [T(x+L) - T(x)]^4 \rangle}{\langle [T(x+L) - T(x)]^2 \rangle^2} \quad ,$$

where T may be either temperature or MIACID and L is the lag in meters. Lag refers to the difference in horizontal position between two measured temperature values (or calculated MIACID values) that are to be differenced. The procedure of calculating lagged flatness is similar to that of calculating autocovariance, only using different operations; a time series is displaced horizontally across itself, differenced, raised to the fourth power, and then averaged. For an independent gaussian process, $\beta(L) = 3.0$; for a nongaussian process, $\beta(L) > 3$. Since the data sample length in this case is limited, the estimate of $\beta(L)$ will be biased low (see Ref. 13) by an amount, $b(N)$, where

$$b(N) = \frac{-6}{M+2}$$

and M is the number of independent intervals of length N contained in the data sample. The problem of nonindependent data samples occurs because the finite size of each data record limits the number of points in the expectation value sum for large lags, thus producing a bias because of the arbitrary limits set on the number of data points. This bias has been removed from all results.

The flatness excess, $\beta(L) - 3$, is a measure of the horizontal independence (the independence of the spectral components). If the data are horizontally independent, then

$$\beta(L) - 3 = [\beta(\Delta x) - 3] \left(\frac{L}{\Delta x}\right)^{-1} \quad ,$$

where Δx is the horizontal distance corresponding to the digital sampling rate. Thus, if the data are horizontally independent, the excess flatness will have a slope of -1 when plotted against log L on a logarithmic axis.

Figure 8 is a plot of the lagged flatness factor for MIACID calculated with thermistors spaced at 5 centimeters and at 50 centimeters; the flatness has been

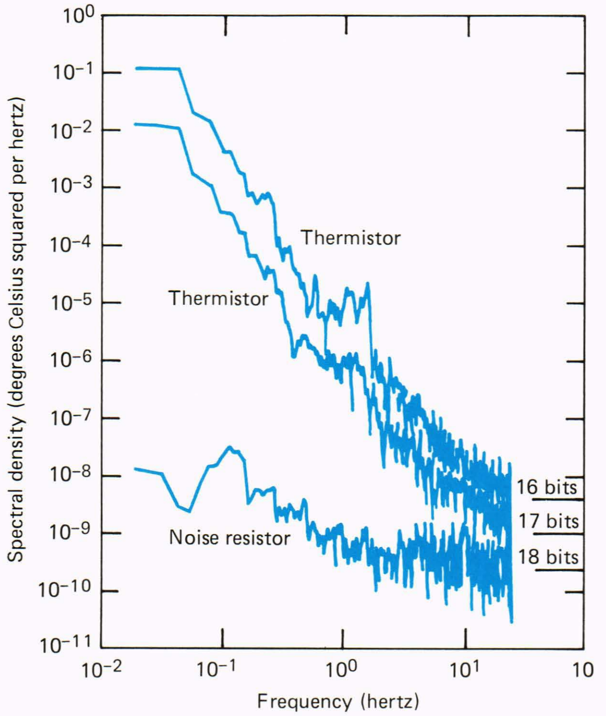

Figure 6—The autospectral density of two thermistors and the noise resistor from gradiometer 10. Equivalent bit noise levels are indicated on the right for a 20° operating range.

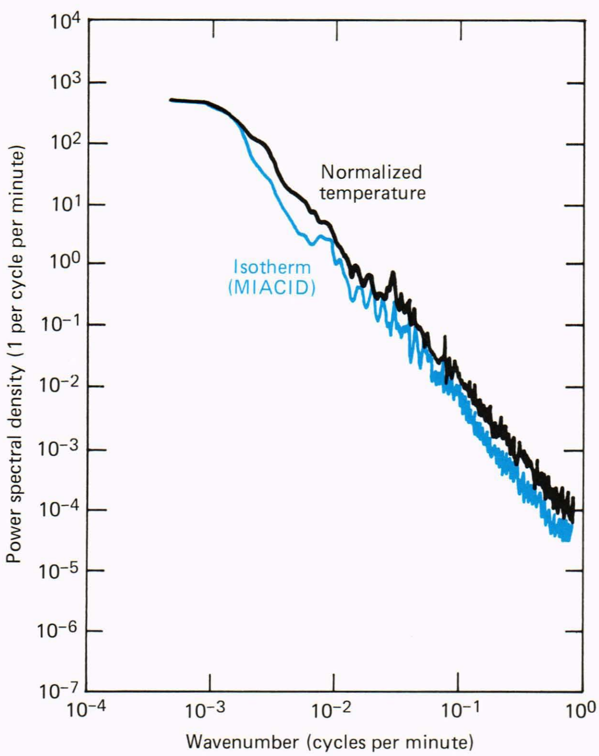

Figure 7—Autospectral density plots of the normalized temperature and isotherms.

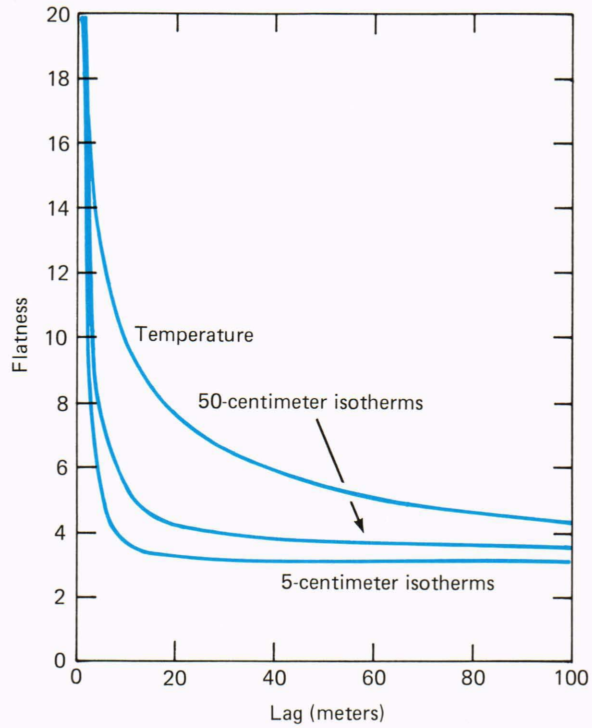

Figure 8—Lagged flatness computed for three series: isotherms calculated at 5 centimeters, isotherms calculated at 50 centimeters, and the temperature (75 kilometers of data averaged).

calculated for a vertical ensemble average of temperatures. Note the substantial drop in value for the MIACID at 50 centimeters as compared to temperature, and the further drop for the MIACID at 5 centimeters. The faster the flatness drops to near the theoretical gaussian value of 3.0, the more gaussian is the series. The horizontal scales for which the series appears gaussian are indicated by the lags over which β is nearly 3.0.

It is clear from Fig. 8 that the MIACIDs are more nearly multivariate gaussian and therefore are better estimators of internal wave displacement than is just pure temperature. It is also clear that the hypothesized vertical resolution effect is important because the 5-centimeter-based MIACIDs are better behaved (i.e., are more nearly gaussian over a broader range of horizontal wavelengths) than are the 50-centimeter-based MIACIDs.

Figure 9 is a plot of flatness excess for the same three quantities shown in Fig. 8. It demonstrates the improvement in horizontal independence achieved with MIACID at 50 centimeters as compared to temperature, and the further improvement for MIACID at 5 centimeters. The two straight lines represent slopes of −1, implying complete independence, and −0.25, a typical value for temperature.[14] It is obvious from the plot that even the MIACIDs at 5 centimeters are not completely independent, but it is also clear that they are more nearly so than either of the other two series.

The reason for the change in slope of the flatness excesses at high lag value is more likely attributable to the smaller number of samples used in the estimate,

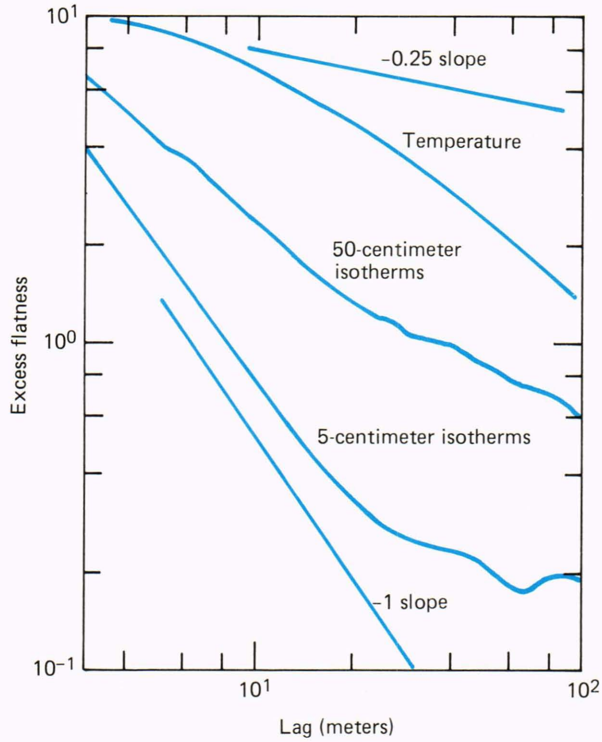

Figure 9—Lagged flatness excess computed for three series: isotherms calculated at 5 centimeters, isotherms calculated at 50 centimeters, and the temperature (75 kilometers of data averaged).

combined with a change in the actual independence at the higher wavenumbers. In any event, the plot is meant to convey only the qualitative assessment made above, and the values of the function at high lag are not of great importance.

CONCLUSIONS

A substantial reduction in the levels of finestructure contamination found in estimates of internal wave displacements has been achieved. This reduction is attributable to the very-high-resolution temperature data from which the displacements were estimated and to the actual displacement and calibration algorithms applied to the data. Reductions were seen both in the autospectral estimates and in the lagged flatness estimates, which supports the original passive finestructure hypothesis. The scales over which the contamination reduction seems to be most effective are the 20-meter and longer horizontal wavelengths. This is not surprising because it is clear from theoretical considerations that turbulent events should become very prevalent at meter scales. The wavelength region between the two domains is a gray area where waves may exist given specific environmental conditions, but these short-scale waves are much more likely to be attributable to local sources and will, therefore, be nonindependent and less gaussian.

Further improvements in the reduction of finestructure contamination may be achievable because the present results are based on data that required substantial corrections for wild points and voltage drift. It is considered likely that the data were corrupted to some degree even after these corrections. The results may be considered, therefore, a least upper bound for finestructure contamination reduction and they demonstrate that reasonably accurate estimates of fluid motion are achievable in an efficient manner from high-resolution towed-thermistor-chain data.

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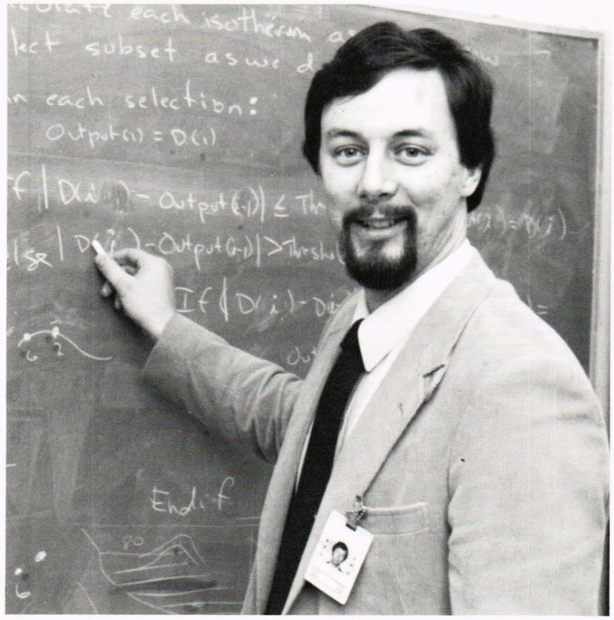

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