Humidity Sensitivity of Atmospheric Temperature Sensors by Salt Contamination

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(Manuscript received 4 February 1977, in final form 6 September 1977)

ABSTRACT

Anomalous results concerning the micrometeorological temperature field in the boundary layer over the ocean have been obtained in many recent experiments. These include lack of an inertial-convective subrange in temperature spectra, unusually large values for the scalar universal subrange constant, underestimation of the sensible heat flux by the bulk aerodynamic formula, gross imbalance of dissipation and production terms in the temperature variance budget equation, and dissimilarities of the temperature and humidity statistics and time traces. Empirically it has been observed that such results occur for unstable conditions when the temperature time series is characterized by a peculiar waveform, termed a "cold spike", which has no counterpart in the humidity field and has not been observed over land.

To explain these results, it is proposed that surfaces of the small temperature sensors (thermistors, thermocouples and resistance wires) commonly used in marine boundary layer experiments become contaminated with salt spray when used over the ocean. Under typical ocean conditions (relative humidity > 70%), the results of Twomey (1953) indicate that the spray will exist as saline drops on the probe surfaces. Water will evaporate from or condense on the saline drops as the humidity around the sensor decreases or increases, respectively. The latent heat of vaporization associated with the evaporation and condensation processes will cool and heat the sensor, and therefore generate erroneous temperature signals. Evidence is presented that most of the anomalous temperature results observed over the ocean, including "cold spikes", may be due to the spray-induced humidity sensitivity of such temperature sensors.

1. Introduction

For about the last ten years, fine-scale high-frequency temperature measurements have been made in the atmospheric boundary layer over the ocean. The purposes of these measurements include the determinations of sensible heat flux and buoyant stability in the marine boundary layer, and the measurement of various universal constants, spectral forms, refractive index data and approach to local isotropy (see, e.g., Gibson *et al.*, 1970; Miyake *et al.*, 1970; Phelps and Pond, 1971; Hasse, 1973; Stegen *et al.* 1973; Friehe *et al.* 1975a; Leavitt, 1975). The required temperature data are usually obtained with small fast-time response sensors—thermistors, thermocouples and fine resistance wires. Such measurements are necessary to improve our understanding of heat transfer, turbulent mixing and turbulence effects on propagation of electro-optical radiation in the marine boundary layer.

However, anomalous temperature results have been obtained from over-ocean experiments which are very different from land or laboratory results. Some of these are as follows:

1) The time series of temperature signals obtained in the marine boundary layer under unstable buoyancy conditions often exhibits a characteristic waveform which was termed a "cold spike" by Phelps and Pond (1971). An example of the cold spike signal, reproduced from Phelps and Pond's paper, is shown in Fig. 1. The cold spike is the portion of the temperature signal which is below the ambient, or baseline quiescent signal. It is most easily seen at the trailing edge (in time) of the "bursts" or "ramps" of the temperature signal. There have been no reports of cold spikes observed in overland or laboratory experiments, nor of similar waveforms measured simultaneously for humidity.

2) The power spectra of the temperature fluctuations typically do not exhibit a well-defined inertial-convective subrange (power spectrum proportional to frequency to $-5/3$ power) in the frequency band for which inertial subranges are found for simultaneous measurements of velocity and humidity fluctuations (Phelps and Pond, 1971; Dreyer, 1974; Leavitt, 1975; Friehe *et al.*, 1975b). The slopes of the measured temperature spectra are found to be less steep than $-5/3$. Normalized temperature spectra have also been observed to exhibit a lack of low-frequency energy (Phelps and Pond, 1971; Leavitt, 1975).

3) Large values of the scalar inertial-convective

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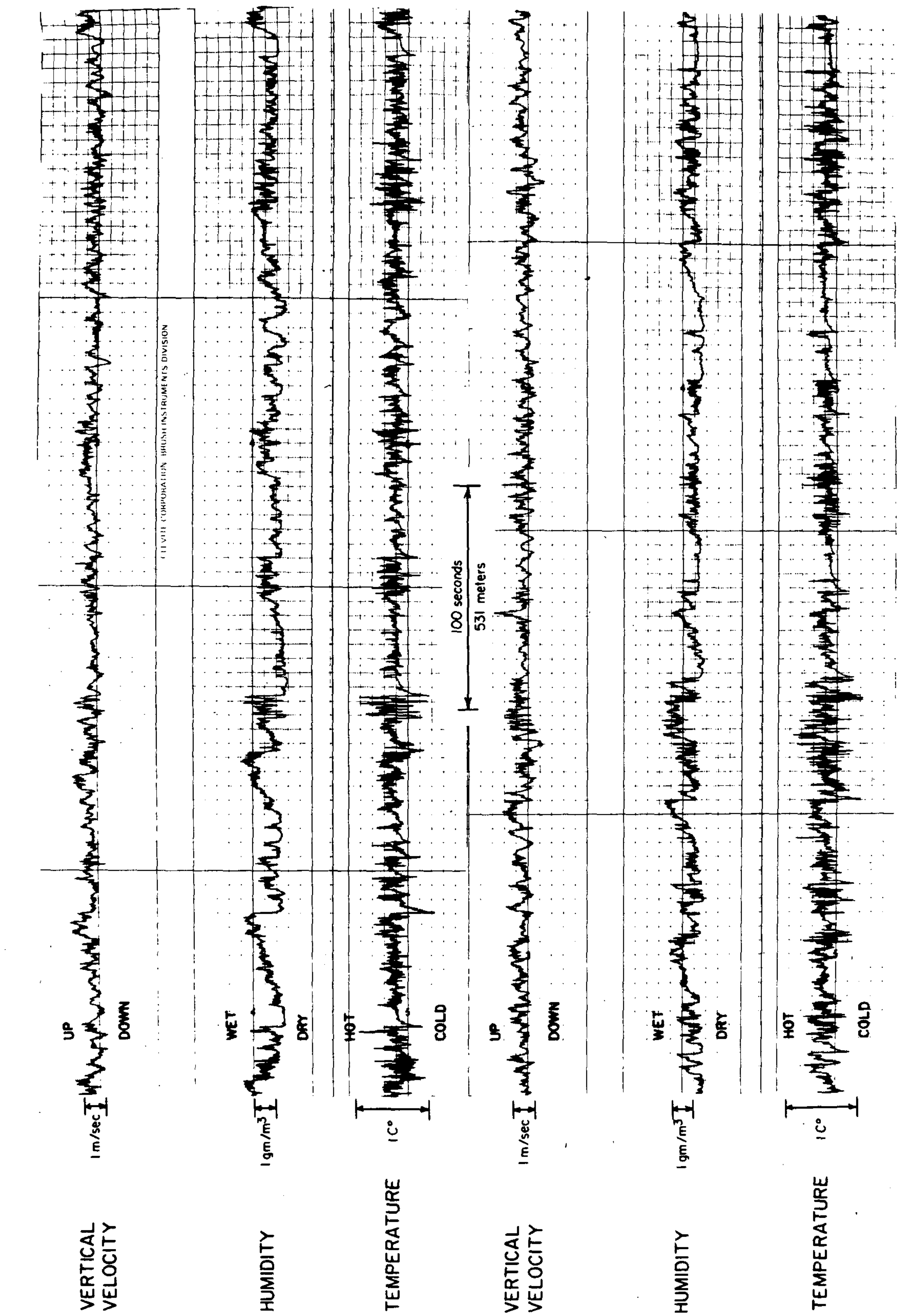

FIG. 1. Time series of vertical velocity, humidity and temperature recorded during unstable conditions in BOMEX. Reproduced by permission from Phelps and Pond (1971).

subrange constant[1] β_θ for temperature power spectra measured over the open ocean have been obtained (or estimated) by Gibson *et al.* (1970) [$\beta_\theta = 1.2$], Stegen *et al.* (1973) [$\beta_\theta = 1.0$], Dreyer (1974) [$\beta_\theta = 0.7$ to 2.4], Leavitt (1975) [$\beta_\theta \approx 4.0$] and McConnell (1976) [$\beta_\theta = 0.53$ to 2.4]. Boston and Burling (1972), reporting temperature measurements over a tidal mud flat, obtained a value of $\beta_\theta = 0.8$. Comparison laboratory and overland measurements have yielded considerably smaller values. Gibson and Schwarz (1963) reported a laboratory measured value of $\beta_\theta = 0.4$, while slightly larger values were obtained from overland measurements [Williams (1974), $\beta_\theta = 0.5$; Champagne *et al.* (1977), $\beta_\theta = 0.45$]. An exception to the large over-ocean values is $\beta_\theta = 0.4$ as obtained by Paquin and Pond (1971) who used the third-order structure function technique to calculate β_θ. Low over-ocean values of β_θ were also reported by McConnell (1976) [$\beta_\theta = 0.43$ to 0.68] who used second- and third-order structurefunction techniques for the calculations of β_θ.

4) The cospectral shapes for the sensible heat flux are very different from those for the moisture flux and momentum flux (Pond *et al.*, 1971; Dreyer, 1974; Leavitt, 1975). In all of the referenced experiments, conditions were unstable with respect to temperature- and humidity-generated buoyancy forces, and a positive correlation of temperature and humidity was obtained. Phelps and Pond, and Leavitt found, however, that temperature and humidity became out of phase at low frequencies for data obtained in the tropical BOMEX experiment.

5) The parameterization of the directly measured sensible heat flux by the bulk aerodynamic formula fails for data exhibiting "cold spikes" whereas it appears to work for the moisture flux and heat flux data not exhibiting cold spikes in the temperature signal (Pond *et al.*, 1971; Holland, 1972; Friehe and Schmitt, 1976).

6) In studies of the temperature variance budget equation in the surface layer, the dissipation term χ was found to be several times the production term (Dreyer, 1974; Leavitt and Paulson, 1975), in contrast to overland results (Wyngaard and Coté, 1971; Champagne *et al.*, 1977) where the two terms were found to be approximately equal. Therefore, estimates of the over-ocean sensible heat flux by temperature dissipation rate measurements have not been successful (Dreyer, 1974; Leavitt, 1975), although Stegen *et al.* (1973) found agreement for the results from BOMEX.

7) Statistics of fine-scale features of the turbulent fields have been used as tests of the existence of local isotropy at high Reynolds numbers, in particular the skewness of the streamwise temperature gradient. Stewart (1969) and Gibson *et al.* (1970) found values of about +0.7 to +1.0 in the marine boundary layer compared to the expected isotropic value of zero. Recent evidence from overland and laboratory results (Mestayer *et al.*, 1976; Gibson *et al.*, 1977; Champagne *et al.*, 1977) indicate that the observed local anisotropy is characteristic of all turbulent shear flows and is not unique to over-ocean results.

Several hypotheses have been advanced to explain some of the above results, and are summarized below:

1) Phelps and Pond (1971) reported temperature and humidity data for unstable conditions from the BOMEX experiment and a preliminary experiment performed off of San Diego. Data from BOMEX showed larger phase shifts between temperature and humidity as well as larger cold spikes than from the San Diego experiment. Phelps and Pond suggested that an upper-air inversion of decreasing humidity and increasing temperature profiles would result in the observed phase reversal at low frequencies in the surface layer if the upper-air mean profile conditions were preserved in the turbulent mixing process in the boundary layer. Also radiative effects in the high humidity conditions of BOMEX were proposed as a possible mechanism for the suppression of low-frequency temperature fluctuations (Phelps and Pond, 1971).

2) Leavitt (1975) obtained temperature results similar to those of Phelps and Pond during BOMEX using different sensors (thermocouples versus platinum resistance wires). Leavitt supported the proposals of Phelps and Pond (1971) and Holland (1972) of upper-air profiles of certain forms as the cause for the observed phase re-

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[1] β_θ is defined by

$$\phi_{\theta\theta}(k_1) = \beta_\theta \chi \epsilon^{-1/3} k_1^{-5/3}, \quad (1)$$

where

$$\langle \theta^2 \rangle = \int_0^\infty \phi_{\theta\theta}(k_1) dk_1$$

θ fluctuating temperature
χ dissipation rate of $\langle \theta^2 \rangle [=2D\langle \nabla\theta^2 \rangle]$
ϵ dissipation rate of $\langle u^2 \rangle /2 [=2\nu \langle e_{ij}^2 \rangle]$
k_1 wavenumber in x_1 direction
D molecular diffusivity of θ
ν molecular diffusivity of momentum
e_{ij} $\tfrac{1}{2}(\partial u_i/\partial x_j + \partial u_j/\partial x_i)$
$\nabla\theta$ gradient of θ.

This is not to be confused with an alternate definition, β_θ':

$$\phi_{\theta\theta}(k_1) = \beta_\theta' N \epsilon^{-1/3} k_1^{-5/3},$$

where N is the dissipation rate of $\langle \theta^2 \rangle /2 [=D\langle \nabla\theta^2 \rangle = \chi/2]$ and $\beta_\theta' = 2\beta_\theta$ which has been used in some publications (e.g., Paquin and Pond, 1971; Kaimal *et al.*, 1972; Leavitt, 1975).

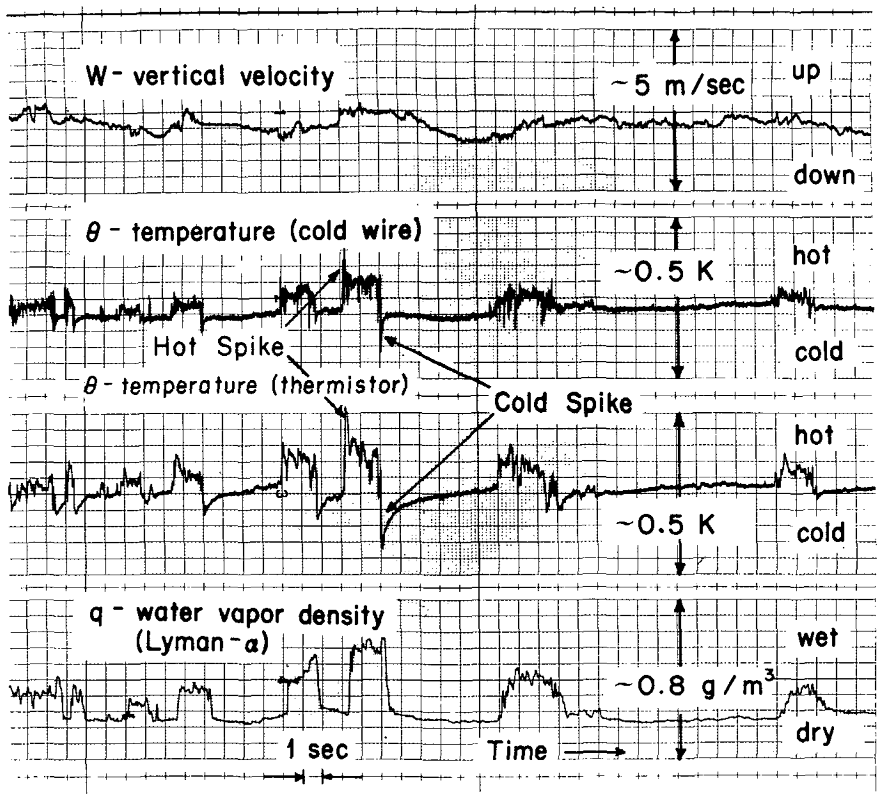

FIG. 2. Time series of vertical velocity, temperature (as measured by both a platinum resistance cold wire and a thermistor) and humidity recorded during unstable conditions in NORPAX. Reference height, $z = 29$ m; mean wind speed $\bar{U} = 6$ m s^{-1}, air temperature $T_{air} = 14.2$°C; sea surface temperature $T_{sea} = 14.7$°C.

versal between temperature and humidity at low frequencies. Also, a mechanism was proposed for the production of cold spikes by a specific mixing process acting on the mean upper-air profiles. Ocean surface temperature fluctuations were also measured during BOMEX and it was suggested by Leavitt (1975) that these could account for differences in temperature and humidity spectral shapes due to variations in the surface temperature field which could cause corresponding fluctuations in the air temperature.

3) Dreyer (1974) proposed evaporation of spray as a source of cold regions in the temperature field. Fine sheets of spray from near the sea surface entrained at the surface of horizontal roll vortices were postulated. As the vortex entrains the dryer air outside, spray evaporation occurs, cooling the layer to produce a cold spike waveform as the layer passes the temperature sensor. The vortices were proposed by Gibson *et al.* (1977) to explain the ramp-like structures of scalar fields in turbulent shear flows.

In the following sections, we review some previous experimental results and present evidence for a new hypothesis explaining the cold spike waveform. We conclude that temperature sensor surfaces in marine air become coated with salt spray which induces sensitivity to fluctuations in humidity. Results are presented from experiments with clean and contaminated probes which show the proposed effect on the time series and power spectra from temperature data obtained at the Scripps Institution of Oceanography pier.

2. Observations

The spray contamination hypothesis is based on a particularly fortunate set of measurements of over-ocean temperature and humidity made during the NORPAX Pole experiment in the winter of 1974. Fig. 2 shows a revealing set of time series from the Pole experiment data including vertical velocity from a sonic anemometer, temperature from both a thermistor and a platinum resistance cold wire, and water vapor density from a Lyman-alpha humidiometer. The sensors were positioned within 0.5 m of each other and were mounted on a telescopic tower on the R/P *Flip*. The measurements were made at a height of 29 m with a mean wind speed of 6 m s^{-1} under unstable buoyancy conditions. Both temperature signals exhibit cold spike waveforms. However, correlated with the leading edge of the square wave-type structures in the humidity signal, "hot spikes" can also be observed in the temperature signal. In addition, the thermistor exhibits larger amplitude hot and cold spikes than the cold wire, which has a much higher frequency response than the thermistor. This evidence suggests the existence of self-heating and cooling processes occurring at both sensors. An obvious candidate for such effects is the latent heat of condensation and evaporation which would actually transfer heat to and from the sensor whenever water vapor is exchanged between the air and the salt droplets on the probe surface.

Subsequent to our formulation of the present spray contamination hypothesis and initiation of the experiments included in this paper, Hicks (private communication) pointed out that he had independently observed that cold spikes in over-ocean temperature measurements were temporarily eliminated by washing the sensors in distilled water. Hicks attributed the erroneous temperature signal to the formation of a humidity sensitive shunt resistance on the probe due to salt spray accumulation. The shunt resistance mechanism would not apply as the cause of the hot and cold spikes shown in Fig. 2 since the temperature coefficients of resistance of the thermistor and platinum wire have opposite signs: a decrease in resistance caused by a humidity-sensitive shunt resistance would give an apparent decrease in temperature from the cold wire circuit, but an increase in temperature for the thermistor circuit.

McConnell (1976) inspected fine platinum resistance wire sensors under a microscope after their use over the ocean and observed salt nuclei deposits on the wires. The sensors were rinsed in distilled water, removing the salt deposits. The temperature spectra computed with the "dirty" wire before washing and with the "cleaned" wire after about 15 min exposure showed no substantial difference in this trial, indicating that the sensor had become recontaminated in the relatively short exposure time of 15 min (Steve McConnell, private communication).

3. Hypothesis

The above evidence suggests that salt spray on temperature sensor surfaces can generate erroneous signals. It is proposed that absorption and desorption of water by the spray-coated sensor is accompanied by heating and cooling effects which produce sensor temperature variation unrelated to the actual air temperature. Salt droplets are able to persist on temperature sensors under most over-ocean conditions due to the hygroscopic nature of sea salt particles which allows droplets to exist in humidity conditions considerably less than saturated. This is a result of Raoult's law which states that the equilibrium vapor pressure will be less over a salt solution than over pure water. To investigate this effect Twomey (1953) collected natural sea salt nuclei (2–20 μm in diameter) on spider webs and observed the phase transition from solid particles to drops as a function of humidity. The nuclei became drops between 71–75% relative humidity at 20°C and drop size increased with increasing relative humidity. Fig. 3, reproduced from Twomey's article, dramatically shows a 20 μm nuclei changing into a drop and increasing in size over the relative humidity range 20 to 97%. Junge (1952) and Fletcher (1962) also show a phase transition curve of drop radius versus relative humidity. A hysteresis effect was noted whereby droplets could remain in a supersaturated solution phase at relative humidities down to 30% as humidity was decreased. Thus drops exist on the probe surfaces under most marine conditions.

As a spray drop is exposed to a decrease in the local humidity, water evaporates from the drop. The latent heat of vaporization is mainly supplied

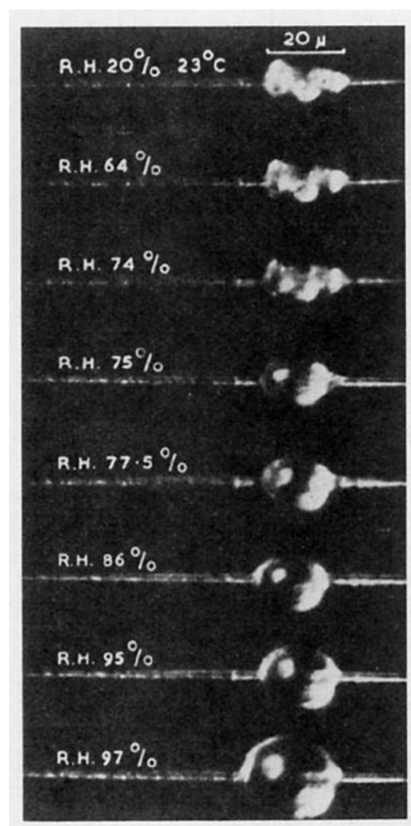

FIG. 3. A natural hygroscopic nucleus at a number of relative humidities, showing a phase change between 74 and 75% relative humidity. Reproduced by permission from Twomey (1953).

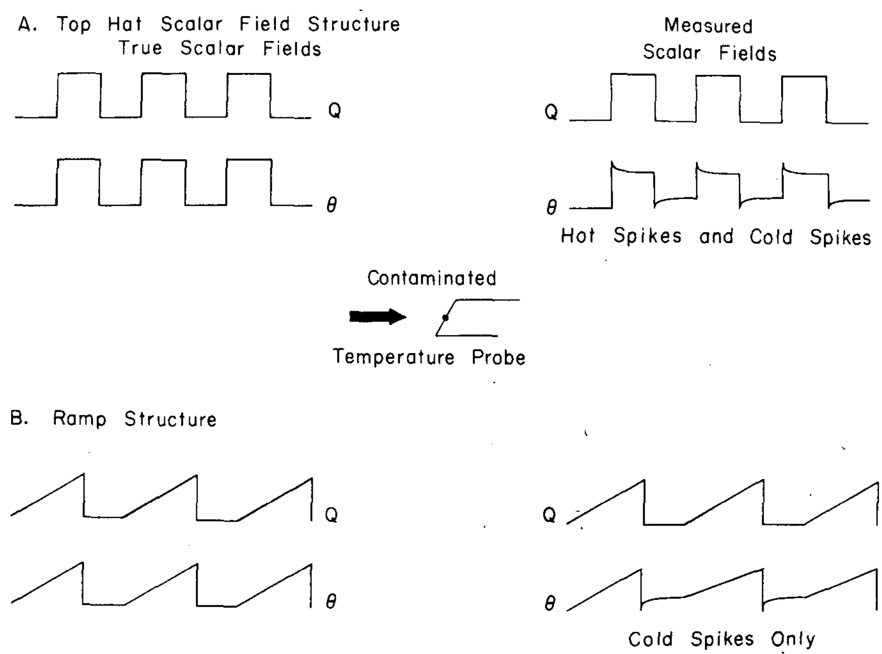

FIG. 4. Model showing the effect of salt spray contamination on a temperature sensor. If the true scalar fields have a top hat structure with temperature and humidity positively correlated as shown in (A) left, the humidity sensitive temperature sensor will exhibit both hot spikes and cold spikes, shown in (A) right. If the true scalar fields have the positively correlated ramp-like structure shown in (B) left, only cold spikes will be evident from the output of the humidity sensitive temperature sensor shown in (B) right.

by the drop, which therefore cools. If the drop is attached to a temperature sensor, the sensor cools. This is the mechanism proposed for the generation of the cold spike. As seen in Fig. 2, the cold spike occurs simultaneously with a sudden decrease of the humidity (within the time lag caused by the separation of the humidiometer and temperature probes). Conversely, when a droplet on the sensor surface is exposed to an increase in humidity, water vapor condenses on the drop and latent heat is released: the drop and the sensor become warmer. This is also shown in Fig. 2 where "hot spikes" are evident in the temperature traces when the humidity increases suddenly. The process is shown schematically in Fig. 4 for the idealized intermittent "top hat" structure of the signals of Fig. 2. The temperature and humidity structure is often more ramp-like than top hat (as in Fig. 1), and large decreases in humidity are therefore found primarily at ramp edges, producing primarily cold spikes. Large hot spikes are not produced by this type of humidity structure (Fig. 4).

The effects of salt spray contamination are not limited to the obvious hot and cold spike waveforms shown in the oversimplified model of Fig. 4. Throughout the body of the turbulently mixed top hat or ramp structure there is a continuous variety of smaller humidity changes which produce a corresponding variety of small changes in the measured temperature signal. These are not easily observed in the strip-chart traces.

A variety of time lags is apparently involved in the salt spray contamination process as can be seen from the traces in Figs. 2, 5 and 6. Time constants for both the evaporation and condensation processes occurring at the contaminated sensor will vary with the size of the droplets supported on the probe. If the evaporation and condensation time constants are not equal, a dc rectification will result, i.e., the average of the probe signal will not be the true mean temperature. In fact, the hot spikes observed in Fig. 2 appear to have shorter time constants than the cold spikes. For mean air temperature sensors, Holmes and O'Brien (1975) reported differences of up to +1.5°C when comparing simultaneous mean air temperature measurements from clean and salt-coated mercury thermometers.

The cold spike has been prominent in past experiments because of the positive correlation of temperature and humidity fluctuations, typical of open-ocean surface layer conditions where the air is unstably stratified with respect to both temperature and humidity. Under conditions where cross stability conditions occur (stable with respect to temperature and unstable with respect to humidity) a negative correlation of temperature and humidity would be expected (see Friehe *et al.*, 1975a) and different types of contamination signals would be obtained.

4. Experiments

In addition to the results shown in Fig. 2 obtained on the R/P *Flip* in the North Pacific during the NORPAX Pole experiment, experiments were conducted at Scripps Pier, La Jolla, to further investigate contamination of probes by spray.

The pier extends about 200 m from the shore and the apparatus was mounted on the end of the pier about 10 m above mean sea level. Measurements were taken when the wind direction was from the sea onto the land and under unstable conditions (with respect to both temperature and humidity) during daylight hours. Wind speeds averaged about 4 m s^{-1}. The equipment used was identical to that used on *Flip*: a Lyman-alpha humidiometer, a 70 μm diameter bead thermistor sensor operated in a dc Wheatstone bridge, a 0.62 μm diameter platinum resistance wire operated in an ac Wheatstone bridge, and a slow response EG&G Model 110 dew-point instrument for *in situ* calibration of the Lyman-alpha humidiometer. The two temperature sensors were positioned within a few millimeters of each other. After one temperature probe had been deployed for 1–3 h to accumulate salt spray, a second probe, either cleaned or new, was mounted nearby so that comparison measurements could be made. The probes were cleaned by repeated rinsing in distilled water. The humidity sensor was about 0.5 m from the temperature probes.

Temperature and humidity signals, recorded on a Hewlett Packard 3960 4-channel analog FM recorder, were digitized at a sampling frequency of 10 Hz. Blocks of records representing 10–20 min of analog data were analyzed. Higher sampling frequencies (i.e., 1000 Hz or more) were used to obtain the high-frequency portion of the temperature spectrum from the platinum resistance cold wire data. The data were analyzed on an IBM 1130 computer.

5. Results

Fig. 5a presents a time series of humidity and two contaminated thermistor temperature signals to show the ramp-like structures with cold spikes similar to those observed in over-ocean experiments. When one thermistor was cleaned by rinsing in distilled water, the cold spikes disappeared, as shown in Fig. 5b. A similar result is shown for the 0.62 μm platinum resistance cold wire in Fig. 6.

The probes were examined under a microscope before and after exposure to the marine environment. All probes exhibiting cold spikes were found to have many salt particles adhering to the wires and needle probe supports. The method of rinsing the probes in distilled water eliminated most of these salt particles. After being rinsed the probes remained "clean," as evidenced by no cold spikes, for periods ranging from about 5 to 60 min. Clearly these results alone indicate that the cold spike waveform can result from a probe contamination phenomenon.

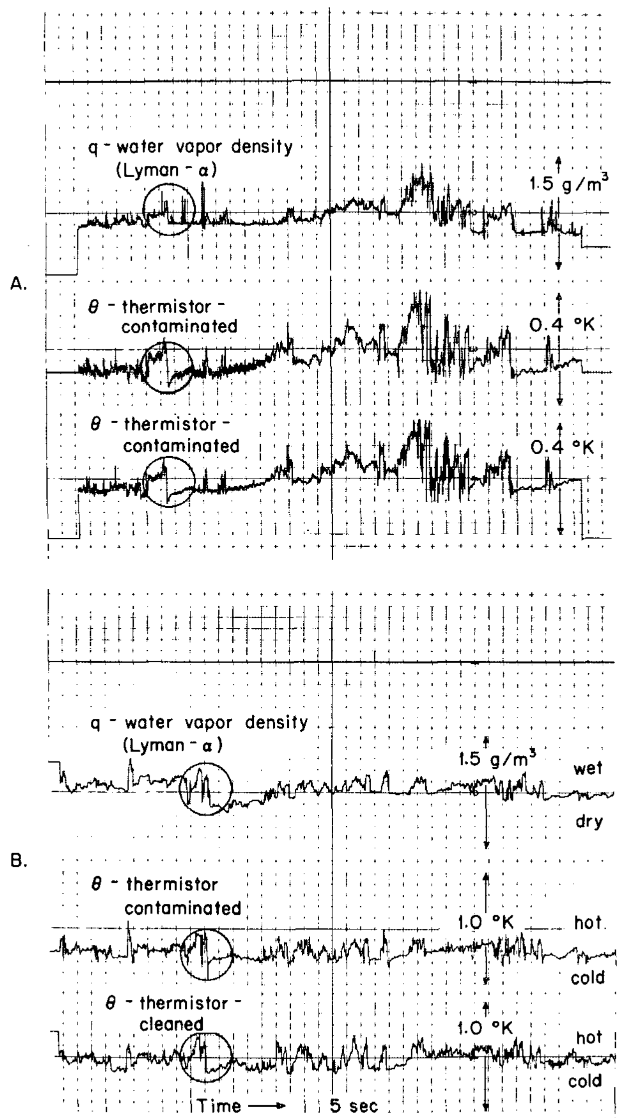

FIG. 5a. Time series of humidity and temperature as measured by two thermistors that have been exposed in the marine environment for two hours. Cold spikes are evident in both temperature signals.

FIG. 5b. One thermistor has been rinsed in distilled water and replaced in the marine environment. The cleaned thermistor exhibits no cold spikes, while the uncleaned probe continues to exhibit the spikes. z = 10 m, $\bar{U}$ = 4 m s^{-1}, T_{air} = 16.7°C, T_{sea} = 17.2°C.

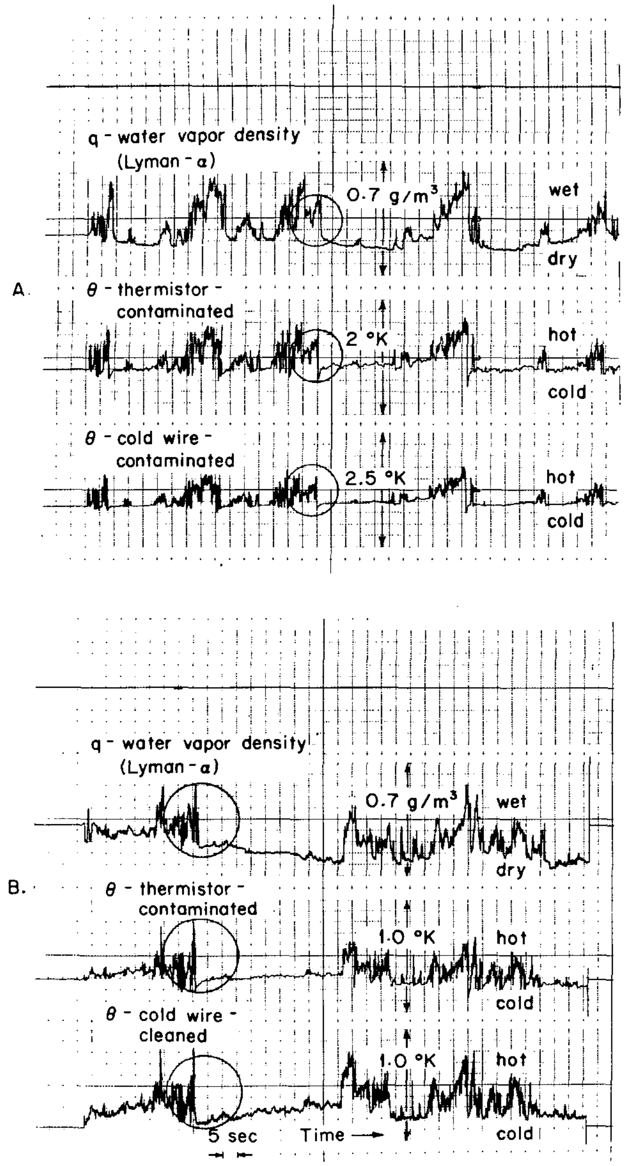

FIG. 6. Comparison between a 70 μm diameter thermistor and a 0.625 μm diameter platinum resistance cold wire. (a) Both sensors exhibit cold spikes after 1 h exposure in marine environment. (b) After being cleaned in distilled water the cold wire no longer exhibits cold spikes, although the uncleaned thermistor still exhibits the spikes. $z = 10$ m, $\bar{U} = 4$ m s^{-1}, $T_{air} = 16.1°C$, $T_{sea} = 19.4°C$.

To further test the effects of salt spray contamination on temperature measurements, a comparison was made between the spectral shapes found from contaminated and cleaned sensor data. Fig. 7 shows the results of the comparison of spectra obtained from simultaneous temperature measurements made with the cleaned and contaminated thermistors that were shown in Figure 5b. The spectra $S(n)$ have been multiplied by frequency n to the 5/3 power so that agreement with the inertial-convective subrange (shown by a straight line of zero slope in this graphical presentation) will be easily observed. At low frequencies the power amplitudes match fairly well but diverge above 0.3 Hz, and the contaminated probe spectral power level increases by a factor of 3 to 5 over the cleaned probe. The variances differ by 25% as measured by the area under the spectra to 5 Hz. The spectra shown in Fig. 8 are from a comparison between concurrent measurements made with a contaminated cold wire and the same wire a few minutes later after it had been cleaned. For this case there is discrepancy in the power levels at even the lowest frequencies.

Fig. 8 also indicates a loss of high-frequency response of the cold wire, as shown by the rapid roll-off of the contaminated spectra above 60 Hz, presumably due to contamination. It was also observed that a cleaned probe had a lower frequency response than a similar new (unused) sensor, confirming results of LaRue *et al.* (1975) and McConnell (1976).

6. Discussion

The shapes of the spectra obtained from temperature measurements in the pier experiment using probes contaminated with salt spray resemble the spectra obtained in previous experiments over the ocean. The present data suggest that spray

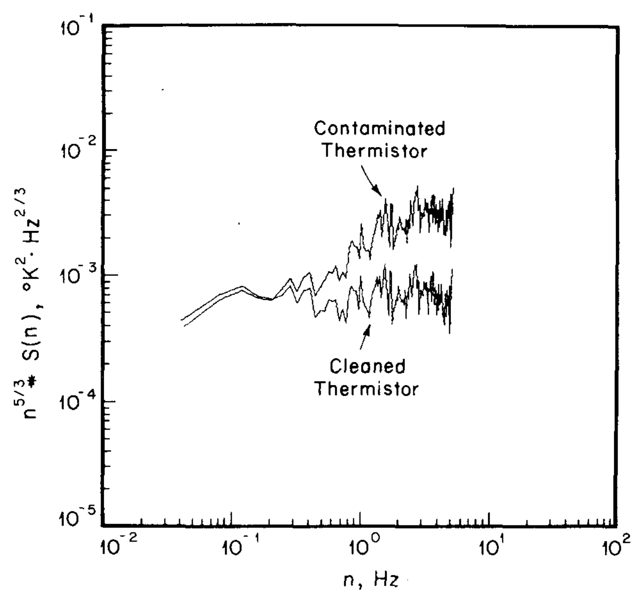

FIG. 7. Power spectra calculated for the cleaned and contaminated thermistor data shown in Fig. 5b, plotted as a functional frequency n. The spectra have been multiplied by frequency to the 5/3 power. The spectra match at the lowest frequencies, but above 1 Hz the contaminated spectrum exhibits a power level 3–5 times greater than that from the cleaned probe.

contamination is largely responsible for the observed differences between the ocean and land spectral shapes. Humidity sensitivity seems to affect the performance of temperature sensors over a large frequency range, possibly including the dc level. The contamination process can be viewed as passing the true temperature signal through a time variable nonlinear filter to produce the measured temperature signal. Figs. 7 and 8 indicate that at low frequencies (between 0.3 and 3 Hz) the contamination distorts the shape of the temperature spectrum, making the slope less steep than $-5/3$. At intermediate frequencies the contamination causes increased power levels and at the high frequencies the presence of the spray decreases the frequency response of the sensor. The distortions of the spectral shapes appear to be somewhat variable and probably depend upon the composition and amount of spray on the sensor, the type of sensor and the history and properties of the humidity field around the sensor.

Direct measurements of the temperature dissipation rate χ are therefore expected to be in error since both the increased power levels and decreased frequency response effect this measurement, although with opposite effects on the magnitude [χ is proportional to the second moment of the spectrum, $k_1{}^2\varphi_{\theta\theta}(k_1)$]. Estimates of χ using the inertial dissipation technique from Eq. (1) will generally yield high values with contaminated probes due to the increased power level in the inertial subrange, whereas estimates of χ from the indicated derivative of temperature may be high or

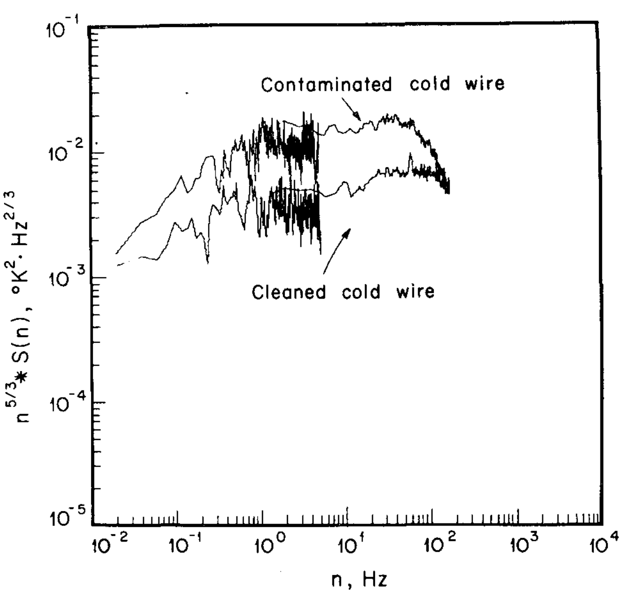

FIG. 8. Comparison of cleaned and contaminated platinum resistance cold wire data. The spectra have been multiplied by frequency to the 5/3 power as in Fig. 7.

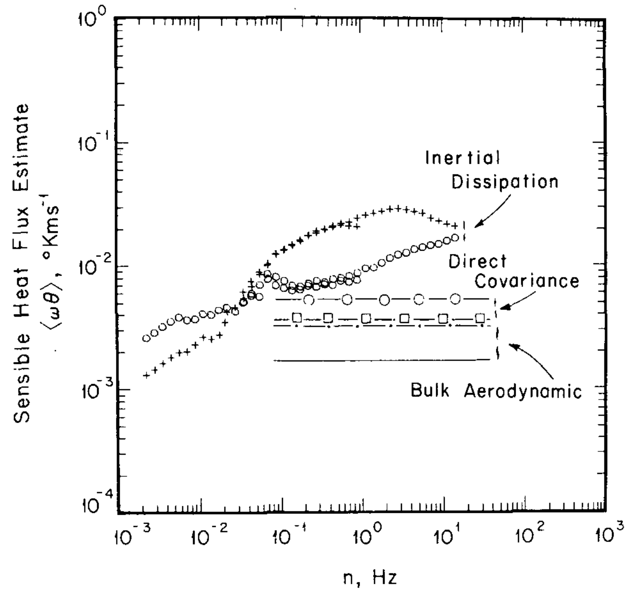

FIG. 9. Comparison of sensible heat flux measurements techniques using both thermistor and platinum resistance cold wire sensors.

Inertial dissipation method	thermistor + + + + + cold wire OOOOO
Direct covariance method	thermistor — O — O — cold wire — □ — □ —
Bulk aerodynamic method	after Friehe and Schmitt (1976) —·—·— after Pond *et al.* (1974) ———

low depending on the extent to which the frequency response has been affected. Similarly, estimates of the universal scalar constant β_θ would also be suspect as β_θ is inversely proportional to χ and directly proportional to the spectral power level.

If the temperature variance budget technique is employed to estimate χ, errors could also result. The technique usually assumes that production equals dissipation, i.e.,

$$-2\langle w\theta\rangle \frac{d\bar{\theta}}{dz} = \chi, \qquad (2)$$

where $\langle w\theta\rangle$ is the vertical velocity-temperature covariance, and $d\bar{\theta}/dz$ the vertical mean potential temperature gradient. However, it is suspected that direct measurements of $\langle w\theta\rangle$ are incorrect, again due to contamination. This is shown by a comparison of various sensible heat flux measurement techniques shown in Fig. 9 for the NORPAX Pole experiment. In Fig. 9, the estimates from the bulk aerodynamic technique are compared with direct covariance and inertial dissipation techniques for measuring sensible heat flux [see Champagne *et al.* (1977) for discussion of techniques]. The smallest value for the sensible heat flux is given by the bulk aerodynamic technique, using both the formula of Friehe and Schmitt (1976), which was based on results largely uninfluenced by "cold spike" contaminated data, and the suggested formula of Pond *et al.* (1974). It is believed that the flux estimated by the bulk aerodynamic formula is closest to the correct value, although the mean air temperature, required as input data for the bulk formula, may itself be in error (Holmes and O'Brien, 1975). The direct covariance method exhibits a higher value, by a factor of 2 or 3, for the sensible heat flux than the bulk aerodynamic technique. The inertial dissipation method yielded the highest value of the three techniques, as shown in Fig. 9. Therefore, any value of the sensible heat flux calculated by the direct or inertial dissipation techniques could be too large by a factor as much as 2.0 or more.

Great differences between the power spectra of the cold wire and the thermistor can be inferred from Fig. 9. Spray contamination may be quite different for the two probes due to the great difference in size and shape of the thermistor and cold wire (70 μm bead versus a 0.62 μm $\times$ 0.2 mm wire). Different aerosol sizes may be on the probes, resulting in different time constants.

The apparent lack of low-frequency energy in normalized temperature spectra can also be shown to be a result of spray-contaminated temperature sensors. Spectral shapes of the contaminated measurements have been shown to be distorted, for example as shown in Fig. 7. Normalization schemes used to compare a contaminated spectrum with other spectra could mask the distorted shape of the raw spectrum and lead to incorrect conclusions. As an example Fig. 7 clearly shows an excess of high-frequency energy for the contaminated data. Yet when the same two spectra of Fig. 7 are normalized according to Monin-Obukhov similarity theory after Kaimal *et al.* (1972), the contaminated data appear to lack low-frequency energy as seen in Fig. 10. [Monin-Obukhov similarity theory as employed by Kaimal *et al.* (1972) effectively collapses all temperature spectra onto a universal curve in the inertial-convective subrange by normalizing with the dissipation rate χ.] The shape of the spectrum from the contaminated sensor in Fig. 10 is typical of over-ocean measurements as reported by Phelps and Pond (1971) and Leavitt (1975). The shape of the spectrum obtained from the cleaned sensor is more typical of the overland results reported by Kaimal *et al.* (1972) and is consistent with Monin-Obukhov similarity theory. Thus, the normalizing scheme can be responsible for suggesting a lack of low-frequency energy.

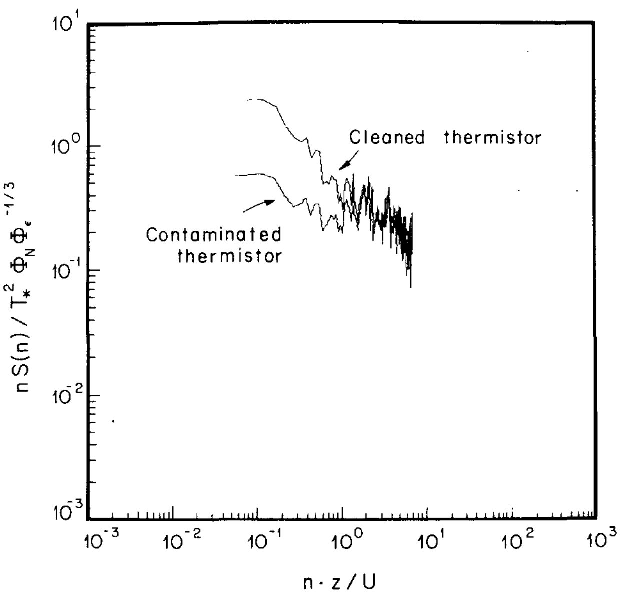

FIG. 10. Comparison of cleaned and spray-contaminated temperature spectra. The spectra have been normalized after Kaimal *et al.* (1972). [T_* is a scaling temperature, Φ_N the normalized dissipation rate of $<\theta^2>/2$, Φ_ϵ the normalized dissipation rate of $<u^2>/2$, z the height at which the measurements were made, $\bar{U}$ the mean wind velocity. See Kaimal *et al.* (1972) for further reference.] At low frequencies there is an apparent lack of low-frequency energy in the spectrum of the contaminated thermistor.

7. Conclusions

Temperature probes were found to become contaminated with salt particles after exposures in the marine surface layer for times ranging from 5 to 60 min. Since salt spray will remain in a solution phase down to relative humidities around 30–40% and salt nuclei will become droplets at relative humidities $\gtrsim$75%, the probes will be wet under most marine conditions. Due to latent heat exchanges, sensors contaminated with salt spray were found to be sensitive to humidity as well as temperature fluctuations. The presence of salt spray on temperature probes accounts for many anomalous temperature results reported from earlier experiments, including "cold spikes", lack of an inertial subrange and lack of low-frequency energy in the spectra. Large values of β_θ, failure of the dissipation rate and direct heat flux measurement techniques, and imbalance of dissipation and production terms in the temperature variance budget equation are also inferred to be due to spray contamination.

The degree to which probe contamination is responsible for some of the anomalous results is still unclear. The spray entrainment hypothesis predicts hot and cold spikes in the temperature field produced by the same mechanism as the sensor contamination hypothesis which masks temperature measurement. The relative magnitude of each effect remains to be tested with adequate sensors. Since the observed contamination effects are quite variable, depending on exposure time and type of sensor, it does not appear possible at the present time to develop a technique for decontaminating the signal to obtain the true temperature. Clearly, more temperature measurements over the open ocean are needed to resolve the questions discussed here, although to do so will require the develoment of new temperature sensors unaffected by spray contamination.

Acknowledgments. We are grateful to F. H. Champagne and J. C. LaRue for their assistance in this work, and to Bruce Hicks for his communication of his experimental observations. The electronic circuits were designed and fabricated by Tom Deaton.

This work was supported by the Office of Naval Research under Contract N00014-75-C-0152 and by The National Science Foundation under Grants IDO75-14055 through NORPAX, and under grants OCD74-22471 and DES75-07223.

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