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ON THE CORRECTION OF SHIPBOARD MINIRADIOSONDES OF THE WESTERN MEDITERRANEAN CIRCULATION EXPERIMENT - JUNE 1986

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Atmospheric soundings taken during the Western Mediterranean Circulation Experiment of June 1986 are found to contain inaccuracies due to instrument miscalibrations and ship-induced distortions. Once a criterion is established to identify those soundings in need of surface-layer modification, several corrective techniques are applied to the data. It is found that a profile correction method using surface measurements corrected for ship-induced distortions is best able to provide realistic and representative soundings within the surface layer.

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1. INTRODUCTION

In a previous report (Haggerty et al., 1988) meteorological surface and upper-air measurements were presented for three cruises of the Western Mediterranean Circulation Experiment (WMCE). Miniradiosonde plots of temperature as a function of pressure revealed the presence of superadiabatic layers, extending from the surface to tens of meters, in many cases. Haggerty et al. believed that ship influences may have been responsible for producing this phenomenon, but no attempt was made at correction.

The modification of the ambient atmospheric and oceanic environments due to the presence of a ship has been documented (Blanc, 1986). Systematic positive errors in the rudimentary measurements of surface shipboard dry- and wet-bulb temperature are to be expected due to the absorption of solar radiation and, in the case of large vessels, internal heat sources. Additionally, slight increase in humidity is likely due to ship-generated sea spray. Although not documented in the literature, it seems reasonable to believe that the temperature and humidity sensors of a ship-launched miniradiosonde would also be subject to similar platform-induced distortions.

This report examines the performance of the miniradiosonde system utilized in the experiment by means of comparison with conventional shipboard meteorological measurements. Based on findings, corrective methods are presented which will serve to mitigate radiosonde errors, and thus provide a more realistic and representative atmospheric sounding.

2. MEASUREMENTS

The data set of this study consists of 55 miniradiosondes and associated surface meteorological observations collected on three cruises in June, 1986. Two cruises were aboard the research vessel USNS Lynch. On the first cruise, 13 soundings were made in the western Mediterranean between Spain and Algeria; on the second, 26 soundings were made near the Strait of Gibraltar. The third cruise, for which 16 soundings are available, was aboard the aircraft carrier USS America, as it steamed from Palma, Spain through the Strait of Messina to Naples, Italy.

2.1 Surface

Surface measurements of temperature, humidity and pressure are of prime importance for this study. Table 1 presents a summary of dry- and wet-bulb temperature, and pressure observations; specifics regarding the Lynch crew shipboard measurements are assumed and

Table 1. Summary of temperature and pressure measurements.

			Dry-Bulb, Wet-Bulb Temperature			Pressure		
Cruise	Number of Radiosondes	Data Source	Type Instrument	Altitude ASL	Location	Type Instrument	Altitude ASL	Location
Lynch 1	13	Louisiana State University (LSU)	Aspirated Psychrometer	4M	Fantail	Aneroid Barometer	4M	Fantail
		USNS Lynch (Crew)	Sling Psychrometer	9M	Bridge	Aneroid Barometer	9M	Bridge
Lynch 2	26	Naval Environmental Prediction Research Facility (NEPRF)	* Aspirated Psychrometer	* 4M	* Fantail	Aneroid Barometer	4M	Fantail
		CALSPAN Corporation	Sling Psychrometer	9M	Bridge	-	-	-
		USNS LYNCH (Crew)	Sling Psychrometer	9M	Bridge	Aneroid Barometer	9M	Bridge
America	16	NEPRF USS AMERICA (Crew)	Aspirated Psychrometer	55M	Upper Deck	Aneroid Barometer	30M	Weather Office

ASL = Above sea level

*CALSPAN Corp. dry- and wet-bulb readings were used by NEPRF for observations corresponding to radiosondes 8-26 (LYNCH 2) after NEPRF instrument breakage.

believed accurate. Independent sets of observations are available for both USNS Lynch cruises, but not for the USS America cruise. Observations of sea surface temperature, wind, solar radiation, clouds, visibility, and sea state are also available at (or near) times of radiosonde launches.

How good are the observations? Blanc (1986) gives typical shipboard psychrometer and aneroid barometer sensor accuracies (i.e., random errors) of $\pm 0.3^{o}$C and $\pm$ 1 mb, respectively. This implies a greatest error of $\pm$ 0.6^{o}C ($\pm$ 2 mb) and a root mean square (rms) "most probable" error of $\pm$ 0.4^{o}C ($\pm$ 1.4 mb) between any two coincidental psychrometer (aneroid barometer) readings. Standard deviations of the differences between USNS Lynch data sets are presented in Table 2. Standard deviations of dry-bulb temperature differences are approximately twice the rms "most probable" error in all cases. A wider scatter is found for standard deviations of wet-bulb temperature differences, with only the Calspan minus NEPRF differences close to the expected rms error. Standard deviations of pressure differences between the Lynch, and the LSU and NEPRF data, are three times the "most probable" error, and twice the greatest error. Standard deviations calculated for the differences between pressures taken from Fleet Numerical Oceanography Center (FNOC) surface charts (which did not incorporate USNS Lynch data) and either Lynch, LSU or NEPRF measurements are also large, varying from 2.9 to 4.0 mb.

Table 2. Difference standard deviations for USNS Lynch dry-bulb temperature, wet bulb temperature and pressure data.

	Standard Deviation			
Difference	No. Data	Dry-Bulb Temp. (°C)	Wet-Bulb Temp. (°C)	Pressure (mb)
Lynch - LSU	13	0.9	0.8	4.4
Lynch - NEPRF	7(6)	1.7(0.9)	1.8	-
Lynch - NEPRF	24	-	-	4.0
Lynch - Calspan	24	0.9	1.7	-
Calspan - NEPRF	7	0.7	0.5	-
Lynch - (LSU+Calspan)	37	0.9	1.4	-
Lynch - (LSU+NEPRF)	37	-	-	4.2

( ) after removal of outlier

Many factors could be responsible for the large differences between measurements, including altitude, location (exposure), time, instrument calibration and measurement technique. Small differences in altitude and time of observations should result in only slight observational disagreements. Both the USNS Lynch's fantail and deck provide comparable exposure to the ambiente, away from sources of local ship heating.

Improper measurement technique is quite common with wet-bulb observations; a dirty muslin, or one too wet or not wet enough, will result in too high a psychrometer reading. A positive bias in Lynch wet-bulb temperature is noted, with all but two of the crew's measurements greater than those of the LSU, NEPRF and Calspan groups; no bias is noted in the Calspan minus NEPRF wet-bulb temperature differences.

Instrument calibration appears to have been a problem in pressure measurements. The Lynch crew measurements were in all cases greater than the derived FNOC surface pressures (ranging from +1.5 to +4.8 mb, with an average deviation of +3.1 mb), and were also greater than the LSU and NEPRF measurements in over 75% of the cases. While no bias is apparent between FNOC pressures and measurements by LSU and NEPRF, a comparison of these data suggests that the aneroid barometers employed by LSU and NEPRF, while calibrated at the beginning of each cruise, went out of calibration a few days thereafter.

With a joint observational effort, the meteorological reports of the USS America's weather office and NEPRF should be in agreement. Although such an agreement in general does occur, a close examination of all available data also indicates that, in some instances, erroneous surface temperature and/or pressure information was used for radiosonde calibrations. A comparison of the USS America's sea level pressure reports and values read from FNOC surface pressure maps shows excellent agreement (standard deviation of 0.6 mb). This result is to be expected, since the USS America's ship reports were used in the construction of the FNOC surface pressure charts.

2.2 Miniradiosonde

A high resolution miniradiosonde system (AIR/Airsonde model AS-1C-PTH) and associated data acquisition device (AIR/ADAS model AIR-3B) were used for determination of atmospheric soundings of pressure, dry-bulb temperature, and wet-bulb temperature during the second USNS Lynch cruise. AIR, Inc. model specifications give an accuracy of $\pm$ 3 mb for the Airsonde pressure sensor, and $\pm$ 0.5° C for the wet- and dry-bulb temperature sensors. A different AIR/Airsonde model was utilized aboard the USS America and for the first USNS

Lynch cruise; with this model, a relative humidity sensor is used in place of a wet-bulb sensor. Radiosondes were launched from the fantails of both the USNS Lynch and the USS America, at 4 m and 12 m above sea level, respectively.

Standard deviations of differences between surface radiosonde values and observations are given in Table 3. Pressure differences are observed to be well in excess of $\pm$ 4 mb, which is the greatest error to be expected, based on AIR, Inc. and Blanc (1986) sensor accuracies. Of the 55 data pairs considered, only four had pressure differences less than this greatest error. Additionally, every radiosonde value except one was less than the observed pressure. The existence of this strong negative bias of very large radiosonde-observation pressure differences appears to sharply contradict the manufacturer's claim that the Airsonde is shipped fully calibrated and requires no baseline check before launch.

Table 3. Dry-bulb temperature, wet-bulb temperature, and pressure standard deviations for the differences between surface radiosonde values and shipboard observations.

Difference	No. Data	Standard Deviation						Pressure (mb)
		Dry-Bulb Temp. (^{o}C)			Wet-Bulb Temp. (^{o}C)			
		Total	Day	Night	Total	Day	Night	
USNS Lynch								
LSU - Sonde	13	0.8	0.9	0.8	1.1	1.4	0.9	9.1
NEPRF - Sonde	26	2.7	3.7	0.5	1.8	2.4	0.5	15.3
(LSU+NEPRF) - Sonde	39	2.3	3.1	0.6	1.6	2.2	0.7	13.6
USS America								
NEPRF - Sonde	16	2.2	2.8	2.0	1.2	1.5	1.1	63.6 (11.9)

( ) Value excludes 3 outliers

Note: USNS Lynch sonde of 25 June (0752 local time) considered only for pressure; wet-bulb temperature exceeded dry-bulb temperature from surface to 700 m.

Examination of the dry-bulb temperature differences between surface radiosonde values and psychrometer readings (Table 3) indicates significant variations (standard deviations of 0.8^{o}C to 2.7^{o}C) among cruises (i.e. meteorological teams). The difference standard deviations for the second USNS Lynch cruise and the USS America cruise are well in excess of a greatest error of 0.8^{o}C, as determined from Blanc (1986) and AIR, Inc. sensor accuracies.

To further examine temperature differences, the data was separated into "day" and "night" measurements. Here, day was arbitrarily designated as 0930 to 1830 local time, an interval a few hours after (before) sunrise (sunset) when shipboard heating due to solar radiation is a significant factor. This temporal grouping of the data results in a very marked disparity of day and night temperature differences for the second USNS Lynch cruise (Table 3). Further examination of this data reveals that, during the day, most (12 of 14) of the radiosonde surface dry-bulb temperature values were in excess of the corresponding psychrometer readings; during the night, small, random radiosonde-psychrometer temperature differences were observed. Little disparity between day and night temperature differences occurred on the first USNS Lynch cruise. Substantially larger nighttime radiosonde/psychrometer dry-bulb temperature differences were reported for the USS America cruise than for either USNS Lynch cruise; this likely reflects the more complex and varying micro-environment of the USS America as recorded by widely separated sensors.

Wet-bulb temperature differences between surface radiosonde measurements and psychrometer readings are also displayed in Table 3. Difference standard deviations for all three cruises are lower for night measurements. The largest standard deviation (2.4 ^{o}C) is noted for the daytime data of the second USNS Lynch cruise; for this data, the radiosonde wet-bulb temperature is found to equal (once) or exceed the psychrometer reading in all cases (14).

What are the contributing factors for the inconsistencies between surface radiosonde-psychrometer temperature measurements? Unlike the miniradiosonde pressure sensor, no systematic bias (due to a problem of instrument calibration) is apparent for the Airsonde temperature and humidity sensors utilized during this experiment. Inspection of the LSU and NEPRF psychrometer measurements reveals neither instrument calibration problems nor faulty measurement techniques. Provided radiosonde and psychrometer sensors were suitably calibrated, the existence of differences between radiosonde and psychrometer measurements seems to imply: 1) that the radiosonde and psychrometer temperature and humidity sensors responded differently to environmental factors, or 2) that the instruments were utilized in an incongruous, inconsistent manner, or 3) that inaccuracies occurred in data reduction and representation.

Given similar dry-bulb and wet-bulb temperature sensor accuracies for the Airsonde and psychrometer (0.5^{o}C and 0.3^{o}C, respectively), it does not seem plausible that large temperature differences can be ascribed to differences in sensor response to the ambiente. In other words, provided both the Airsonde and psychrometer instruments are properly calibrated and employed, environmental conditions such as the wind speed, and the amount of solar radiation and cloud cover, should have similar influences on both Airsonde and psychrometer temperature measurements.

Due to the rather benign and steady meteorological conditions encountered during the three WMCE cruises, differences in time between shipboard measurements and radiosonde launch, even if a few tens of minutes, are not likely to have been a major contributor to the observed large radiosonde-psychrometer temperature differences. Altitude and location differences between radiosonde and psychrometer measurements were quite large aboard the USS America; as a consequence, due to differential superstructural heating, widely separated sensors could register significant temperature differences. Examination of the raw radiosonde data indicates that imperfect measurement technique, including placement of the Airsonde upon a hot deck surface and launching of the sonde before wet- and dry-bulb temperature sensor stabilization could occur, was the predominant contributor to the very large daytime radiosonde-psychrometer temperature differences during the second USNS Lynch cruise. The raw radiosonde data from the first USNS Lynch cruise and from the USS America also suggests that, in several instances, radiosondes were launched before the Airsonde sensors had fully adjusted to the ambiente.

The inability to accurately determine a radiosonde launch time from the raw data contributed to radiosonde-psychrometer dry- and wet-bulb temperature differences for some data from the USNS Lynch (first cruise) and the USS America. Such data reduction errors were most critical for those sonde launches where the temperature and humidity sensors were still adjusting to the ambiente. Comparisons of the USS America weather office data with NEPRF dry- and wet-bulb temperature reports reveal inconsistencies in a few instances; because of this, the corresponding radiosonde-psychrometer differences are subject to uncertainty.

3. MINIRADIOSONDE CORRECTIONS

3.1 Entire Sounding

Radiosonde errors due to instrument miscalibration should be considered invariant since any improperly calibrated instrument is not likely to self-correct. Consequently, soundings based on poorly calibrated sensors need to be corrected consistently throughout, from launch to last data transmission.

In the previous section, the conclusion was reached that the Airsonde pressure sensor did not perform suitably during the WMCE due to instrument calibration problems. Airsonde soundings may be corrected for pressure by utilization of available surface pressures - either shipboard measurements (from aneroid barometers) or FNOC values (from surface charts). This correction, or calibration, simply involves the addition of the signed value of the surface pressure observation minus the surface radiosonde value, to all pressure values (surface to top) of the sounding under consideration. Since evidence indicates that, during both USNS Lynch cruises, the aneroid barometers used for surface pressure measurements were not free from calibration problems, the utilization of FNOC derived surface pressures is preferable over shipboard measurements for USNS Lynch Airsonde pressure calibrations. Without evidence to the contrary, USS America shipboard barometer measurements are assumed suitable for calibration purposes.

In their data volume, Haggerty et al. (1988) calibrated all soundings by the above-described method, using shipboard pressure measurements. Additionally, the soundings of the first USNS Lynch cruise and the USS America cruise were calibrated, in an analogous manner, for temperature and humidity, using shipboard psychrometer measurements. The need for such entire-layer, uniform sonde corrections for temperature and humidity is not established, since the data suggests that neither the Airsonde temperature nor humidity sensors experienced calibration problems.

As discussed in the previous section, data reduction errors occurred in several soundings for the first USNS Lynch cruise and the USS America cruise. For these data, any adjustment (for corrective purposes) in the time of launch would change the surface Airsonde measurements. If the "corrected" Airsonde surface pressure value is subsequently calibrated with a surface measurement, pressure values for the entire sounding would be altered and, existing temperature and humidity values would be adjusted to slightly different pressure levels.

3.2 Surface Layer

Distortions in temperature and humidity measurements of a ship-launched Airsonde are induced by that ship's superstructure. Such ship-induced distortions can be greatly aggravated by improper radiosonde launch procedures. Fortunately, though, radiosonde errors due to ship influences (e.g. ship heating) should diminish rapidly and soon disappear as a sonde moves steadily away from the ship's influence and adjusts to the "free" ambiente. In such a case, corrections to a sounding would only need to be applied for a limited vertical layer above the ship's surface.

In order to select those soundings of the WMCE which are in need of modification, a selection criterion must first be established. To set this criterion, a virtual potential temperature is calculated for the average surface dry- and wet-bulb temperatures (20.8°C and 18.0°C, respectively), and pressure (1015.2 mb), during the WMCE. (N.B., the transformation to virtual potential temperature is made for the sake of data simplicity, and is used henceforth.) Based on sensor accuracies given by Blanc (1986) and AIR, Inc., this virtual potential temperature (θ_v = 294.75° K) would have a greatest error of $\pm$ 0.43° C, if calculated from shipboard psychrometer and aneroid barometer measurements, and a greatest error of $\pm$ 0.82°C if derived from Airsonde sensors. The combined error, 1.25°C, represents a critical limit, being the greatest expected difference between shipboard and Airsonde virtual potential temperatures. This critical limit is based solely on sensor accuracies; no consideration is given to the effects of ship-induced distortions on sensors, nor measurement differences due to time, location or procedures. For this report, soundings where the magnitude of the difference between the observation virtual potential temperature, as derived from shipboard psychrometer and aneroid barometer measurements, and the sonde virtual potential temperature, calculated from the surface Airsonde temperature, humidity and (corrected) pressure measurements, exceeds 1.25°C will initially be considered candidates for correction.

Examination of the 39 soundings from the USNS Lynch indicates that 12 have virtual potential temperature differences (sonde minus observation) greater than 1.25°C. All of these soundings occurred in the early afternoon; in all cases, differences appear to be directly related to improper Airsonde launch procedures. Additionally, one sounding from the first USNS Lynch cruise had a sonde virtual potential temperature 1.5°C less than the observation virtual potential temperature. Since the raw data suggests that the Airsonde launch technique was correct, it is conceivable that the observational value is incorrect. Because of uncertainty, this sounding is best not corrected.

Due to considerable altitude and location differences between the Airsonde and shipboard measurements aboard the USS America, the criterion for selection of soundings for correction (viz., sonde-observation virtual potential difference > 1.25°C) is not as firm for USS America soundings as those of the USNS Lynch. Nonetheless, in spite of obvious shortcomings, this 1.25°C difference criterion does provide a convenient and suitable way to identify those USS America soundings which would benefit from surface-layer corrective methods.

Sonde-observation virtual potential differences exceeded 1.25°C in ten of the USS America soundings; this result is based on several subjective judgments as to which surface measurements - NEPRF's or the USS America deck log's - are valid. In 9 of these 10 cases, the sonde virtual potential temperature exceeded that derived from surface measurements; of these nine, only two occurred during the day (0930 to 1830 local time) when shipboard heating due to solar radiation is important. In the remaining case, the observation exceeded the sonde virtual potential temperature by 1.5°C. Here, unlike the other 9 soundings, the sonde air temperature lay between the sea surface temperature (SST) and the shipboard air temperature measurement (at ~55 m); this suggests that the sonde's near-surface profile be best left uncorrected.

A listing of the 21 WMCE soundings initially chosen for surface-layer correction is given in Table 4. Various correction methods, ranging from the simple to the complex, can be applied to these soundings. Because high-resolution, low-level profiles are not available for the undisturbed atmosphere surrounding the ship, there is no definitive way to assess how well any particular correction method performs in providing a more realistic and representative atmospheric surface-layer profile. Obviously, any method which utilizes surface shipboard measurements would be subject to the reliability of such data.

The first correction method to be examined (Method 1) makes direct use of shipboard measurements to modify the near-surface atmospheric profile. Starting with the sonde's first two virtual potential temperature values above the surface, the corresponding slope is extrapolated down to the surface. If the extrapolated surface virtual potential temperature falls within a preassigned limit about the independent observation of virtual potential temperature, the extrapolated slope represents the surface-layer modification to the sounding. If the extrapolated value does not fall within the prescribed limits of the observation virtual potential temperature, the next higher profile slope, corresponding to the previous highest sonde value under consideration and the one immediately above, is extrapolated downward

Table 4. WMCE June, 1986 soundings initially chosen for surface-layer correction.

Cruise	Day	Launch Time GMT	Cruise	Day	Launch Time GMT
Lynch 1	05	1150	Lynch 2	17	1203
				18	1152
America	18	0031		20	1148
	18	0607		22	1051
	19	0708		22	1209
	22	0606		23	1149
	22	1157		24	1147
	23	0612		25	1152
	23	1313		26	1144
	24	0633		28	1149
	25	0555		29	1141

Local Time = Greenwich Mean Time (GMT) + 2 hours.

to the surface. If the extrapolated surface virtual potential temperature falls within the specified range about the surface observation value, then this extrapolated slope is the sounding correction. If not, the entire process is repeated, until an acceptable value is found.

In this method, the shipboard virtual potential temperature is assigned to the same altitude as the sonde surface virtual potential temperature. For the USS America cruise, this means that ship measurements taken at 55 m are assumed valid at 12 m, the sonde launch height. This assumption is reasonable considering lapse rates found within the marine planetary boundary layer, which normally are less than a few tenths of a degree over a vertical depth of 43 m.

Obviously, the profile correction resulting from this method is very dependent upon how close the surface extrapolated virtual potential temperature is required to be to the observation virtual potential temperature. In general, the larger this difference, the less the modification (in shape and depth) of the sounding; contrarily, the less this difference, the more the sounding modification. There is no guarantee that this method will always work; failure could occur if the initial surface sonde-observation virtual potential temperature difference was exceedingly large and/or the required surface extrapolated-observation virtual potential temperature difference was very small.

An appropriate value for the surface extrapolated observation virtual potential temperature difference of Method 1 is 0.88°C. This value represents the "most probable" rms expected difference, as determined from Blanc (1986) and AIR, Inc. sensor accuracies at the WMCE average surface virtual potential temperature (294.75°K). Application of Method 1 to the 21 designated radiosondes of Table 4, using the 0.88°C correction criterion, results in an average surface virtual potential temperature sonde correction (viz., decrease) of 3.1°C. The depths over which the soundings are corrected range from 3 to 168 m above the launch site, averaging 74 m. An example of a Method 1 correction is given in Figure 1.

A variation on the above method (designated Method 2) involves the correction of the surface observation virtual potential temperature for ship-induced distortions. According to Blanc (1986), systematic positive errors occur in shipboard dry- and wet-bulb temperature measurements, as the air is warmed due to solar heating of the ship's superstructure and deck; additionally, humidity readings are slightly high due to ship- generated sea spray. Blanc gives typical ship-induced errors of +0.5° C (0.0°C) and +0.7°C (+0.2°C) for daytime (nighttime) dry- and wet-bulb temperature, respectively. These values correspond to an approximate +0.6°C (+0.1°C) error in daytime (nighttime) virtual potential temperature. In this method, sonde virtual potential temperature values, including surface extrapolated values, are not corrected for ship-induced distortions.

Once a surface observation virtual potential temperature has been corrected for ship-induced distortions, Method 2 proceeds exactly as Method 1. Because the 1.25°C selection criterion is here applied to the difference between the sonde surface virtual potential temperature and the corrected observation virtual potential temperature, two other USNS Lynch soundings (2 June 1548 GMT and 27 June 1150 GMT), in addition to those listed in Table 4, qualify for correction. For these 23 radiosondes, application of Method 2 yields an average surface virtual potential temperature sonde correction (viz., decrease) of 3.3°C. Soundings are corrected over depths ranging from 25 to 230 m, with an average (mean) correction depth of 90 (78) m. An example of a profile corrected by this method is shown in Figure 1.

As expected, Method 2 surface sonde virtual potential temperature corrections, and accompanying profile correction depths, equaled or exceeded Method 1 values in all cases. Interestingly, a comparison of Method 1 and 2 results reveals that, for all 9 USS America soundings, Method 1 and 2 profile corrections are exactly the same; this result occurs but once for USNS Lynch soundings.

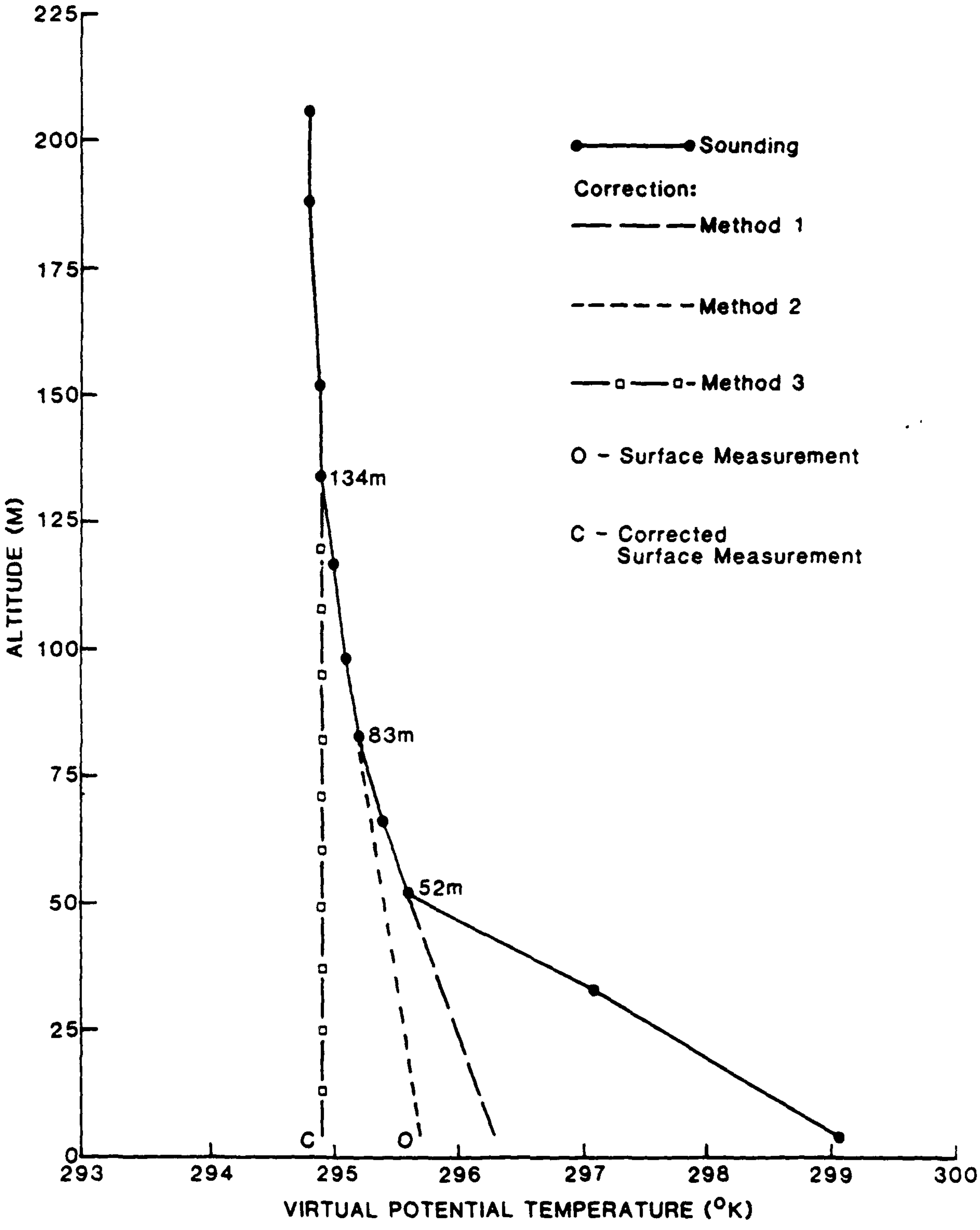

Figure 1. USNS LYNCH sounding of 28 June 1149 GMT, with Method 1, 2, 3 profile corrections.

Method 3 is based on the widely accepted concept of a well-mixed surface marine boundary layer. A well-mixed boundary layer is neutrally stratified, with virtual potential temperature constant (or very nearly so) with height. Over the oceans, mixed layers are very common at heights from some meters to several hundreds of meters above the sea surface. A surface mixed-layer is found in all 55 WMCE soundings.

Unlike Methods 1 and 2, shipboard measurements are not required in Method 3, but this method does require the calculation of sonde virtual potential temperature slopes. In Method 3, sonde (2-point) virtual potential temperature slopes are examined sequentially (from the lowest to the next higher) until a slope of less than $|.005|^{\circ}$C/m is encountered. This slope, extended downward to the surface sonde height, represents the profile correction. As with previous methods, there is no guarantee that this method will always work.

The slope criterion of $|.005|^{\circ}$C/m was arbitrarily chosen. Segments of any sonde where the virtual potential temperature gradient is less than $|.005|^{\circ}$C/m are considered neutrally-stratified, "constant" virtual potential temperature layers. For a typical sonde data spacing of 20 m, this criterion equates to a change in temperature of only 0.1°C. Considering the accuracies of the Airsonde's pressure, temperature and humidity sensors, this $|.005|^{\circ}$C/m slope criterion for determination of the surface well-mixed layer is very robust.

To examine the performance of Method 3, the 23 soundings selected for correction with Method 2 were utilized. The average base of the mixed-layer (and the depth of the profile correction) was 90 m. Interestingly, in about 70% of the cases, the slope at the base of the "constant" virtual potential temperature layer was exactly equal to zero. Although average sonde surface virtual potential temperature corrections were comparable to Methods 1 and 2 (at 3.2°C), in six instances the Method 3 corrected sonde surface virtual potential temperature exceeded the surface observation virtual potential temperature (corrected for ship effects) by more than 0.88°C. Method 3 profile corrections differed from those of Method 2 for 40% of the soundings. An example of a Method 3 profile correction appears in Figure 1.

The existence of surface shipboard observations within the WMCE data makes boundary-layer profile corrections with Methods 1 or 2 more advantageous than with Method 3. The definition of the lower extremity of a boundary-layer profile, as done in Methods 1 and 2, permits a true (although simple) interpolative process. By correcting for ship-induced distortions in surface observations, Method 2 is best able to provide a vertical profile of the undisturbed boundary layer away from a ship.

Another method which merits consideration is a surface-layer correction based on Monin-Obukhov (M-O) similarity theory. With this theory, a dimensionless virtual potential temperature gradient in any quasi-steady, locally homogeneous surface layer is defined by,

$$\frac{\partial \theta_v}{\partial z} = -\ (\theta_{v_*} / z\kappa)\, \phi_{\theta_v} \tag{1}$$

where z is the height above the surface, κ is von Karman's constant, θ_{v_*} is a virtual potential temperature scaling factor, and ϕ_{θ_v} is a profile shape function. This formula is best suited for the semi-empirical profile (or gradient) technique, which utilizes high-resolution measurements of wind speed, temperature and humidity at multiple altitudes. Without such measurements, as in the case of the WMCE, formula (1) can be solved by the bulk aerodynamic method, which calculates surface fluxes based on available SST and shipboard measurements.

Given bulk method estimates of the surface stress, and the sensible and latent heat fluxes, the gradient scaling parameter θ_{v_*} can be determined. The profile shape function ϕ_{θ_v} is represented in terms of the dimensionless M-O stability parameter,

$$\zeta = z/L = zg\kappa\theta_{v_*} / \theta_{v_z} u_*^2 \tag{2}$$

which gives the ratio of buoyant production of total kinetic energy (TKE) to mechanical production of TKE within the atmosphere's surface layer. In formula (2), L is the M-O length scale, g is the acceleration due to gravity, and u_* is the wind speed scaling parameter (determined from the surface shear stress). Formulae for $\phi_\theta(\zeta)$, for neutral, stable and unstable stratifications, are given by Walmsley (1988). Under near-neutral stability conditions, $|\zeta| <= 0.02$, the virtual potential temperature profile exhibits a linear form when plotted on a semi- logarithmic graph (i.e., ln z vrs. θ_v). With increased stability or instability, the profile becomes nonlinear, and nonlinear corrections need to be applied.

Although very useful in boundary-layer studies, similarity theory is not a good choice for WMCE sonde corrections for several reasons. Compared to previous methods, it is more complex and difficult to apply. The bulk method requires that shipboard measurements of wind, temperature and humidity be at the same height; during the three WMCE cruises, this never occurred. In order to satisfy this requirement, measurements would need to be adjusted to a common altitude, by means of a priori assumptions as to shapes of the wind, temperature and humidity surface-layer profiles.

A more fundamental difficulty with a correction method based on similarity theory concerns the reliability of the data. In simple terms, accurate measurements of SST, air temperature, humidity and wind are required. Results of the previous section suggest that errors in USNS Lynch and USS America shipboard measurements were not always at expected values. In the bulk method, SST and an assumption of 100% relative humidity define the virtual potential temperature at the air-sea interface. Comparisons of USNS Lynch bucket (LSU + NEPRF) and injection (Lynch crew) sea surface temperatures, raise serious doubts concerning data accuracy. Here, for 36 data pairs, a standard deviation of 1.6^{o}C is found. This value is well in excess of a $\pm$0.7^{o}C rms expected difference, based on Blanc's (1986) $\pm$0.5^{o}C bucket and thermometer sensor accuracy and an assumed similar SST sensor accuracy for the injection method. Unlike other studies (Ramage, 1984), no apparent systematic bias is noted between bucket and injection temperatures.

Further evidence of the unsuitability of the WMCE shipboard and SST data for similarity theory is given in Figure 2. Here, 36 air-sea temperature differences, as calculated from USNS Lynch (LSU and NEPRF) data, are plotted against analogous differences computed from Lynch crew data. Neutral stability conditions, defined as an air-sea temperature difference <= 0.5^{o}C, are observed in only one third of the cases for each data set; of these cases, agreement between data sets (in regards to neutral stability) occurred but just once! Overall, a large standard deviation of 1.9^{o}C occurs between LSU and NEPRF, and Lynch crew, data sets. These results imply that, in many instances, near-surface profiles determined from similarity theory would differ markedly in shape and/or slope orientation (i.e., sign) depending upon which set of shipboard and SST measurements were used.

Even with suitably accurate shipboard and SST measurements, further complications could arise in the application of similarity theory to correct surface-layer radiosonde data. In general, there is no guarantee that a derived near-surface profile, or such a profile extrapolated vertically, will intercept any given vertical sounding or, if it does, that such interception would be "smooth" and not at a sharp angle. Provided one of these two conditions arises, further surface-layer profile modifications would be needed to realistically and smoothly "mesh" the near- surface derived profile with the noncorrected vertical sounding at mixed-layer height and above.

Up to this point, profile correction methods from the base of the sounding upward have been considered. An additional correction, above-deck and typically over a shallow depth of several tens of meters, is required for half of the 16 USS America soundings. This correction eliminates anomalously warm data points recorded as a sonde ascended through

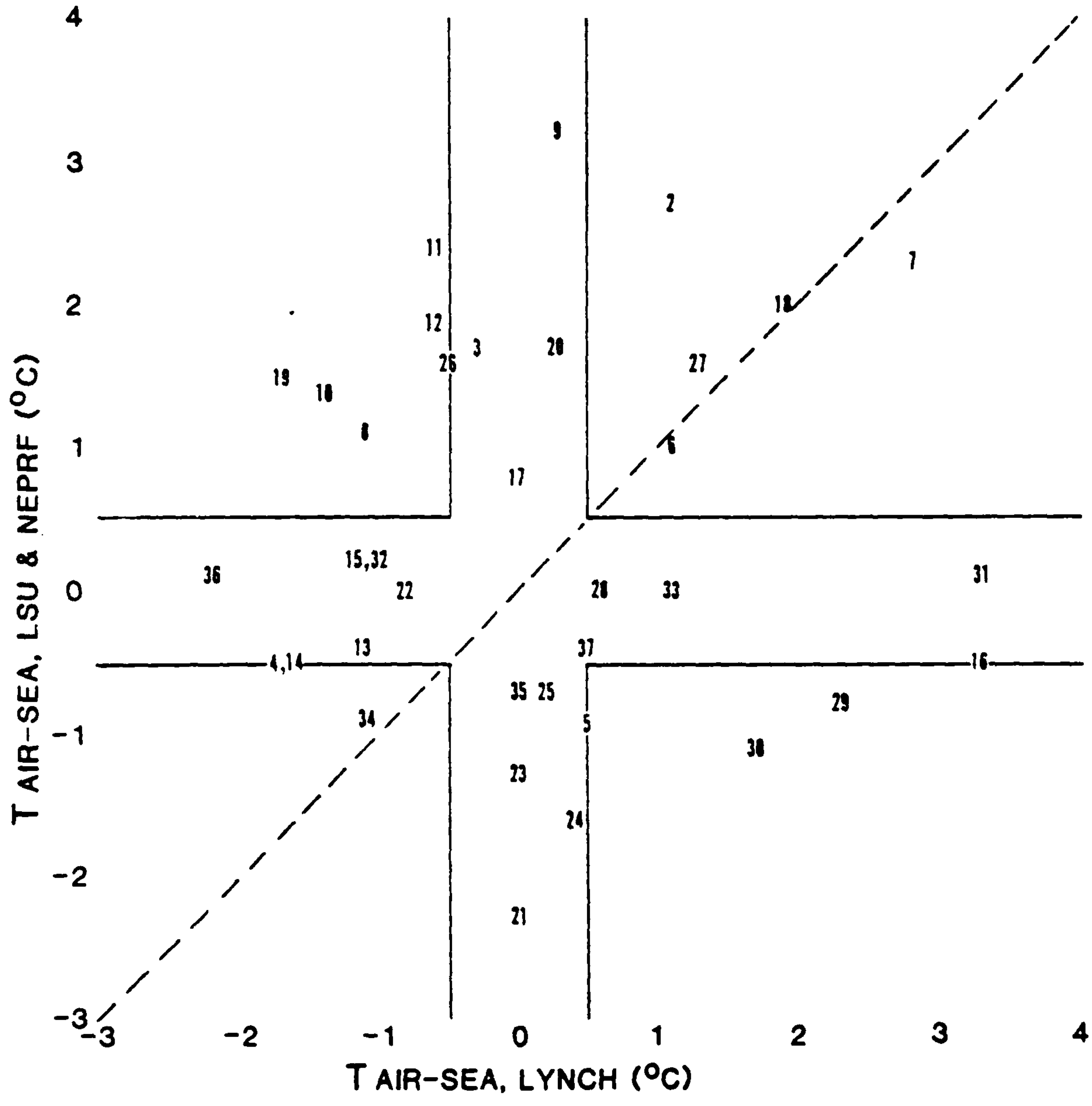

Figure 2. USNS LYNCH air-sea temperature differences: abscissa, LYNCH crew; and ordinate, LSU & NEPRF. Data are given by radiosonde launch sequence number. Dashed line represents perfect correlation. Neutral stability, $T_{air\text{-}sea} \leq 0.5°C$, delineated for each data set.

the aircraft carrier's exhaust plume. To apply this method, USS America sounding data points (up to 100 m above launch deck) are sequentially checked (bottom upward) for a point-to-point virtual potential temperature "jump" of >= 0.5°C. If found, this "jump" point is eliminated, as well as all values immediately above, until a point-to-point virtual potential temperature decrease of >= 0.5°C is encountered. A line connecting the sounding discontinuity endpoints represents the exhaust plume correction. An example of this correction is given in Figure 3. Where required, this correction should be applied before any of the previously discussed surface-layer corrections (Methods 1, 2, or 3).

4. SUMMARY AND DISCUSSION

Atmospheric soundings obtained during the WMCE are found to contain inaccuracies due to instrument miscalibrations and ship- induced distortions. For all soundings, inaccurate pressure data can be adequately calibrated using reliable, independent surface values. Dry- and wet-bulb temperature data should not be "calibrated," but rather only corrected within the surface layer.

Based on typical sensor accuracies, a criterion is established to identify those soundings in need of surface-layer modification. Various techniques are presented which, if utilized, would mitigate the adverse influences of ship-induced distortions on sounding data within the near-surface layer. A correction method based on similarity theory is not advisable due primarily to insufficient accuracy of shipboard data. Where required, it is recommended that WMCE surface-layer profiles be modified using surface measurements corrected for ship-induced distortions (Method 2).

It can be argued that the utilization of any of the surface-layer correction methods described in this report, which in many cases essentially results in the extention of a sounding's mixed-layer profile down to the surface, counters one of the main attributes of the miniradiosonde - namely, high-resolution profile data within the atmosphere's boundary layer. However, for many applications, the use of high-resolution boundary layer data contaminated by ship-induced distortions is more detrimental than the use of a more simplistic, surface marine mixed-layer profile. Over the open ocean, high-resolution boundary layer data is most advantageous at and some meters above the sea surface, where strong gradients in temperature, humidity and wind typically occur; above a few tens of meters, the undisturbed surface marine boundary layer is normally well-mixed. Ship-induced distortions aside, this suggests that much of the essential fine structure of the near-surface marine boundary layer would not be captured by miniradiosondes launched from high-decked ships.

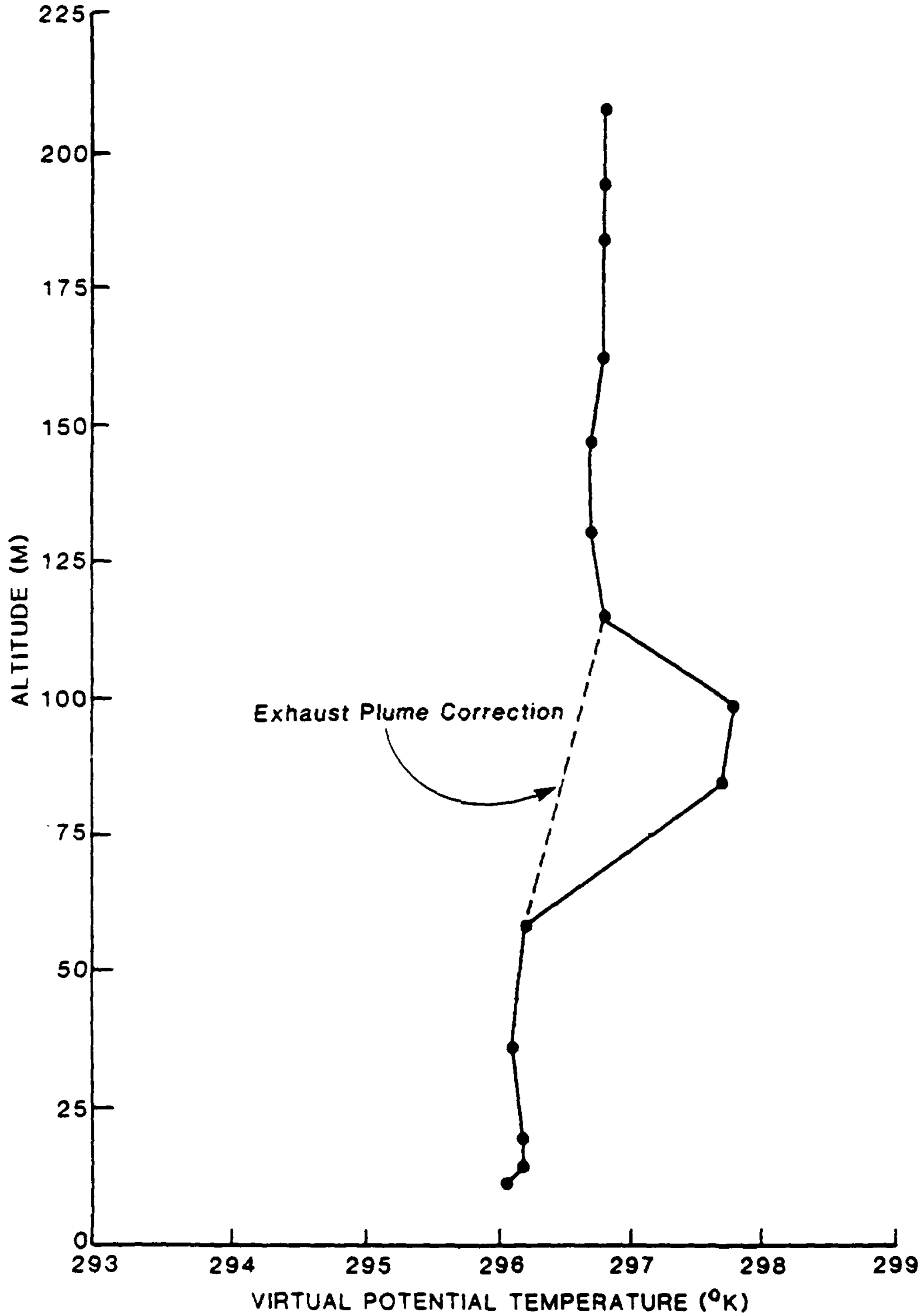

Figure 3. USS AMERICA sounding of 20 June 1831 GMT, with exhaust plume correction.

The surface-layer correction methods presented in this report are applicable not just to WMCE soundings, and not just for virtual potential temperature profiles, but to any high-resolution radiosonde data, represented in any temperature or humidity parameter. In fact, marine meteorologists and oceanographers have, and will continue, to employ (usually by visual, subjective means) these and similar methods for correction of unacceptable, anomalous surface-layer radiosonde data caused by ship-induced distortions.

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