NOAA Technical Memorandum NWS T&ED-16

DEPARTMENT OF COMMERCE
UNITED STATES OF AMERICA

PRECISION OF NATIONAL WEATHER SERVICE UPPER AIR MEASUREMENTS

Sterling, Va.
August 1980

U.S. DEPARTMENT OF COMMERCE / National Oceanic and Atmospheric Administration / National Weather Service

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NWS T&EL 10 Analysis of Cloud Sensors: A Manual Height Measurement System. Staff, Observation Techniques Development and Test Branch, March 1971, 15 pp. (COM-71-00549)

NWS T&EL 11 Discussion of Sensor Equivalent Visibility. Staff, Observation Techniques Development and Test Branch, July 1971, 35 pp. (COM-71-00964)

NWS T&EL 12 Standardized Functional Tests. Walter E. Hoehne, December 1971, 15 pp. (COM-72-10324)

NWS T&EL 13 Evaluation of Common Ceilometer Technology. Staff, Observation Techniques Development and Test Branch, December 1971, 66 pp. (COM-72-10262)

NWS T&EL 14 (REREX) Remote Readout Experiment for Clouds and Visibility. Staff, Observation Techniques Development and Test Branch, December 1973, 56 pp. (COM-74-10535)

NWS T&EL 15 Progress and Results of Functional Testing (Supplement to NOAA Technical Memorandum NWS T&EL-12). Walter E. Hoehne, April 1977, 16 p. (PB-285-608)

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Walter E. Hoehne

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UNITED STATES
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Philip M. Klutznick, Secretary

NATIONAL OCEANIC AND
ATMOSPHERIC ADMINISTRATION
Richard A. Frank, Administrator

National Weather
Service
Richard E. Hallgren, Director

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PRECISION OF NATIONAL WEATHER SERVICE UPPER AIR MEASUREMENTS
NOAA TECHNICAL MEMORANDUM NWS T&ED-016

Walter E. Hoehne
National Weather Service, Test and Evaluation Division
Functional Experimentation and Test Branch
NOAA, Sterling, Va.

ABSTRACT. The functional precision of upper air measurements was determined by comparing measurements made simultaneously by two radiosondes attached to the same balloon and tracked by two radiotheodolites. Functional precision is a measure of the reproducibility of a measurement and is defined as the root-mean-square (rms) of the measuring systems. The data for this determination were obtained from 50 weekly balloon flights. The results were compared to results of a similar determination made in 1973 before recent changes in the measurement process. Comparisons were made at 300 m height increments and 10 mb pressure increments in addition to the simultaneous comparisons. Statistical parameters were calculated to evaluate the representativeness of data and determine the correlation of the size of the measured difference to height of the measurement.

1. BACKGROUND

The Test & Evaluation Division of the National Weather Service (NWS) has for a number of years been conducting a program to establish the quality of measured meteorological data used by the NWS. Included in the data produced by the NWS are synoptic upper air data obtained from radiosondes. The same instrumentation is used by the NWS for all such upper air observations and precision is one measure of the quality of the data obtained.

The definition of precision implies repeated measurements of the same quantity by the same instrument. Due to atmospheric variability it is not possible to make the same measurement repeatedly with one instrument. For this reason, a program to standardize the determination of precision for meteorological measurements was inaugurated several years ago by the Test & Evaluation Division. To help identify it as a special statistical parameter the precision determined by the standardized test is termed "functional precision" and is the root-mean-square (rms) difference between measurements made by identical instruments at as nearly as possible the same time from as nearly as possible the same point in the atmosphere.

A full description of the program is contained in NOAA Technical Memoranda, NWS T&EL-12 and T&EL-15. The rules for making standardized functional tests as described in those publications were followed in the determinations described in this report. A summary of the procedure is included as appendix 1.

2. DATA ACQUISITION

Once each week for a period of 50 weeks starting in the spring of 1978, two radiosondes were flown on a single balloon train. These sondes were identical in that they were the same solid state model produced by the same contractor, and from the same manufacturing lot. They were separated vertically by 5 m. The data were received and recorded by two NWS Radio Theodolites (WBRT-60). These two radio theodolites are as similar as conformance to NWS installation, maintenance, and operational procedures can make them. The data were processed by identical NWS minicomputers according to NWS upper air operational procedures. The data were then recorded according to the time assigned to evaluation levels (mandatory and significant) for each sonde of every flight. These data were used to make the statistical calculations.

The differences in the data are the net result of the entire measurement process. Included are differences produced by the radiosonde; the tracking, receiving, and recording equipment, and human differences in manual data extraction. The precision determined is the precision of the measurement, not that of any part of the instrumentation involved.

3. OBSERVATION PROCEDURES

NWS upper air observations have remained conceptually unchanged since their inception. The pressure, temperature, and relative humidity of the atmosphere are measured by balloon-borne sounding devices. The measurements are radioed to and recorded at an upper air observatory where a radio directional tracker determines the angular position of the sonde. The pressure, temperature, and humidity data are extracted periodically from the record according to rules set forth in Federal Meteorological Handbook No. 3, "Radiosonde Observations". Determinations are made at certain prespecified (mandatory) pressure levels. They are also made at additional (significant) levels to ensure that a linear interpolation of temperature and/or humidity between levels will not differ from recorded values by more than prespecified amounts. The vertical distance between levels is calculated using the hypsometric formula. The height of a given level is the sum of the vertical distances between all levels below it. The time of flight to each level, and its height, produce a time/height relationship from which the height of each angular position is determined. The direction and horizontal distance that the sonde moves between position determinations is calculated by trigonometry from the height and the angular measurements. The direction moved is a measure of wind direction and the distance moved divided by the time between determinations is the measurement of wind speed.

Until recently the data extraction and calculations were done by manual graphic methods. Now, however, level selection is done manually but the extracted data is entered into a minicomputer and the calculations and report preparation are performed automatically.

4. COMPARISON BY TIME

The first comparison was made by interpolating the data from sonde #2 (the lower sonde on the train) to provide a reading of pressure, temperature, and dew-point depression for each evaluation level of sonde #1 (the upper sonde). A similar interpolation of the data from sonde #1 was made to give pressure, temperature, and dew-point depression readings for each level of sonde #2. A comparison was made by subtracting each measured quantity at a given time reported by lower sonde on the flight train from the corresponding value measured by the upper sonde. This produced a comparison of measurements at the same time of flight. Histograms of these data were prepared as shown in figures 1, 2, and 3. The rms difference in these measurements is what we call functional precision unless a bias has been introduced by the comparison process. The heat and humidity produced by the upper sonde effects the readings of the lower sonde. This effect would not be present in ordinary operational soundings; therefore, the bias (mean difference) produced was removed and the functional precision is obtained from the standard deviation.

The histograms include a scale to indicate the absolute frequency (cell counts) of the occurrence of differences within a particular cell (size limits) and a scale of relative frequency (the ratio of the number of differences within a cell to the total number of samples). The cell limits shown are the lower value of the cell designated. A plot of a normal curve (skewness = 0, kurtosis = 3) with the same mean and standard deviation as the sample has been added to each histogram.

4.1 Pressure

The precision of the pressure measurement ($\pm$ 1.9 mb) is identical with the precision determined several years ago using older model vacuum tube radiosondes. The statistical parameters (third and fourth moment) indicate that the sample can be considered a portion of a population that is normally distributed about a mean value of 0. The small mean difference (-0.02 mb) is in the right direction for the physical location of the sonde (i.e. the mean of the pressure measurement differences indicated that on the average, the lower sonde reported the higher pressure). A 95% confidence level test shows that the mean lies between -0.07 and +0.03 mb.

4.2. Temperature

The temperature measurement when based on time of flight produced a precision ($\pm$ 0.67°C) which is taken from the standard deviation because of a bias (-0.14°C) that resulted from heat of the battery in the upper sonde. The precision is not as good as that measured previously ($\pm$ 0.5°C) but the bias is somewhat reduced from the previous determination (-0.2°C), probably because of the significantly smaller battery used by the new solid state radiosondes. The Student's t test indicates the bias is now between -0.16 and -0.12 at the 95% confidence level.

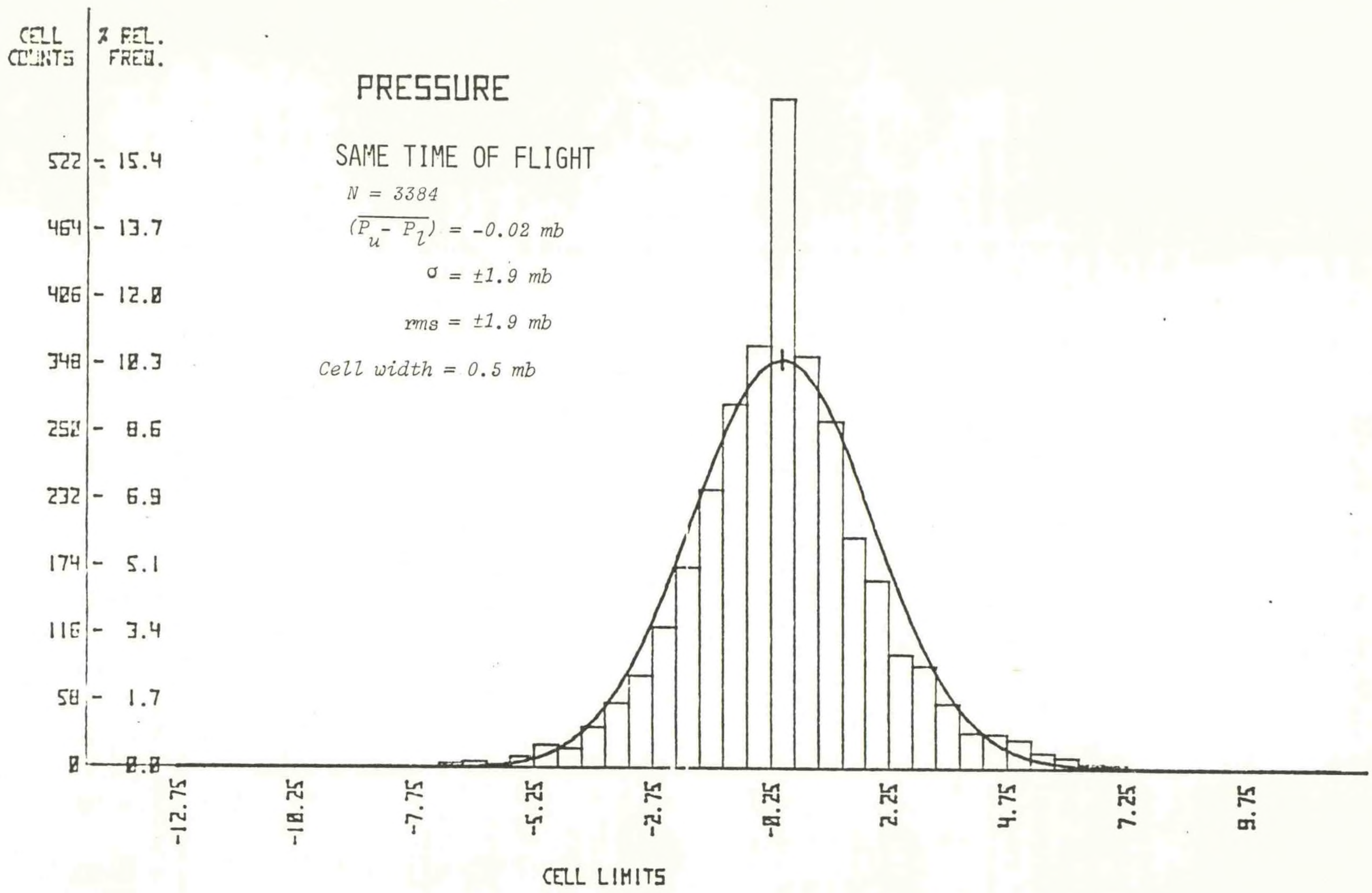

Figure 1 - Same time of flight - pressure

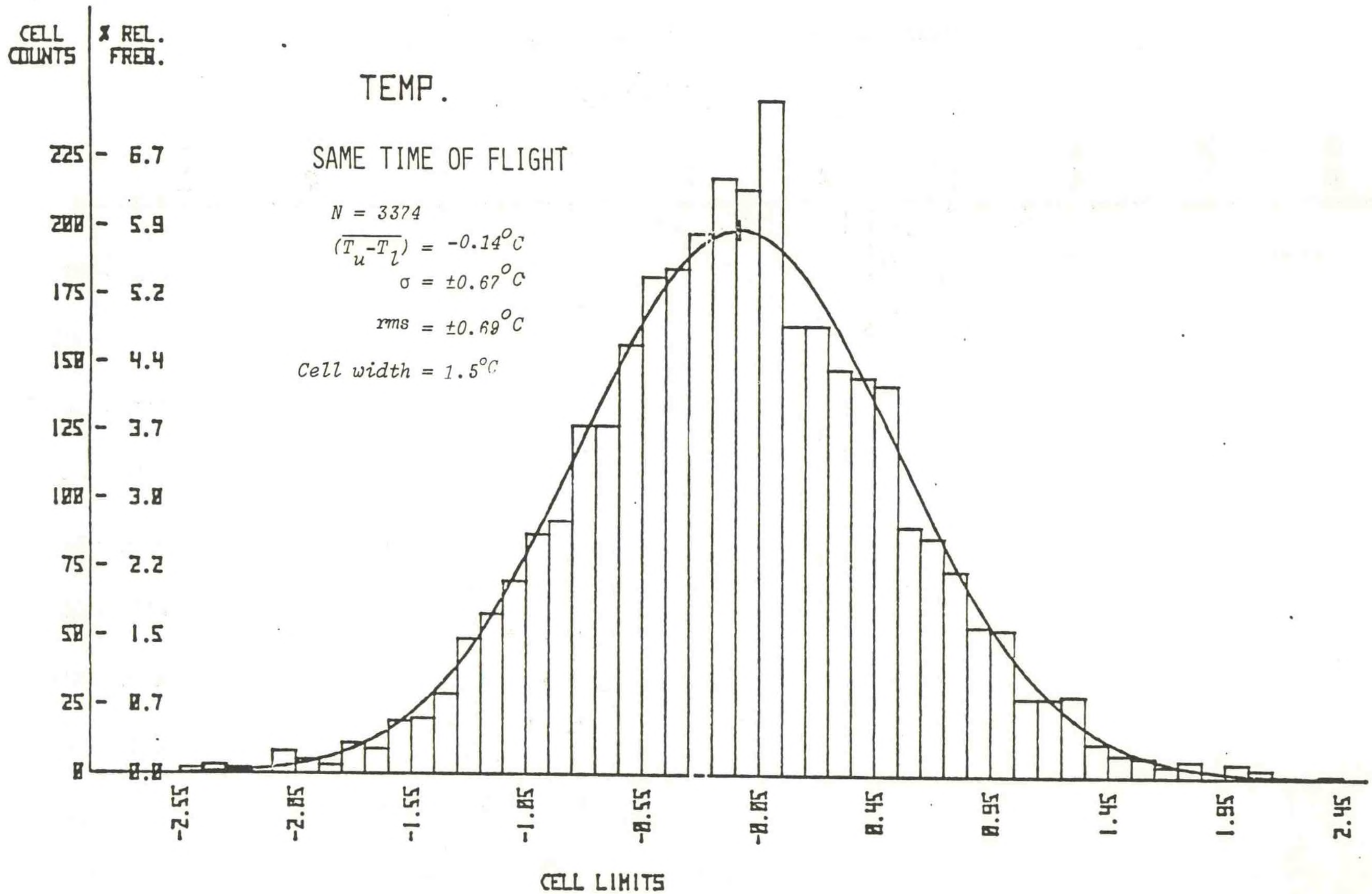

Figure 2 - Same time of flight - temperature

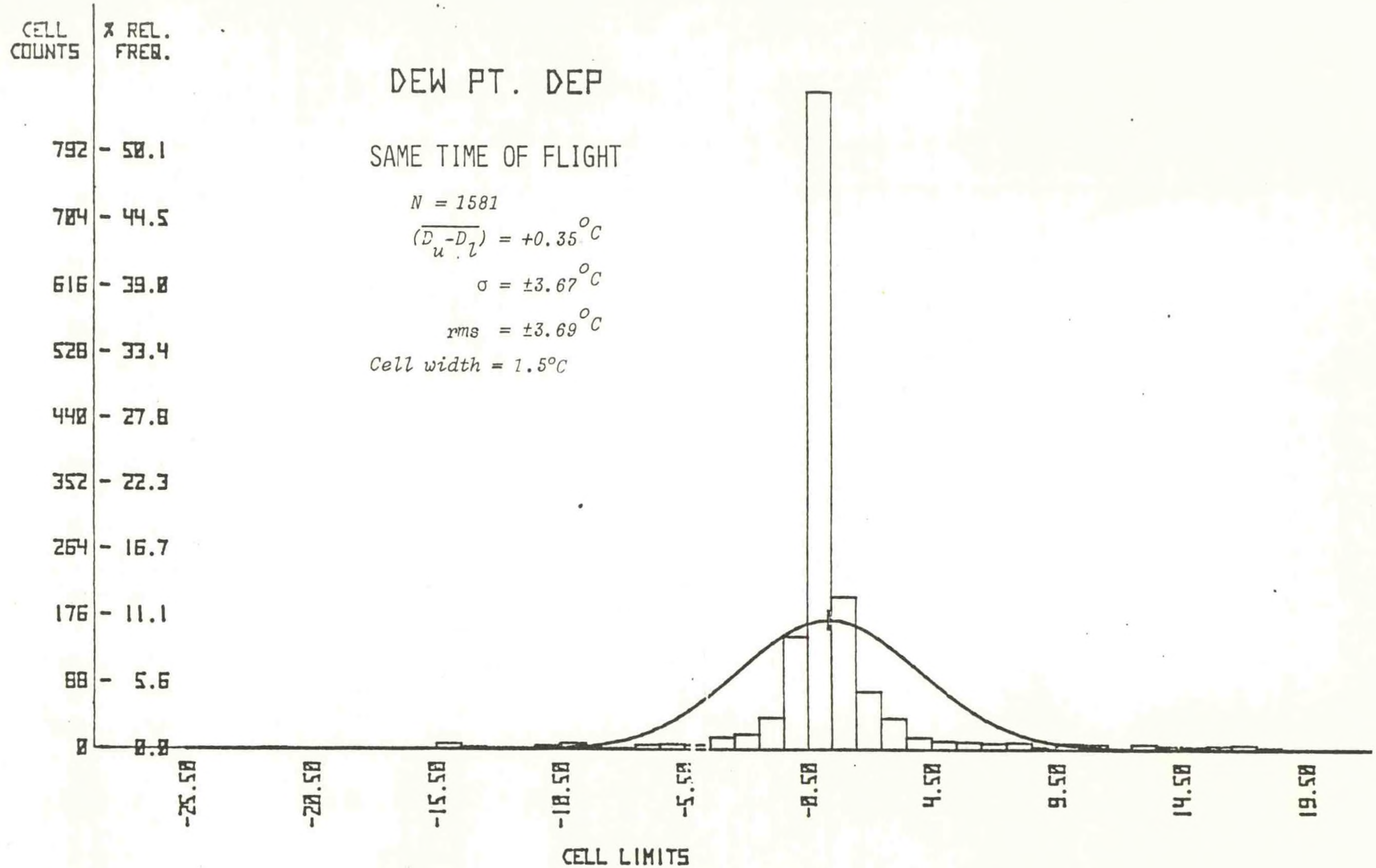

Figure 3 - Same time of flight - dew-point depression

4.3 Dew-Point Depression

The precision of the dew-point depression ($\pm$ 3.67°C) was almost identical to that measured in the previous determination. Here again the precision is taken from the standard deviation rather than the rms because of the bias caused by moisture from the water activated battery in the upper sonde. The size of this bias has also decreased from 0.9° to 0.35°C because of the much smaller battery used in the solid state radiosonde. The statistical test shows this bias is now between 0.2° and 0.5°C.

4.4 Height

A histogram was also prepared for the comparison of the height calculated for each time of flight for each radiosonde (fig. 4). This is a calculated value and not an independent measurement. The value for the precision determination $\pm$ 92.9 m is taken from the standard deviation because of the -7.6 m bias resulting from the bias in the temperature measurement. Sonde #2 was 5 meters below sonde #1 on the train, which would cause a bias of +5 m. Tests show the bias to be between -8.0 m and -6.0 m due to the effect on measured virtual temperature of heat and humidity from the battery in the upper sonde.

5. COMPARISON BY HEIGHT

The direct measurement of pressure, temperature, or dew-point depression from a particular time of flight is almost never used in meteorological operations. These measurements are reported according to the calculated height or a given pressure value. For this reason, two more sets of precision calculations were made to produce a precision value for the meteorological data as actually reported and transmitted. In the first set, the differences in pressure, temperature, and dew-point depression were calculated at the same calculated height. To do this, files were made of the flight data by interpolating the raw data between levels and obtaining a pressure temperature and dew-point depression value for each 300 m height increment above the surface. Unfortunately, the data from the previous determination were lost in a flood before these calculations could be made; therefore, no comparison values are available. The result of the statistical calculation are presented in figures 5, 6, & 7.

5.1 Pressure

The result of calculating height by the hypsometric formula is demonstrated by the reduction of the precision of the pressure measurement at any given height to $\pm$ 0.7 mb as compared to the $\pm$ 1.9 mb obtained from the direct measurement at a given time. The bias (0.1 mb) is a result of the test method. The height is calculated and the pressure at each specific 300 m height increment is interpolated from the pressure/height relationship. Because of the bias in temperature and humidity, the distance between constant pressure levels calculated for sonde #1 will be less than that calculated for sonde #2. Since pressure decreases with height, the pressure at any prespecified height from sonde #1 will be less than that from sonde #2. The magnitude of this bias is between -0.08 and -0.12 mb.

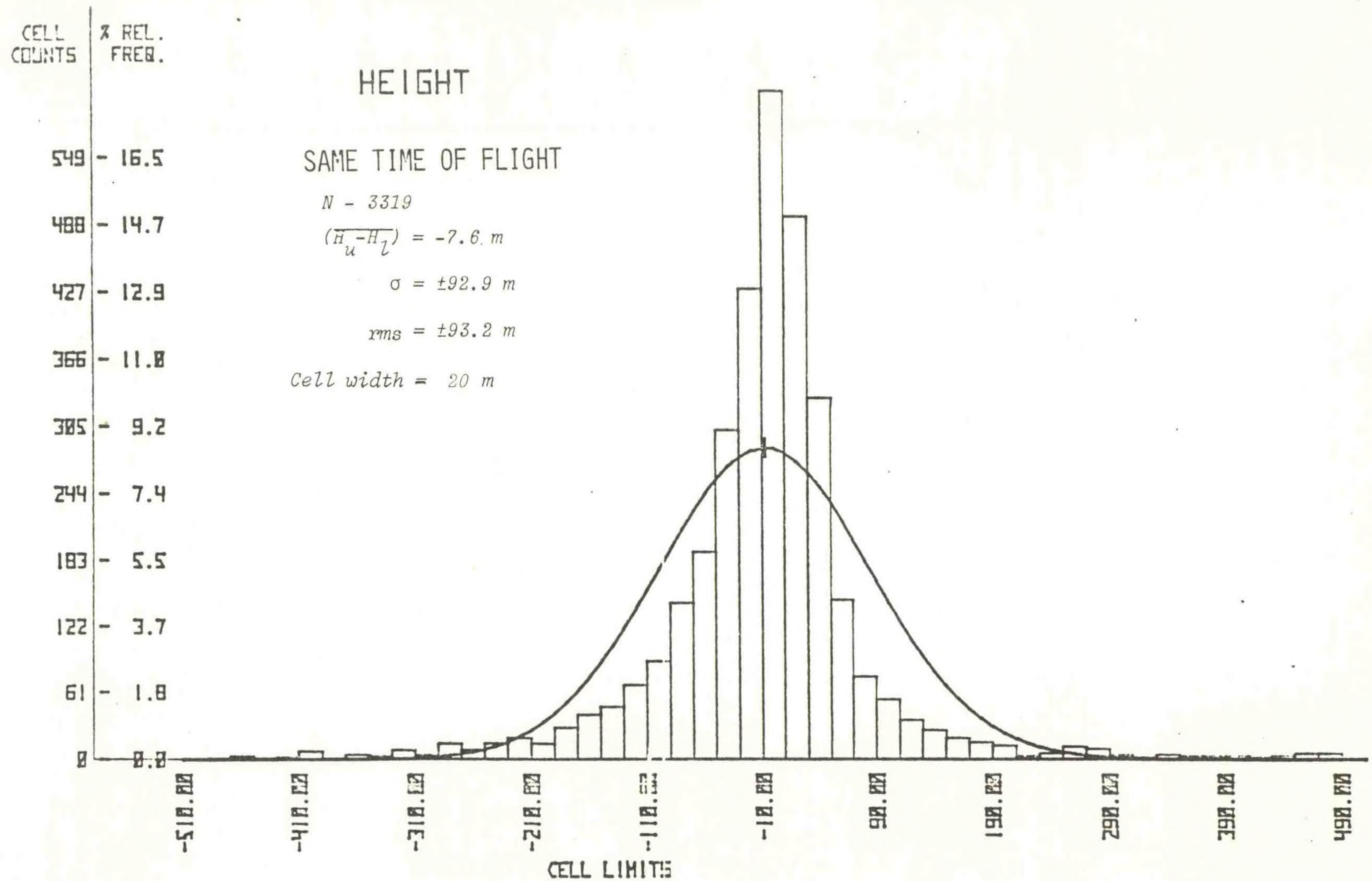

Figure 4 - Same time of flight - height

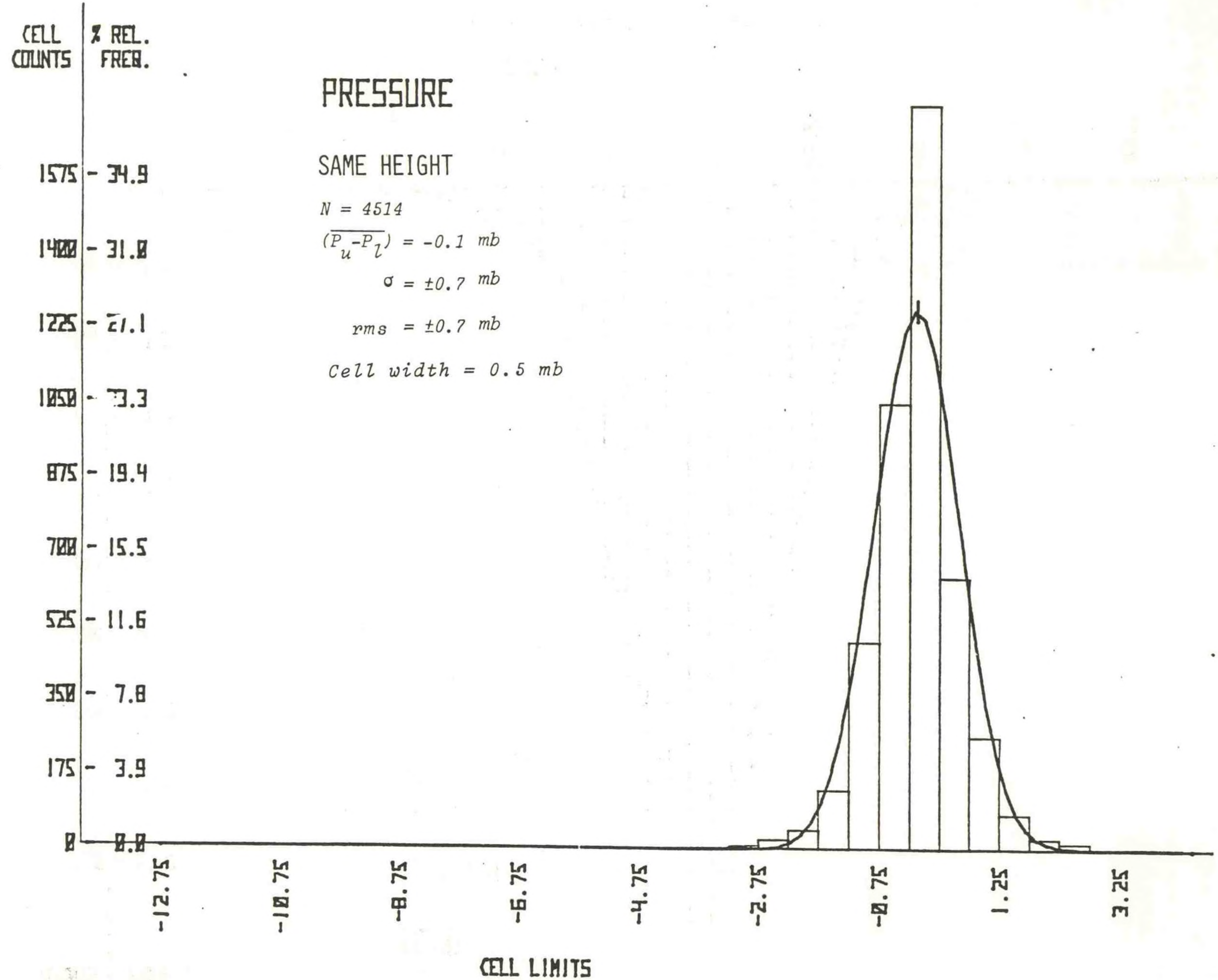

Figure 5 - Same height - pressure

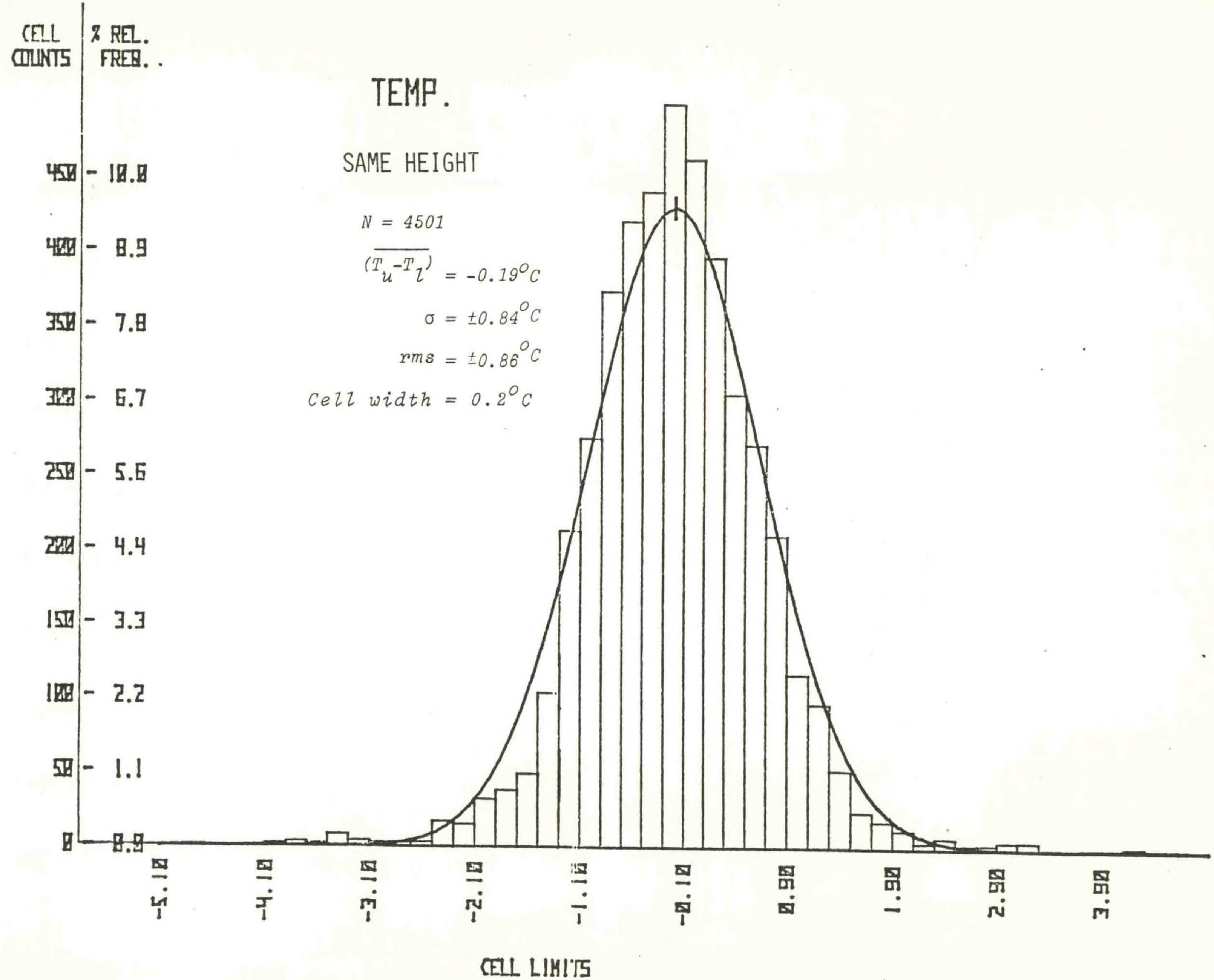

Figure 6 - Same height - temperature

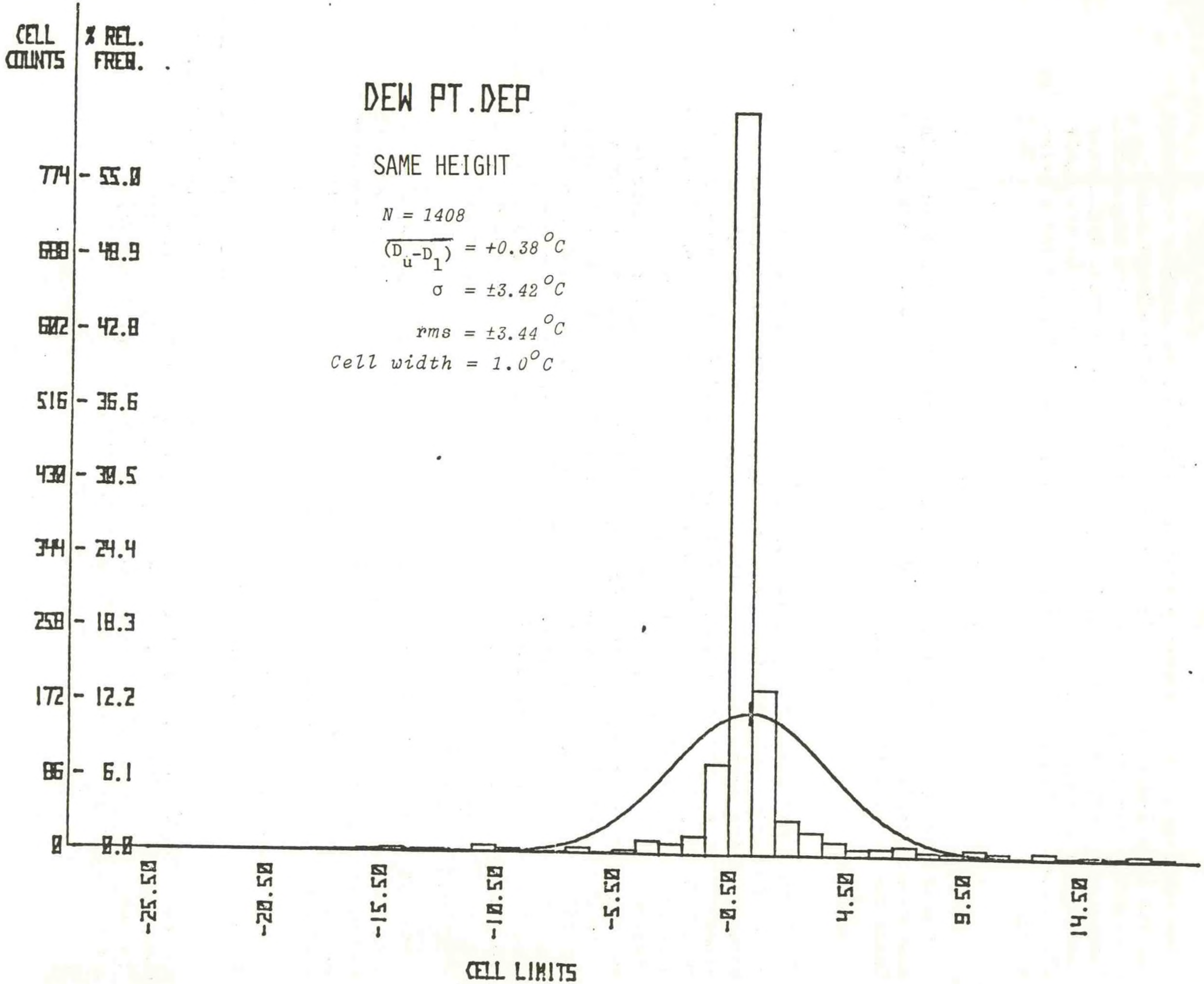

Figure 7 - Same height - dew-point depression

5.2 Temperature

The temperature measurement precision ($\pm$ 0.84°C) is slightly degraded and the bias (-0.19°C) slightly increased by the interpolations and calculations involved in converting to a comparison by 300 m increments. Statistical tests show that this change in the bias is real, indicating that the precision of the raw temperature measurement made by the upper air system is slightly better than the temperature reported for a particular height.

5.3 Dew-Point Depression

The statistics do not indicate a similar degradation in the dew-point depression precision ($\pm$ 3.42°C) and in fact indicate a slight enhancement. There was no significant change in the bias.

5.4 Wind

The wind measurements are produced by the ground tracking system. Direct comparison of directions and speeds are somewhat meaningless because of the large differences in direction that can occur at low speeds. Instead the rms vector difference is used for determination of functional precision. This produces a gamma function frequency distribution because the vector difference has only positive values with a maximum frequency at 0 difference. To obtain a normal distribution similar to the others in this report, the difference vectors in the same direction or to the right of the comparison vector were assigned positive values. The difference vectors to left or in the opposite direction were assigned negative values. The resulting histogram (fig. 8) has the same rms vector difference as the gamma function but the mean difference is 0. The other parameters indicate a normal distribution with an rms = standard deviation = $\pm$ 6.0 kt ($\pm$ 3.1 m/s). This shows some degradation from the previous determination of $\pm$ 5.4 kt ($\pm$ 2.8 m/s).

The calculation of precision in terms of the rms vector difference is not very useful operationally. Wind information is reported as speed and direction. The precision of the speed measurement can be approximated by the rms vector difference so that the functional precision of the wind speed is approximately $\pm$ 6.0 kt ($\pm$ 3.1 m/s).

The functional precision of the wind direction varies with wind speed (s) and can be approximated trigometrical $\pm \cos^{-1} \dfrac{s + 6.05}{(s^2 + 12.5\, s + 53.4)^{\frac{1}{2}}}$.

For wind speed $\leq$ 6 kt, the functional precision of the direction is more than 18° and for speeds in excess of 350 kt the precision is less than the resolution of the measurement (1°). Some additional values are given below:

Measured wind speed	Approximate functional precision of direction
10 kt	$\pm$ 14°
20 kt	$\pm$ 9°
30 kt	$\pm$ 6°
40 kt	$\pm$ 5°
120 kt	$\pm$ 2°

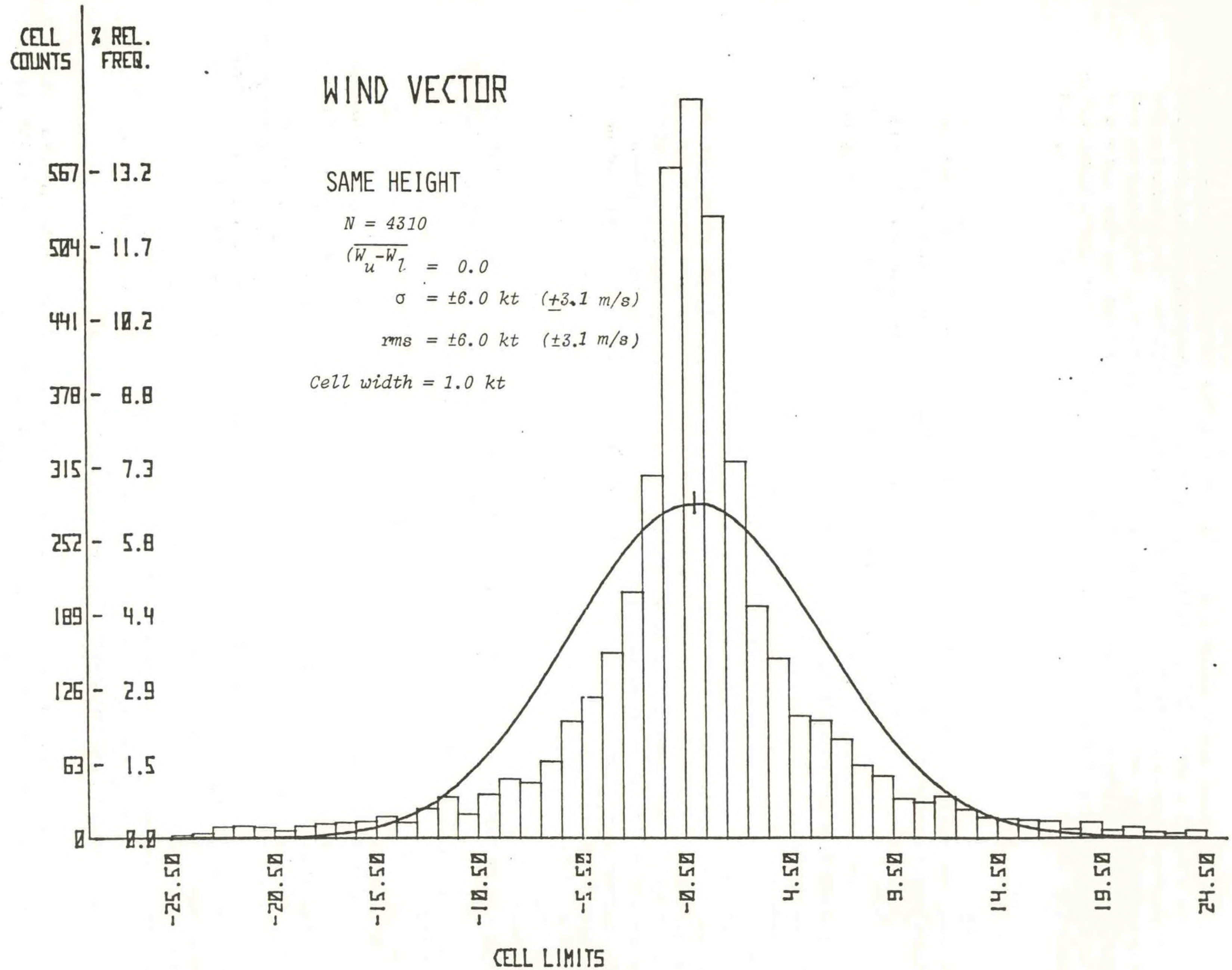

Figure 8 - Same height - wind vector

6. COMPARISON BY PRESSURE

In certain uses, (e.g., in the preparation of upper air charts) the calculation of height and the measurement of temperature and dew-point depression are reported at constant pressure values. To complete the statistical set, therefore, the precision of height, temperature, and dew-point depression was calculated by interpolating the raw data and producing a comparison at 10 millibar increments. The histograms with the associated statistical parameters are shown in figures 9, 10, and 11.

6.1 Height

The height comparison as in the comparison of pressure at constant height shows clearly the effect of calculation by the hypsometric formula. It indicates that two radiosondes in the same place would agree on the height of a particular pressure level within about 24 m. The bias (-4.0 m) is a result of the temperature bias produced by heat from the battery in the upper sonde.

6.2 Temperature

The precision of the temperature measurements for the given pressure (again using the standard deviation because the battery heat from the upper sonde produced a bias of $-0.13^{\circ}C$) is slightly better than the precision calculated at a given instant of time so that for given pressure we find the precision of the temperature measurement to be $\pm 0.61^{\circ}C$.

6.3. Dew-Point Depression

The precision of the dew-point depression was also enhanced giving a precision (using the standard deviation) of $\pm 3.26^{\circ}C$. The bias ($0.35^{\circ}C$) due to water vapor from the upper sonde is unchanged.

7. VARIATION WITH HEIGHT

Finally, the correlation with height of the difference between the two measurements was calculated. Comparing pressure difference with height produced a correlation coefficient of -0.36 for pressure difference measured at a given time. The least-squares, best-fit linear regression equation is $\Delta P = 2.16 \times 10^{-5} H$, where H is the height in meters. As a rough check, the precision of all readings between 10 and 30 km was calculated as $\pm$ 1.0 mb, which is equal to the value obtained from the linear regression equation when H = 20 km.

The linear correlation coefficient with height of the precision of temperature and dew-point depression were less than 0.3 and by predetermined standards not considered significant.

Taking the precision of reported pressure at 300 m height increments and comparing it to the height also produced a correlation coefficient of -0.36. The corresponding linear regression equation is $\Delta P = 0.79 - 2 \times 10^{-5} H$.

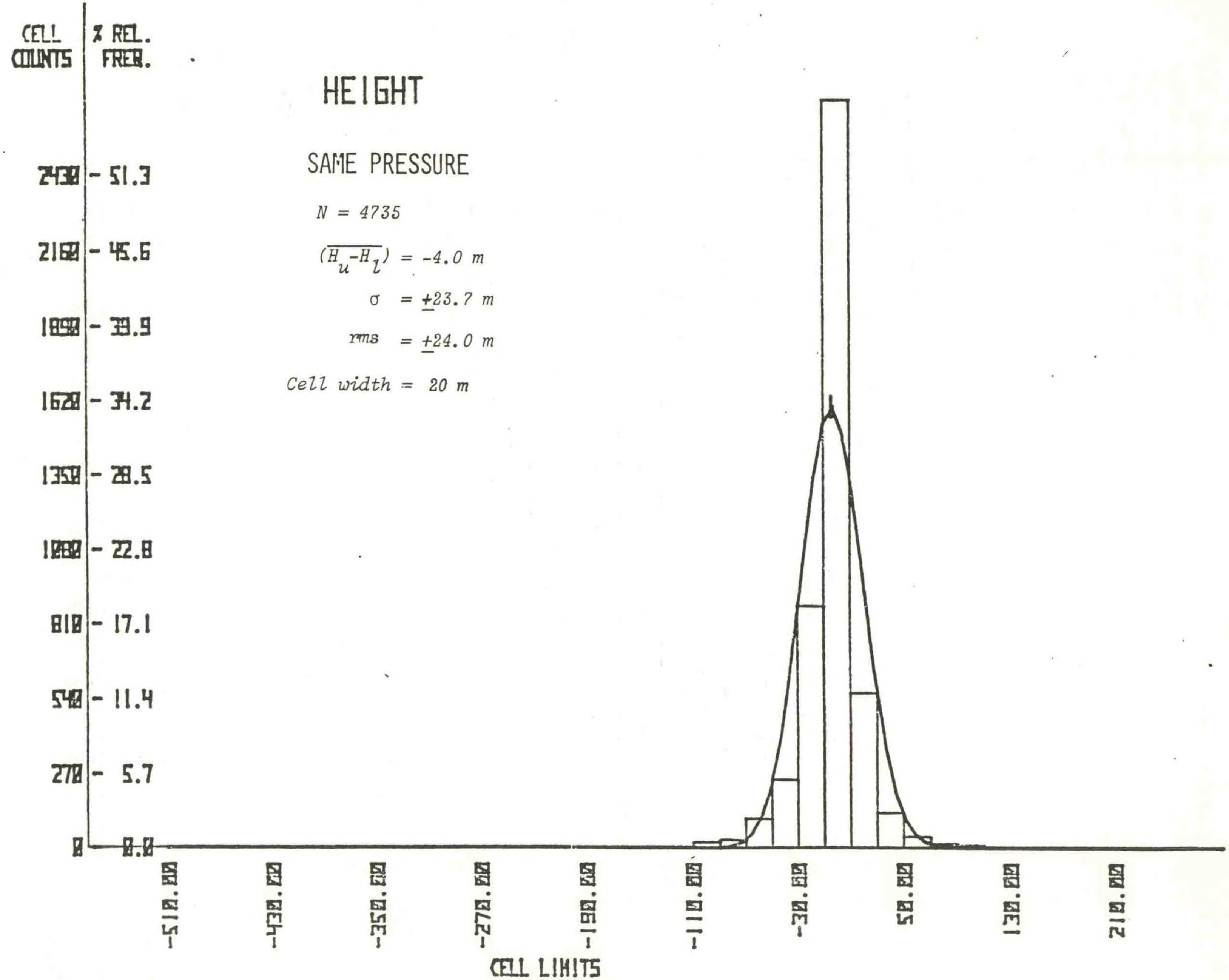

Figure 9 - Same pressure - height

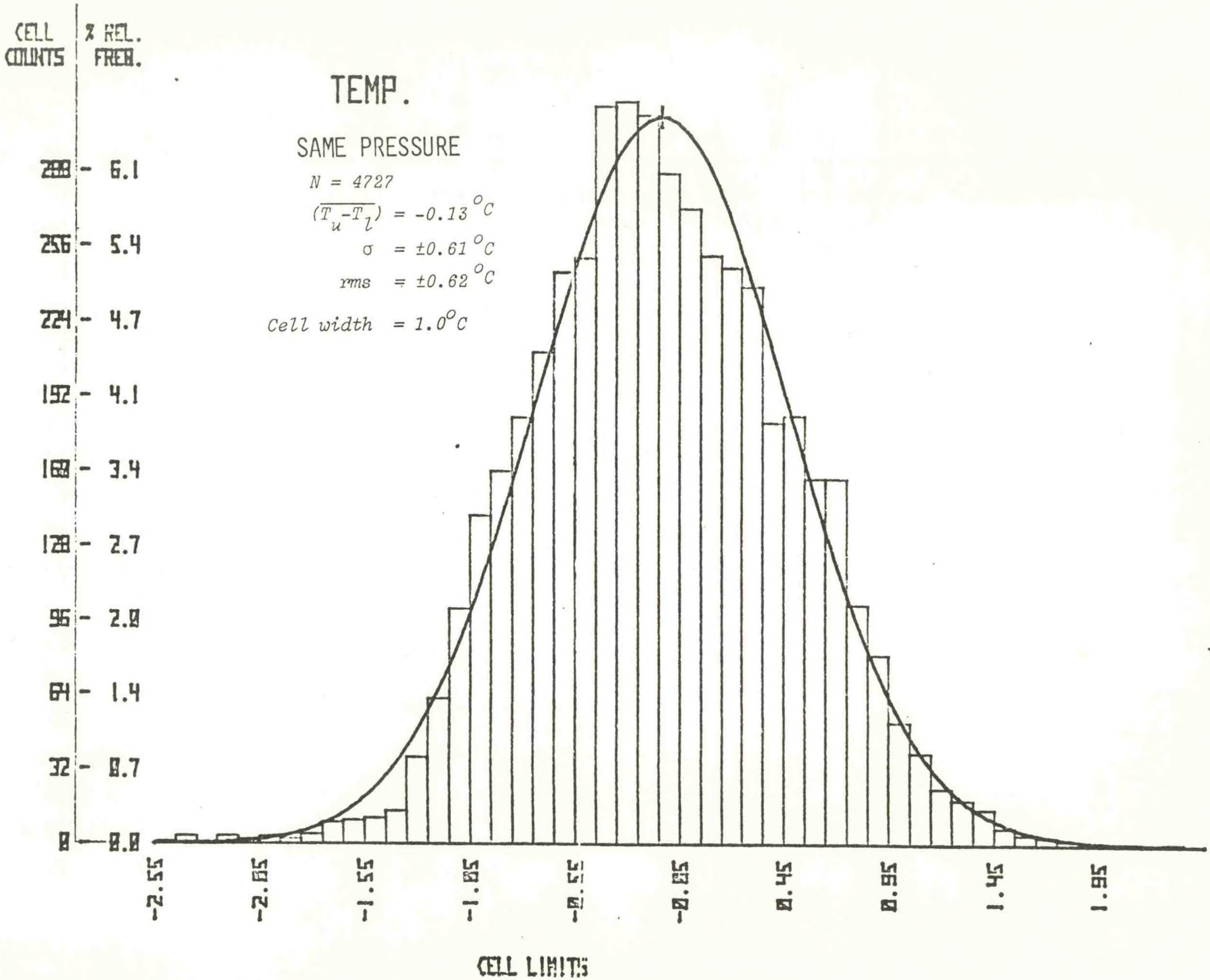

Figure 10 - Same pressure - temperature

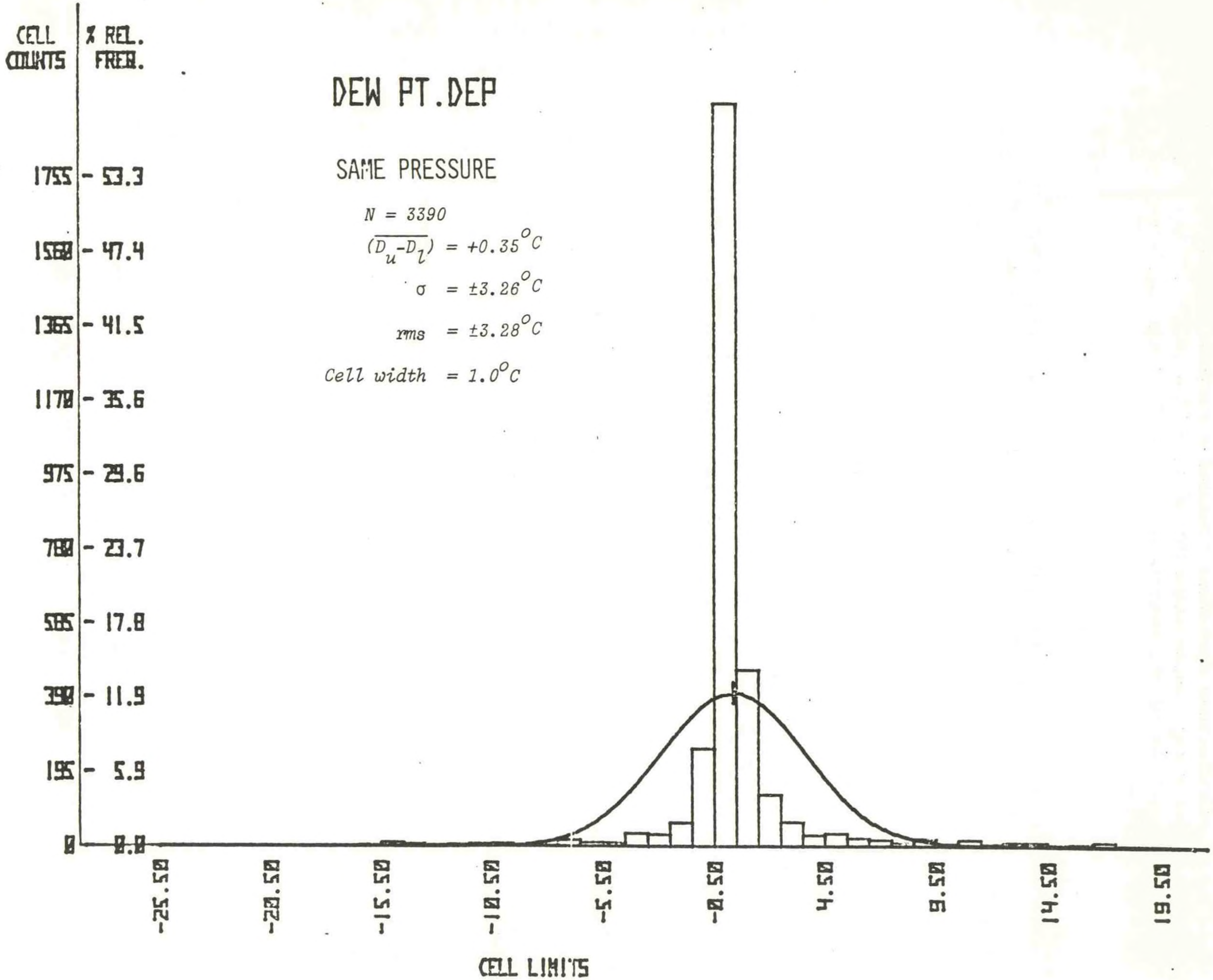

Figure 11 - Same pressure - dew-point depression

Comparing the difference in height calculations with the pressure at which those calculations were made produced a correlation coefficient of 0.56 and a linear regression equation of $\Delta H = 38 - .038P$. Table 1 shows the precision of the height measurement for each of the mandatory pressure levels.

8. SUMMARY

The correlation coefficients and linear regression equations are presented in table 2. The precision determinations are summarized in table 3.

Table 1 - Variation of Height Precision

Pressure (mb)	Height precision (m)
1000	± .5
850	± 6
700	± 11
500	± 19
400	± 23
300	± 27
250	± 29
200	± 30
150	± 32
100	± 34
70	± 34
50	± 36
30	± 37
20	± 37
10	± 38

Table 2 - Linear Relationship

Quantity	Correlation Coefficient	Linear regression equation
	At same time of flight	
Pressure vs height	-0.36	$\Delta P = 2.1 - 6x10^{-5}H$
	At same pressure	
Height vs pressure	-0.56	$\Delta H = 38 - .038P$
	At same height	
Pressure vs height	-0.36	$\Delta P - 0.79 - 2x10^{-5}H$

P = Pressure in millibars

H = Height in meters

ΔP = Precision of pressure report

ΔH = Precision of height report

Table 3 - Functional Precision

Quantity		Bias
	At same time of flight	
Pressure	$\pm$ 1.9 mb	0.0
Temperature	$\pm$ 0.67°C*	-0.14°C
Dew-point depression	$\pm$ 3.67°C*	0.35°C
Height	$\pm$ 92.9m*	-7.6m
	At same height	
Pressure	$\pm$ 0.7 mb	-0.1 mb
Temperature	$\pm$ 0.84°C*	-0.19° C
Dew-point depression	$\pm$ 3.42°C*	0.38°C
Wind vector	$\pm$ 6.0 kts ($\pm$ 3.1 mps)	0.0
Wind speed (approximately)	$\pm$ 6.0 kts ($\pm$ 3.1 mps)	
Wind direction (approximately)	$\pm \cos^{-1} \dfrac{s + 6.05}{(s^2 + 12.5\ s + 53.4)^{\frac{1}{2}}}$	s = wind speed
	At same pressure	
Height	$\pm$ 23.7m*	-4.0m
Temperature	$\pm$ 0.61°C*	-0.13°C
Dew-point depression	$\pm$ 3.26°C*	0.35°C

*Precision taken from standard deviation because of bias interduced by heat and humidity of battery in upper sonde.

APPENDIX 1

FUNCTIONAL TESTING

A paper of the Second Symposium on Meteorological Observations and Instruments described the standardization of functional tests. Before this standardized method for testing instruments was instituted, new sensors were usually evaluated by comparison with an existing instrument system. Output differences between the two systems were tabulated and analyzed statistically to produce mean differences, variance, etc. However, these statistical results could not be properly evaluated because no information was available on the difference that could be expected from two like instruments. It was not known whether the difference between the two instruments was larger, smaller, or the same as would have been observed had the systems been alike. A concept called functional precision was developed to provide a measure of the difference that could be expected from two like instruments. The concept was then expanded to include a measure of comparability.

Functional precision is the rms of the difference between readings from two or more identical sensors operating in the same environment. The operational importance of functional precision is that it tells you when differences between readings from different stations using the same type of sensor are significant. If two stations report wind directions differing by 10° and the functional precision of the instruments had been determined to be 15° we can assume that the difference may not be real but simply the result of the lack of precision of the instruments. Comparability is calculated in the same manner as functional precision, however, different sensor systems measuring the same parameters are compared. Comparability is used to determine if there will be a significant change in the data when a new sensor is introduced into the NWS operation system. Briefly:

a. Measurements are made in a volume not more than 10 m in horizontal distance and 1 m in vertical extent.

b. Measurements are made simultaneously.

c. The measurements are compared in pairs with a time interval between pairs of measurements at least twice the time constant of a particular measuring instrument.

d. The rms of the difference is calculated to provide functional precision if the systems are the same, comparability if the systems are different.

e. The maximum number of pairs of measurements practical will be obtained with no less than N pairs utilized for a precision determination where $N \geq \left(\frac{3\sigma}{\Delta}\right)^2$. σ = standard deviation, Δ = one increment of resolution.

f. Data are tested for correlation with size and/or with other quantities. Functional relationship is reported if the correlation is ≥ 0.3.

g. Bias or mean difference is reported if it equals or exceeds one increment of resolution. The reason for the bias is reported if it can be determined.

h. If the bias is caused by the comparison process, the functional precision is obtained from the standard deviation about the mean difference.

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