The Operational Complex Quality Control of Radiosonde Heights and Temperatures at the National Centers for Environmental Prediction. Part I: Description of the Method

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ABSTRACT

The quality control of meteorological data has always been an important, if not always fully appreciated, step in the use of the data for analysis and forecasting. In most quality-control approaches, erroneous data are treated as nonrandom ''outliers'' to the data distribution, which must be eliminated. The elimination of such data traditionally proceeds from coarse to finer filters. More recent methods use the fit (or lack of fit) of such data to an analysis, excluding the data, to determine whether data are acceptable. The complex quality-control (CQC) approach, on the other hand, recognizes that most rough errors are caused by human error and can likely be corrected. In the CQC approach, several independent checks are made that provide numerical measures of any error magnitude. It is only after all check magnitudes, called residuals, are calculated that data quality is determined and errors are corrected when possible. The data-quality assessment and correction is made by the sophisticated logic of the decision-making algorithm (DMA). The principles and development of the method of CQC for radiosonde data were given by Gandin. The development of CQC at the National Centers for Environmental Protection (NCEP) for the detection and correction of errors in radiosonde heights and temperatures, called the complex quality control for heights and temperatures (CQCHT), has progressed from the use of a complex of hydrostatic checks only to the use of statistical and other checks as well, thereby becoming progressively sophisticated. This paper describes a major restructuring in the use of the radiosonde data and in the logical basis of the DMA in the operational CQCHT algorithm at NCEP so that, unlike the previous implementations, all data levels are treated together, thus potentially allowing the correction at any level to influence subsequent correction at adjacent levels, whether they are mandatory or significant. At each level, treated one by one from the surface upward, all available checks are used to make the appropriate decisions. Several vertical passes may be made through the data until no more corrections are possible. Final passes look for ''observation'' errors. The methods of error determination are outlined, and the effect of errors on the residuals is illustrated. The calculation of residuals is described, their availability for each type of data surface (e.g., earth's surface, mandatory level, significant level) is given, and their use by the DMA is presented. The limitations of the use of various checks are discussed.

1. Introduction

a. General

As analysis techniques continually become more advanced and numerical prediction models steadily increase in skill, quality control (QC) procedures assume relatively greater importance in forecast quality and consistency. Even in the age of many diverse satellite-derived observations, radiosonde temperatures (and derived geopotential heights) and winds continue to be among the most accurate observations available. However, these observations, along with surface observations from land and ship, are among the most sensitive to large error, primarily because of the possibility for human intervention. This paper discusses the operational QC of radiosonde-derived geopotential heights and temperatures at the National Centers for Environmental Prediction (NCEP).

b. Errors in meteorological data

The term *error* is used with a variety of meanings in meteorology. In the context of this paper, the term error is understood to be the difference between the *reported* value of a meteorological parameter and its *actual* value. It is emphasized that the characterization of errors that follows is appropriate to those detectable in the final decoded report. As such, there are additional sources of error possible that are not present in the original measurement (e.g., change in sign of the temperature).

It is important to distinguish between random, rough,

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and systematic errors in meteorological data. *Random errors* are inherent in all data and are caused by a variety of factors, such as (nonsystematic) measurement errors or small-scale turbulence. Being more or less independent from each other at different points and times, they form what is called a random noise in the data. It is, of course, impossible to correct random errors, but it is important to properly take into account the noise level, usually characterized by the root-mean-square (rms) random error, when performing operations with the data, including their QC.

Unlike random errors, the so-called *rough errors* in meteorological reports occur comparatively seldom; the majority of reports do not contain any rough errors. Each rough error has its definite cause, which may happen in the course of measurement, processing, or communicating the data. It is the task of the QC to detect each rough error in arriving reports and, if possible, to correct erroneous data. Otherwise, it must mark the data for rejection from the operational data assimilation system or for assimilating them with smaller weights. Certainly, some errors of this kind may be rather small. It is, however, impossible even to recognize any such error unless its absolute value substantially exceeds the noise level. It should also be made clear that it is generally impossible for QC to distinguish between a rough error in measurement, having a definite cause, and a large random measurement error. It is not necessary to make such a distinction, however, because data containing either kind of error should be rejected.

The errors of the third category, the *systematic errors,* are usually small, but, unlike rough and random errors, they persist in time (or space). Such errors may result from some insufficiencies either in measurement devices or in procedures designed to take care of these insufficiencies. Substantial averaging, normally in time (e.g., over a month), is needed to detect systematic errors.

Depending upon their origin, rough errors may be divided into three categories: observational, computational, and communication-related errors. *Computational errors* are those originating in the course of processing the sounding data, particularly in the computation of mandatory surface heights at the station. All rough errors made before this processing began are called, in this paper, *observational errors,* and all rough errors made after the processing ended are called communication-related errors (or, simply, *communication errors*).

The category of observational errors thus contains not only measurement errors, but also those made at the station when the rawinsonde signals were received and put into the processing. It is natural to use a common term for these errors, because the QC has no method to distinguish a large (random) measurement error from a large (nonrandom) error from another source (e.g., error in the communication from the instrument to the ground or in recording of the value at the ground).

Communication errors result from corruption of a datum after being used in calculating heights from the temperatures and moisture. Therefore, they lead to hydrostatic inconsistencies between the heights and temperatures, although it is possible for multiple errors to cause some or even all of these inconsistencies to cancel each other. Communication errors can arise from many different causes, some of which may be distinguished by complex quality control (CQC). At a radiosonde station that is not fully automated, any manual handling of the data may lead to its corruption. One such place is the encoding of the data, where the code itself may in some cases be ‘‘error-encouraging.’’ For instance, the use of the tenths digit of the temperature to indicate the sign often leads to temperatures of the wrong sign in the coded message. Another example is the lack of the high-order digits in the reported height, which sometimes can lead to ambiguity for a radiosonde decoder. When the rough communication error is of human origin, the error tends to have simple characteristics: sign error, error in one digit, or error by interchange of digits. As the majority of communication errors are indeed of human origin, it is suitable in correcting data to look for an original value that would have resulted from such a simple error.

c. QC methods

Common QC methods may be characterized as 1) sequential, 2) Bayesian, or 3) CQC. There are several points of similarity in these methods, but they may be differentiated as follows. Sequential QC is the traditional method whereby each stage in the QC passes on to the next only those data that pass the previous stage. Testing begins by rejecting nonphysical or impossible values, with subsequent tests becoming more refined. There is often a comparison with neighbors or a ‘‘buddy’’ check applied. The data are usually given flags to reflect confidence in their quality.

Bayesian QC (Lorenc and Hammon 1988) explicitly uses prior knowledge about the probability of certain kinds of rough errors along with knowledge of the error properties of the data to determine the probability of error for each datum. It is assumed that data either are good but with a known observation error distribution or are bad and should not be used. These bad data may have any magnitude and are characterized by a more or less constant probability distribution.

The CQC method (Gandin 1988) uses the same information on the statistical structure of errors that is critical to the Bayesian QC, but the emphasis is not only in determining which data are bad but also in *correcting* those data that it can. For this reason, its methodology is different. CQC begins by computing error estimates from as many elemental checks of the data as are available. No decision is made regarding data quality until these error estimates (residuals) are available from all the checks. The complex of residuals is used to classify the cause of each rough error and, in many situations, to correct the error. All decisions regarding the data are made in the decision-making algorithm (DMA), which is the ''heart'' of the code and involves complicated logic. The CQC method, as implemented at NCEP for the diagnosis and correction of radiosonde heights and temperatures, explicitly looks for typical (simple) errors (e.g., temperature sign errors). It should be emphasized that the purpose of CQC is not to reject the data that differ most from the background, if they are correct, but rather to reject or correct wrong data even if they differ only by a small amount from the background. Because the QC method depends heavily upon the statistical nature of all errors, no QC method can correct or reject all data with rough errors, avoid rejecting some data with no rough errors, or even avoid ''correcting'' good data, but it should be designed to minimize such wrong behavior. (Note: the use of ''complex'' here to mean ''composed of two or more parts'' is the origin of its use in the term ''complex quality control.'' It is not used to mean ''complicated'' even though this attribute is certainly true of CQC algorithms.)

d. Development of CQC and its use at NCEP

The principles of CQC and its early development and application are outlined by Gandin (1988). Its first application at NCEP, employing only a complex of hydrostatic checks, is described in Collins and Gandin (1990). This early version was referred to as comprehensive hydrostatic quality control (CHQC). The performance of CHQC at NCEP for a two-year period is given in Gandin et al. (1993). The current paper describes the currently operational ''complex quality control for heights and temperatures'' (CQCHT) at NCEP, containing the full set of checks. The earlier methods for checking significant level temperatures (Collins 1990, 1998a) are supplanted by the method described here. This paper also shows CQCHT performance statistics for one year of operational use, updating information in Morone et al. (1992). There are some data for which the CQCHT is not used, namely, hurricane reconnaissance and dropsonde data. For these situations, the forecast background fields may have significant error, leading to bad QC decisions.

The principles of CQC have been applied elsewhere in addition to NCEP. The first CQC was developed and applied in the Union of Soviet Socialist Republics by Gandin and others. More recently, an advanced version of CQC was developed by Alduchov (Alduchov and Eskridge 1996; Eskridge et al. 1995) for the Comprehensive Aerological Reference Dataset project at the National Climatic Data Center. NCEP's CQCHT was recently adopted by the U.S. Navy for operational use. For the evaluation of the quality of a wide range of data types, a CQC with multiple checks, including multivariate checks, with simplified error determination but no error correction is used at NCEP.

e. The need for man–machine mix in QC

The connection between performing data analysis and the quality control of the data has always been close. The hand preparation of data for manual and automated analysis performed both implicit and explicit QC with the objective of smoothing the data, making it internally consistent, and removing errors (Panofsky 1949; Gilchrist and Cressman 1954; Berthorsson and Döös 1955; Cressman 1959).

From the early days of numerical weather prediction, human judgment has combined with machine processing (man–machine mix). For QC, there is good reason to maintain that partnership if the fullest utilization of the data is to be made. It is impossible to perform routine manual QC of the data, simply because of its volume. The automated routines are now sophisticated enough to recognize situations in which they may be in error, however, and the suspected data may be automatically directed to humans for further examination. This partnership, which is practiced at NCEP, has two benefits: it allows the most specific judgment where it is needed, and it allows feedback to the automated QC for its improvement.

f. Characteristics of meteorological data allowing QC

Sophisticated QC is made possible by two related characteristics of meteorological data. First, the data have spatial and temporal continuity. Second, there are redundancies of various kinds that can be used to cross-check the data.

Meteorological fields, for example, temperature and geopotential height, are not random, but rather have a smooth variation in the horizontal, vertical, and time. The same is true of the variations of the difference of observations from a short-term forecast (usually 6 h), sometimes called the background, which we denote, following Thiébaux and Pedder (1987) and Gandin (1988), as the increment [called observation increment or innovation vector by Daley (1991) and others].

One measure of the horizontal and vertical variation of meteorological fields is given by the spatial autocorrelation of the fields, which, for the horizontal correlation of the 500-hPa height increment, falls to a value of about half its maximum at a distance of 500 km (Daley 1991). Temperature has a similar horizontal scale. The vertical scale for temperature is much shorter than for height, as would be expected from the integral relationship between them, and the vertical correlation for height falls to about half in 3 km so that only the closest data in the vertical should be used in statistical quality checking. The temporal correlation scale for height and temperature is long enough to allow temporal interpolations of up to 24 h that are useful for QC. With smoothness of the height and temperature fields on a scale larger than the spacing of many observations—in the horizontal, the vertical, or time—interpolation checks are meaningful, providing a kind of spatial or temporal redundancy.

An important redundancy of special kind is just the 6-h forecast of heights and temperatures. Such a forecast embodies the past knowledge of the state of the atmosphere, projected to the present time. The difference between an observed value and the 6-h forecast—the increment—gives a powerful check of the data.

Very strong redundancy is also provided by the operational practice of measuring temperature and relative humidity as a function of pressure by the radiosonde, calculating geopotential heights from them using the hypsometric equation, *and then reporting both.* Any corruption in either temperature or height may be detected and is usually corrected. In many cases, only the complex of hydrostatic discrepancies—differences between thicknesses calculated from heights and thicknesses calculated from temperature and moisture—caused by such corruption is needed to make a correction, as performed by early versions of CQC for radiosonde data at NCEP.

g. Outline of this paper

The purpose of CQC is to detect rough errors from whatever cause, to correct those errors when feasible, and to mark for rejection or use with small weight all others. Section 2 provides further details of the principles of CQC and describes the checks used. The reaction of the checks to particular errors is discussed in section 3, which leads naturally to consideration of error detection methods in section 4 and the DMA design in section 5. The design of this DMA contains several features that differ significantly from earlier versions at NCEP. All levels are considered together, and corrections are performed in a way that allows more complicated corrections to be made more confidently and in a natural sequence.

2. General principles of CQC and the checks

a. General principles

A complete exposition of CQC principles and general methodology may be found in Gandin (1988). The following emphasizes some important considerations. The CQC method differs from other methods of QC both in the checks selected for use and in the way the checks are used. When using statistical interpolation checks, it must be recognized that the influence of erroneous data at surrounding (horizontally, vertically, or temporally) data can adversely affect the residual. If a single optimal interpolation check from all surrounding data were to be used, then the unique determination of data errors would be difficult. However, if such a check is broken up into its component parts—horizontal, vertical (and perhaps temporal), then the location of an error may be determined with much greater certainty. The horizontal check indicates the pressure level of an error, and the vertical check indicates the horizontal position of an error. If both horizontal and vertical check residuals agree in sign and sufficiently well in magnitude, then not only is the location of the error known with some certainty, but suspicion of the influence of bad data at other locations is lessened, and the residuals provide an estimate of the error magnitude. The increment itself provides further valuable information on the location and magnitude of errors. A single combined check cannot provide this information, and so the CQC uses elemental checks. It also favors the use of a minimal number of surrounding data for the various checks to minimize the possible impact of bad data at locations other than the one being checked.

Perhaps the most important check used by CQC is the hydrostatic check of the heights and temperatures. The hydrostatic residuals form the backbone for error determination and correction. Many operational QC methods do not make any use of this powerful check (although preprocessing steps generally will utilize a hydrostatic check).

The CQC's DMA does not make any decisions regarding data quality until all the check residuals are available, and it uses as many checks as possible in its decisions. Some levels have more checks available than others; all those that can be calculated are used by the DMA. The CQC's DMA tries to determine and to take into account in its decisions the origin of every suspected rough error, and it tries to correct as much data as possible. The checks that it uses are discussed in the following sections.

Because the CQCHT uses a forecast background in several of its checks, it is somewhat sensitive to the specifics of the forecast model providing the background. For a global model, an observation of temperature, for instance, may not be representative to the scale of the model, and the observation should be considered suspect. For the same observation, a mesoscale model might predict the phenomenon responsible for the temperature, and the temperature should not be suspect. If each model produces the background used with the QC of its input assimilation data, *and the underlying statistics used in the QC are appropriately developed from the appropriate forecast model,* then the QC will also be appropriate for each model's input data. It is noted that the hydrostatic check, to be discussed first, is not at all sensitive to a background. Furthermore, the hydrostatic check is the most productive of all.

b. The hydrostatic check

The hydrostatic residual is the difference between the two values of the thickness of a layer between mandatory level heights, that is, calculated by the heights and calculated independently by the virtual temperatures. The calculation of the thickness from virtual temperature duplicates as closely as possible the original

TABLE 1. Coefficients *A* and *B*.

Pressure range (hPa)	*A* (m)	*B* (m K^{-1})
1000–925	623.3	1.141
925–850	676.1	1.238
850–700	1552.3	2.842
700–500	2690.2	4.924
500–400	1784.1	3.266
400–300	2300.1	4.210
300–250	1457.7	2.668
250–200	1784.1	3.266
200–150	2300.1	4.210
150–100	3241.8	5.934
100–70	2851.7	5.220
70–50	2690.2	4.924
50–30	4084.2	7.476
30–20	3241.8	5.934
20–10	5542.0	10.145

calculation made at each observation station. Because of the possible error in either or both of the moistures and significant level temperatures as well as in the heights, the CQCHT actually calculates three versions of the hydrostatic residual. Using the barometric formula and no intervening significant levels, the basic form of the hydrostatic residual for a layer between two mandatory levels *l*1 and *l*2, each containing a height and temperature, is

$$s^m_{l1,l2} = z_{l2} - z_{l1} - A_{l1,l2} - B_{l1,l2}(T_{l1} + T_{l2}), \quad (1)$$

where T is the virtual temperature in degrees Celsius and z is the geopotential height. The coefficients A and B are given by

$$A_{l1,l2} = \frac{RT_0}{g} \ln\left(\frac{p_{l1}}{p_{l2}}\right) \quad \text{and} \quad B_{l1,l2} = \frac{R}{2g} \ln\left(\frac{p_{l1}}{p_{l2}}\right), \quad (2)$$

where $T_0 = 273.15$ K, R is the gas constant for dry air, and g is the acceleration of gravity. Table 1 shows the values of A and B for the layers between mandatory levels. The appendix contains a complete list of variables and symbols used. A second form of this residual [Eq. (1)], call it $s^m_{l1,l2}$, is calculated using temperature rather than virtual temperature.

The third form of the hydrostatic residual utilizes all levels, including significant level temperatures and moisture. In this case, the hydrostatic residual is

$$s^s_{l1,l2} = z_{l2} - z_{l1} - A_{l1,l2} - \sum_{i=l1}^{l2-1} B_{i,i+1}(T_i + T_{i+1}), \quad (3)$$

where T is the virtual temperature, $A_{l1,l2}$ has the same meaning as before, and

$$B_{i,i+1} = \frac{R}{2g} \ln\left(\frac{p_i}{p_{i+1}}\right). \quad (4)$$

From this set of three hydrostatic residuals, a decision is made on which is likely most accurate, and it is used for the majority of decisions. Presuming that all three forms of the hydrostatic residual are available, if all three agree with each other to within 15 m, then $s^s_{l1,l2}$ is used. Otherwise, if $s^n_{l1,l2}$ and $s^m_{l1,l2}$ agree to within 15 m, then $s^m_{l1,l2}$ is used. Last, if neither of these two conditions is met, then $s^n_{l1,l2}$ is used. As a general rule, this ‘‘best’’ $s_{l1,l2}$ is used, but not in all cases. For the diagnosis of temperature errors at mandatory levels, for instance, the influence of a bad temperature is best reflected in the hydrostatic residual if either $s^n_{l1,l2}$ or $s^m_{l1,l2}$ is used. For more information about the specific use of the hydrostatic residuals, see section 3d.

c. *Baseline check*

A special form of the hydrostatic residual provides the baseline residual, which is a measure of the mismatch between the lower heights and temperatures of the upper-air report and the station elevation. It is computed by making a hydrostatic computation downward from the first complete (i.e., with nonmissing height and temperature) mandatory level above the surface to the reported surface pressure. The baseline residual s^b is the difference between the station elevation z_s, given by the report, and the hydrostatically determined height at the surface pressure. It is

$$s_b = z_1 - z_s + \sum_i \left[\frac{RT_0}{g} + \frac{R}{2g}(T_i + T_{i+1}) \ln\left(\frac{p_{i+1}}{p_i}\right)\right], \quad (5)$$

where the sum is over the layers as stated above, including the use of all reported intervening temperatures, and z_1 is the height of the first complete mandatory level above the surface. The (virtual) temperature is in degrees Celsius. The baseline residual has units of height.

It is sometimes convenient to consider the baseline data mismatch from a different point of view. One may ask what the pressure inconsistency is between the reported surface pressure and the pressure obtained when working down hydrostatically from the first complete mandatory level to the reported station elevation. By this computation, the surface pressure residual is obtained, given by

$$s^p = p_s\left\{1 - \exp\left[\frac{2g}{R}\left(\frac{z_0 - z_s}{2T_0 + T_s + T_{s+}}\right)\right]\right\}$$

with

$$z_0 \equiv z_1 + \sum_i \left[\frac{RT_0}{g} + \frac{R}{2g}(T_i + T_{i+1}) \ln\left(\frac{p_i}{p_{i+1}}\right)\right], \quad (6)$$

where $s+$ refers to the first level above the surface. Other symbols have the same meaning as before, and the summation is over the same layers. Figure 1 shows the arrangement of data for this check.

d. *Incremental check*

Recognizing the value of a 6-h forecast in identifying errors, the *increment* (or observed increment) is cal-

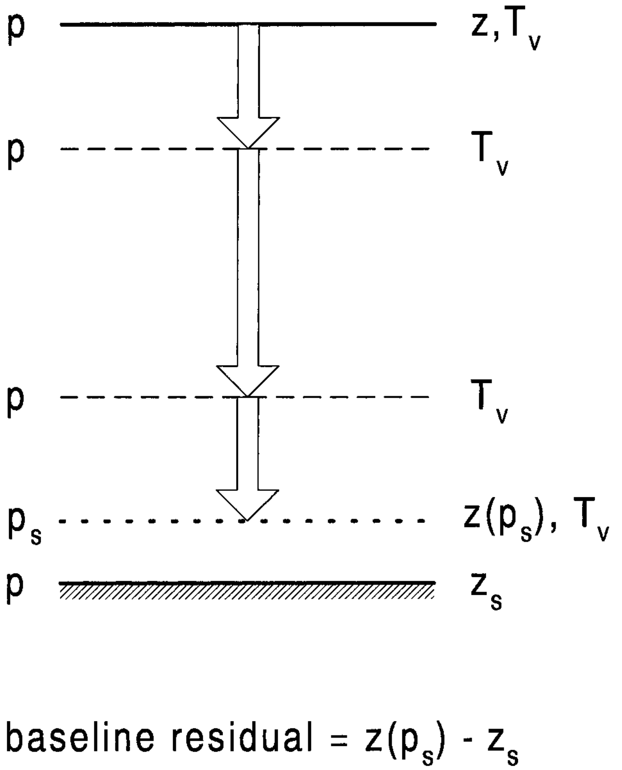

FIG. 1. Arrangement of variables for the baseline residual. The hydrostatic computation proceeds downward from the first complete mandatory level to the station elevation, using any intervening (virtual) temperatures.

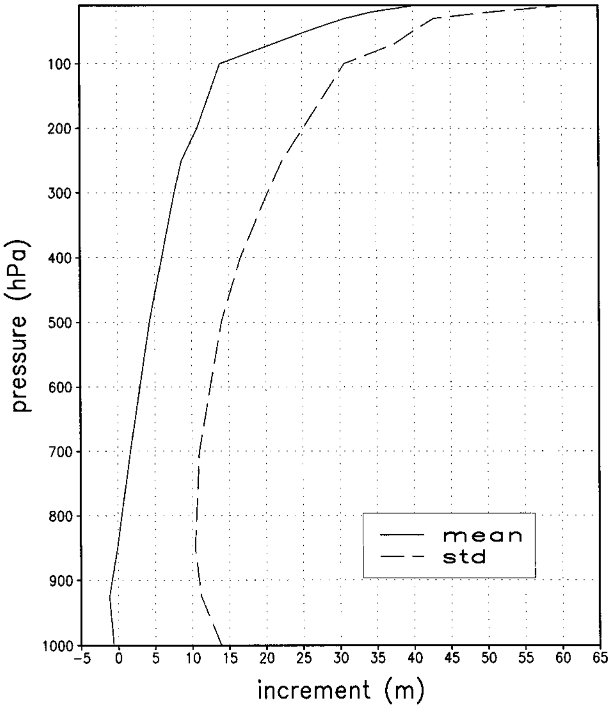

FIG. 2. Height increment mean and standard deviation at mandatory levels, calculated from data for all reporting stations at 81 data times from Jan to Mar 1999.

culated, defined as the difference between a reported value and its forecast value, interpolated both horizontally and vertically to the data location. Within NCEP's operations, the data are provided to CQCHT in a locally defined Binary Universal Form for Data Representation (BUFR) format called "prepbufr." In prepbufr, the background (6-h forecast) values, interpolated to data locations, are already part of the file. Thus, the increment is defined as

$$i = o - g \tag{7}$$

for each height and temperature, where i is the observed increment, o is the observed value, and g is the 6-h forecast value interpolated to the observation location. Figures 2 and 3 show sample statistics for the height and temperature increments. The figures show the mean and standard deviations for all observations for 81 data times from January to March 1999, stratified by pressure. Statistics of this nature form the basis for determining whether a residual is large. However, statistics for that purpose are sampled over a much longer period of time.

As a check by itself, the increment could usually be used for error detection, but at the risk of making a significant number of wrong decisions. This is because the forecast used to calculate the increment is not per-

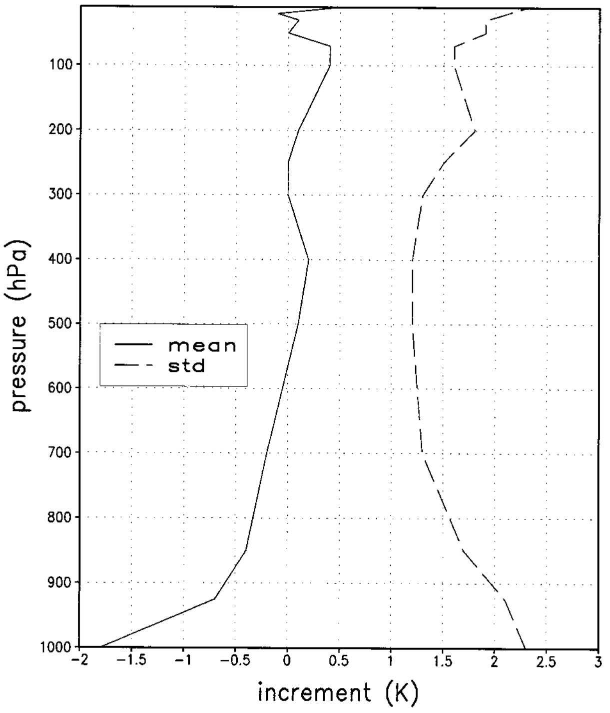

FIG. 3. Temperature increment mean and standard deviation at mandatory levels, calculated from data for all reporting stations at 81 data times from Jan to Mar 1999.

fect. There would be the tendency to delete good observations where the forecast was most in error and where the observations might possibly be needed most for the following forecast. Therefore, it is imperative to use all checks, and indeed all other checks, with the exception of the lapse rate check, are more sensitive than the increment check.

For errors at the surface, it is useful to define the surface pressure increment, the difference between the reported surface pressure and the 6-h forecast surface pressure, vertically adjusted from the model terrain to the station elevation.

e. Horizontal statistical check

The horizontal statistical check is based on horizontal optimal interpolation of increments to the observation location, excluding the observed datum in the interpolation. The horizontal residual is the difference between the increment at the observation location and the horizontally interpolated value. The horizontal statistical check uses at most one increment from each quadrant surrounding the station, using the closest in each quadrant, if any are less than 1000-km distance. It is calculated only if surrounding increments are available within at least two quadrants.

The purpose of the statistical checks (horizontal and vertical) is not to make the most accurate estimate of the value of each datum at its observation location, excluding the datum, but rather to make a reasonable estimate of its value using information only at the same pressure (horizontal check) or horizontal position (vertical check). Therefore, it is sufficient to use reasonably estimated statistical characteristics of the data in the interpolation formulation, and indeed the QC results of this CQC are not sensitive to the interpolation details. This is true partly because of the generally smooth variation of increments in the absence of error and the erratic variation of increments in the presence of error but, more important, also because of the heavy use of the powerful complex of hydrostatic residuals that is used in most decisions. All statistical properties necessary for this CQC have been measured with the appropriate forecast model as background and from a history of the residual statistics over long-term use.

The horizontal residual is calculated as (see, e.g., Thiébaux and Pedder 1987)

$$s_l^h = i_l - \sum_{i=1}^{m} w_i i_i \qquad m = 2, 3, \text{ or } 4, \tag{8}$$

where s_l^h is the horizontal residual (at a point l), i_l is the observed increment, and w_i are the weights, determined from

$$\begin{vmatrix} 1+\varepsilon & r_{12} & r_{13} & r_{14} \\ r_{21} & 1+\varepsilon & r_{23} & r_{24} \\ r_{31} & r_{32} & 1+\varepsilon & r_{34} \\ r_{41} & r_{42} & r_{43} & 1+\varepsilon \end{vmatrix} \begin{vmatrix} w_1 \\ w_2 \\ w_3 \\ w_4 \end{vmatrix} = \begin{vmatrix} r_{01} \\ r_{02} \\ r_{03} \\ r_{04} \end{vmatrix}, \tag{9}$$

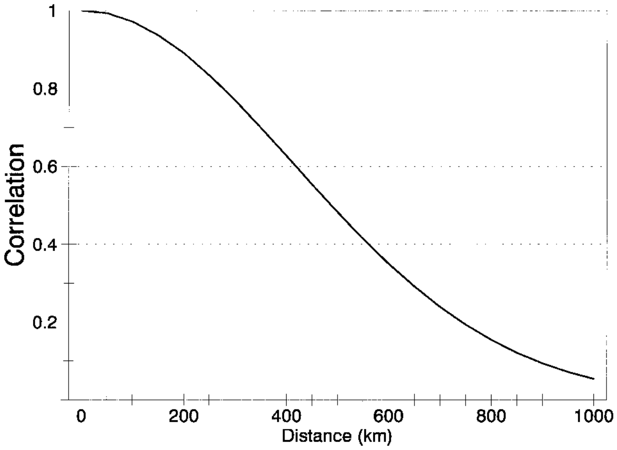

FIG. 4. Horizontal height autocorrelation as a function of distance used by horizontal check.

where ε is the ratio of 6-h observation error variance to forecast error variance, estimated to be 0.5, and r_{ij} is the correlation between the increments at points i and j. The observation point is denoted by the subscript 0. The horizontal correlations are modeled with a squared exponential that depends only upon distance. It is shown in Fig. 4 and is given by

$$r_{ij} = \exp(-kd_{ij}^2), \tag{10}$$

where d_{ij} is the distance between points i and j. The constant k has the experimentally determined value of $3.5 \times 10^{-6}\ \mathrm{m}^{-2}$. The equation for the weights is solved by a standard matrix method.

The horizontal check can be calculated only at mandatory levels, given that it uses only data at the same pressure level. Its sensitivity, as evidenced by the standard deviation of the horizontal check (see Figs. 5 and 6), is less than either the incremental or vertical checks but is valuable as corroborative evidence when available.

f. Vertical statistical check

The vertical residual is the difference between the observed increment and the increment interpolated vertically from the nearest data points for the same station, one above and one below. Thus, the vertical residual is given by

$$s_l^v = i_l - w_{l-1} i_{l-1} - w_{l+1} i_{l+1}, \tag{11}$$

where $l - 1$ is the first level below and $l + 1$ is the first level above the data level l. The weights are determined to give minimal rms error. For a formulation of the problem and solution, see Thiébaux and Pedder (1987). The weights are given by

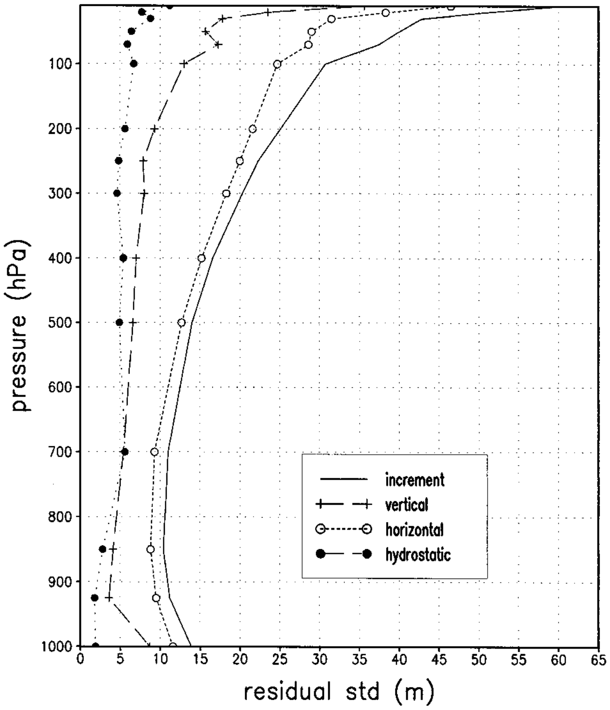

FIG. 5. Height check standard deviations for 81 data times from Jan to Mar 1999.

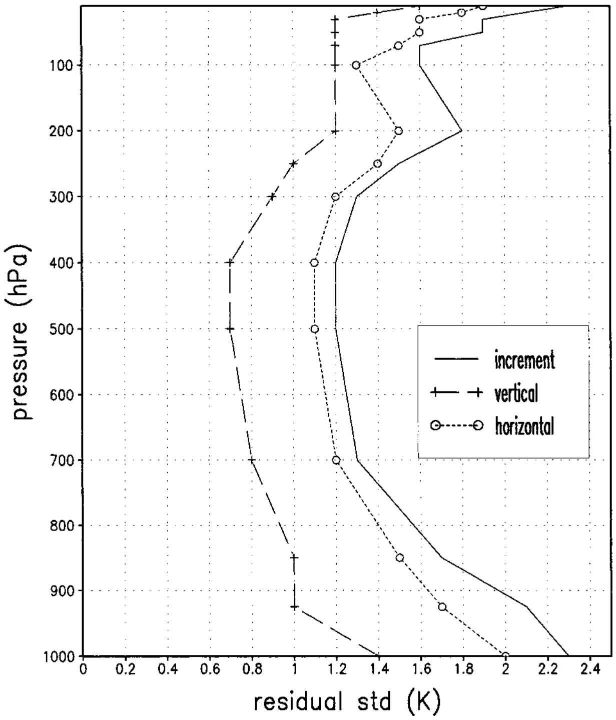

FIG. 6. Temperature check standard deviations for 81 data times from Jan to Mar 1999.

$$w_{l+1} = \frac{(1+\gamma)r_{l,l+1} - r_{l,l-1}r_{l-1,l+1}}{(1+\gamma)^2 - r^2_{l-1,l+1}} \quad \text{and}$$

$$w_{l-1} = \frac{(1+\gamma)r_{l,l-1} - r_{l,l+1}r_{l-1,l+1}}{(1+\gamma)^2 - r^2_{l-1,l+1}}, \tag{12}$$

where $r_{i,j}$ is the vertical correlation of increments between level i and j, and $\gamma = 0.5$ is the assumed ratio of the observation to 6-h forecast error variance. The vertical correlation model used is

$$r_{l1,l2} = \frac{1}{1 + c_a\left|\ln\left(\frac{p_{l1}}{p_{l2}}\right)\right|^{1.2}}. \tag{13}$$

A form for the vertical correlation, close to this one, is suggested by Bergman (1979). The value of c_a is 1.1 for height and 8.0 for temperature. Figure 7 shows the correlations as a function of the ratio of the two pressures. The height correlation falls off much more slowly because of the large vertical correlation of the height increment through the hydrostatic approximation.

The vertical check is most sensitive to rough data errors. It is calculated for all levels for height and temperature. This check is not sensitive to errors in the increment, because any forecast errors are generally highly correlated in the vertical.

g. Lapse rate check

The lapse rate is computed between each temperature and the temperature of the layer immediately above. The lapse rate is placed in one of four classes: 1) absolutely stable, 2) conditionally stable (stable with respect to unsaturated air but unstable with respect to saturated air), 3) unstable, and 4) unstable with loose limits (with 2 K added to the level temperature above).

The lapse rate is used in three ways. When temper-

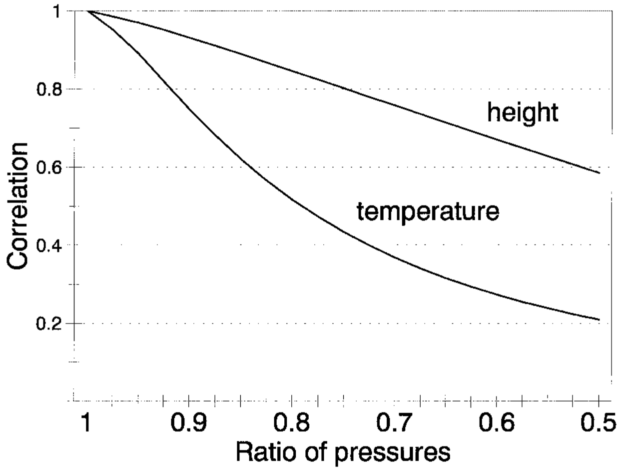

FIG. 7. Modeled vertical variation of autocorrelation of height and temperature as a function of the ratio of the two pressures. These variations are used by the vertical checks.

ature observation errors are indicated by other checks, an unstable lapse rate may change the diagnosis from suspect to bad. When a lapse rate is unstable, the temperatures involved in the check will not be used as influencing data in the horizontal check of temperature. The lapse rate check is used to make sure that corrections to temperature do not create superadiabatic layers (with loose limits). Because the check is never used by itself, it does not lead to bad decisions, even in the presence of moderately unstable layers, as may be found, for example, in convective situations, particularly with the Vaisala, Inc., RS-80 sonde.

h. Temporal check

The temporal check is not used for NCEP everyday operations but is potentially valuable for retrospective analyses and forecasts such as the NCEP–National Center for Atmospheric Research 40-Year Reanalysis (Kalnay et al. 1996). The check, included in CQCHT but not normally used, is identical to the one used in the reanalysis project.

The temporal residual is calculated as the difference between the observed (full) value and the value interpolated linearly from adjacent times, at 12 or 24 h away. In order to eliminate the use of bad influencing data in the temporal check, it is computed only if the increments for the data at off times are within acceptable limits. There is also an attempt to take into account the fact that the temperature shows a strong diurnal signal at lower levels and that the height shows a diurnal signal, primarily at higher levels.

The temporal check is potentially most useful in the absence of the horizontal check (i.e., at isolated stations). Its sensitivity to data errors is of the same order as the horizontal check, and it is completely insensitive to forecast errors (except indirectly through data selection for the check).

3. The use of checks in the presence of ‘‘noise’’ and rough errors

All the checks may be thought of as various forms of redundancy. The increment compares the observation with the 6-h forecast. The horizontal and vertical checks compare the (observed) increment with their horizontally and vertically interpolated values. The hydrostatic check compares the thickness computed from the heights with the value computed from the temperatures with the hydrostatic equation.

The purpose of the checks is to diagnose rough errors. In addition to the influence of rough errors from many different origins, all the checks are subject to ‘‘noise,’’ that is, the values entering the checks are modified by various influences. Some of the sources of this noise are forecast error, interpolation error, error of representativeness, true observation error, and sampling error. Most of these errors are unbiased and can be considered to be random, with a normal distribution. Further, they will generally be uncorrelated with each other.

a. The checks with noise

The increment [Eq. (7)] is modified by the influence of noise to become

$$i = \hat{o} + o' - g \equiv \hat{i} + i', \tag{14}$$

where $\hat{o}$ is the ‘‘true’’ value of the observation, o' is the observation error, g is the 6-h forecast value that contains forecast and interpolation errors, $\hat{i} \equiv \hat{o} - g$ is the true increment (containing forecast and interpolation errors), and $i' \equiv o'$ is the increment error.

The horizontal and vertical residuals are also changed by the presence of noise and become

$$\begin{aligned} s &= i_0 - \sum w_i i_i \\ &= \hat{i}_0 - \sum w_i \hat{i}_i + i'_0 - \sum w_i i'_i, \\ &\equiv \hat{s} + s' \end{aligned} \tag{15}$$

where the summation is over the appropriate influencing points for the check. The s' includes the influence of both analysis and observation errors.

The hydrostatic equations for layer hydrostatic residuals, with random errors z' in height and T' in temperature, are

$$s_{i,i+1} = z'_{i+1} - z'_i - B_{i,i+1}(T'_i + T'_{i+1}). \tag{16}$$

Included in the primed variables are the ‘‘sampling’’ errors as well as the observation errors. These sampling errors arise because not all temperatures used at the reporting stations in solving for the heights are reported. By convention, because there are no observation errors in z, let the z's represent the sampling errors.

b. The statistics of the noise

The mean and standard deviation of the noise components can, in principle, be determined by calculating them from a large sample of the residuals in which rough errors have been eliminated. Note that if the forecast is unbiased and the increment noise is uncorrelated with either the observations or the 6-h forecast, then the standard deviation of the increment for a large sample is equal to the sum of the standard deviation of the forecast error plus the standard deviation of the increment noise. Likewise, under similar assumptions, the sample standard deviations for the horizontal and vertical residuals are equal to the sum of the standard deviation of the interpolation error plus the standard deviation of the residual noise. Unfortunately, the largest uncertainty in carrying out these calculations is the forecast error, making any estimate of the noise standard deviation even more doubtful. For the hydrostatic check, however, the background is not relevant, and the residual standard deviation, as displayed in Fig. 5, may be considered to represent the check noise standard deviation.

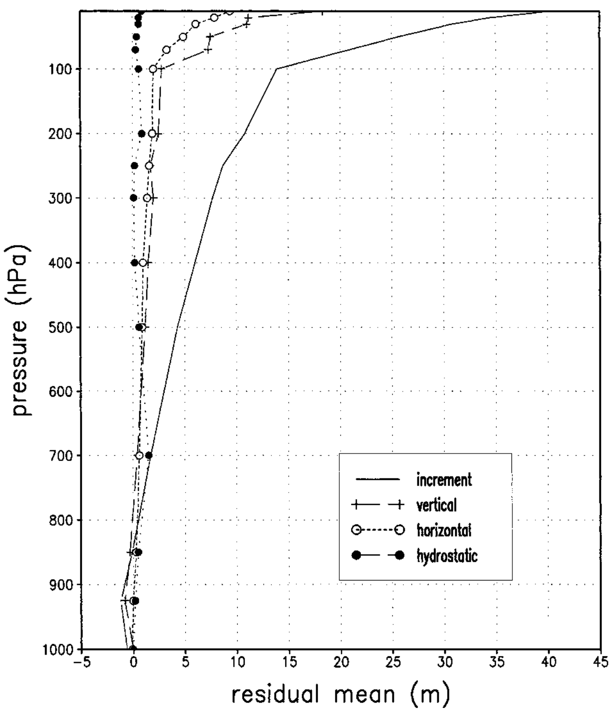

FIG. 8. Check means for height for 81 data times from Jan to Mar 1999. Includes increment, horizontal, vertical, and hydrostatic checks.

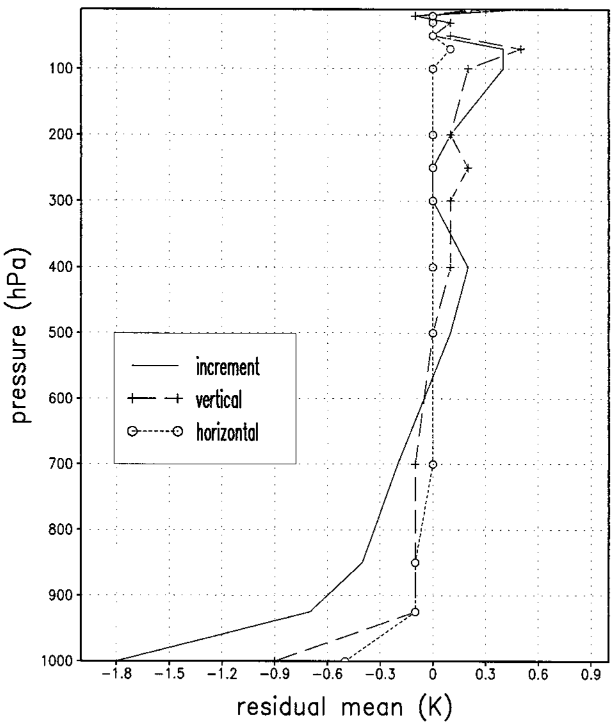

FIG. 9. Check means for temperature for 81 data times from Jan to Mar 1999.

c. Determination of suspicion of error

The standard deviation of the various residuals, in the absence of data error and collected over an extended period of time, is used to set limits for the likelihood of rough error. Figures 5, 6, 8, and 9 show the standard deviations and means for the various check residuals (in the absence of data error) as a function of pressure. As an example of the method for determining whether an error is or is not suspected for a datum, consider the increment when a rough error r is present. The increment becomes

$$i = \hat{i} + i' + r. \tag{17}$$

Remember that $\hat{i}$ contains forecast and interpolation error and i' contains observation error. The three terms on the right of Eq. (17) should be uncorrelated, so that

$$\overline{i^2} = \overline{\hat{i}^2} + \overline{i'^2} + \overline{r^2}, \tag{18}$$

where the overbar represents a statistical mean. An error is suspected by this check if

$$r^2 > \alpha(\overline{\hat{i}^2} + \overline{i'^2}), \tag{19}$$

where α is determined experimentally. The right-hand side of Eq. (19) is just the value obtained from a large sample of the increment with rough errors excluded. Similar limits are developed for the other checks. Only when errors are suspected for a datum is further analysis performed by the DMA.

d. Suggested error corrections

The hydrostatic residuals in most instances form the complex from which suggested corrections are determined. A complete list of suggested corrections, based on the values of the hydrostatic residuals, may be found in Collins (1998b). The general methodology will be outlined here for a single rough error in temperature. Suppose the (mandatory) level of the error is 2 and the adjoining (mandatory) levels are 1 and 3. Then, the hydrostatic residuals [Eq. (1)] for the two layers are

$$s_{12} = z_2 - z_1 - A_{12} - B_{12}(T_1 + T_2), \quad \text{and}$$
$$s_{23} = z_3 - z_2 - A_{23} - B_{23}(T_2 + T_3). \tag{20}$$

Now, the variables are potentially divided into three parts as in Eq. (17). However, a rough error is assumed to be present only in the midlevel temperature t_2. Substituting $T_1 + t'_1$, and so on, and dividing by the Bs yields (with $x_{ij} \equiv s_{ij}/B_{ij}$)

$$x_{12} = (z'_2 - z'_1)/B_{12} - t'_1 - t'_2 - t_2 \equiv x'_{12} - t_2, \quad \text{and}$$
$$x_{23} = (z'_3 - z'_2)/B_{23} - t'_2 - t'_3 - t_2 \equiv x'_{23} - t_2. \tag{21}$$

The objective is to determine a value of t_2 that minimizes the approximation errors in the presence of the random errors x'_{12} and x'_{23}. The error can be defined as $E^2 = x'^2_{12} + x'^2_{23}$. Setting the derivative of E^2 with respect to t_2 equal to zero and solving for t_2 gives

$$t_2 = -\frac{1}{2}(x_{12} + x_{23}). \tag{22}$$

with substitution of (22) into (21) and use of the definition of the error, the minimum error is

$$(E^2)_{\min} = \left[x_{12} - \frac{1}{2}(x_{12} + x_{23})\right]^2 + \left[x_{23} - \frac{1}{2}(x_{12} + x_{23})\right]^2$$
$$= \frac{1}{2}(x_{12} - x_{23})^2. \qquad (23)$$

Let us consider the approximate error t_2 a little more closely:

$$t_2 \approx -\frac{1}{2}(x_{12} + x_{23})$$
$$= t_2 + \frac{1}{2}\left(\frac{z'_2 - z'_1}{B_{12}} + \frac{z'_3 - z'_2}{B_{23}} - t'_1 - 2t'_2 - t'_3\right). \qquad (24)$$

All the terms within the parentheses are small and random and *may* cancel. There is potential trouble if the layers are too thin, however, particularly if $B_{12} \rightarrow 0$ or $B_{23} \rightarrow 0$ [see Eq. (2)]. In that case, any small random error would lead to large error in the t_2 estimate. The layers 1000–925 and 925–850 hPa are near the low limit of thickness for which Eq. (22) provides a reliable estimate of the error. There is no such limitation on layer thickness for single level height corrections.

The estimate of the temperature error given by Eq. (22) provides the best estimate from a statistical point of view, but it does not recognize that many rough errors are of human origin and therefore may be ‘‘simple’’ in a certain sense. Human errors most often are due to the miscoding of temperature sign, the error in a single digit, or the interchange of digits. CQCHT contains logic that looks for a correction to an error that is close to the functionally derived correction [e.g., Eq. (22) for single temperature error] and yet resulted from a simple cause.

4. Detection of errors by CQC

It is emphasized that all of the residuals are calculated before any decisions are made, and the CQC will use the agreement of the *values* of the various residuals, including increment, in making its decisions.

It is not only the residuals at the suspected error location that are important, but also the pattern of the residuals within the observation vicinity. This is true because, of all the residuals, only the increment does not involve data at other locations. The vertical, hydrostatic, lapse rate, and baseline checks all use data separated vertically, while the horizontal check uses data separated horizontally. Put another way, an error in height, say, will affect the increment at the data location, the hydrostatic residuals for the layers above and below (perhaps also the baseline residual), the vertical residuals for the data levels above and below, and, if not properly eliminated from use, the horizontal residuals at neighboring points at the same level. A temperature error would, in addition, affect the lapse rates for the layers above and below.

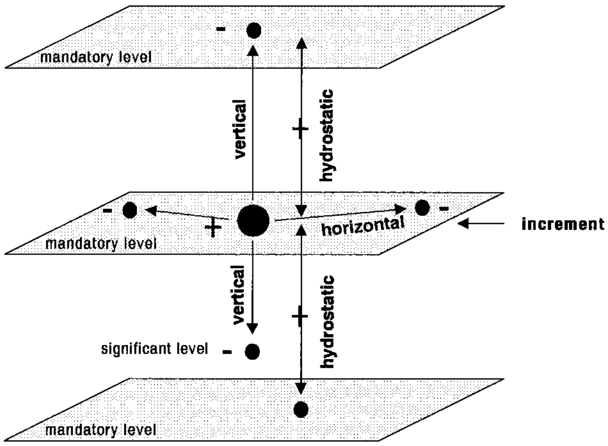

FIG. 10. Arrangement of variables for check at mandatory level. A positive temperature error is assumed. For a positive height error, the lower hydrostatic residual would be positive and the upper one would be negative.

Some of the dependency of the check results is illustrated in Figs. 10–12. Figure 10 shows the effects of a temperature communication error at a *mandatory* level upon various residuals. The error in the datum is assumed to be positive, indicated by a plus sign. Note that the vertical check for temperature uses the nearest temperature above or below, whether they be at mandatory or significant levels. The horizontal check is only performed at mandatory levels. Two neighboring points are shown in the figure. At the datum point under consideration, the horizontal and vertical residuals would be positive. Likewise, for this assumed positive temperature error, both hydrostatic residuals are also positive, indicated by a plus sign. If the error were in height, then the lower hydrostatic residual would be positive, the upper hydrostatic residual would be negative, and the vertical check for height would use the same levels as the hydrostatic check.

The error at the data point causes what may be called ‘‘side effects.’’ The ‘‘−’’ at several of the data points is meant to indicate that a ‘‘+’’ error in the temperature at the observation point would produce a negative residual (vertical or horizontal, depending upon the point) at these other points. The smaller size of the ‘‘balls’’ representing some locations is used to indicate that the magnitude of the residuals at these points is smaller than at the data point under consideration.

Figure 11 shows the residuals associated with a temperature communication error at a *significant* level. Again, the vertical check uses the closest temperatures above and below. The ‘‘−’’ at levels used in the vertical check indicates that a vertical check performed at these levels would have the side effect of being more negative than if the data at the observation point under consideration had no error. The lapse rate checks use the same

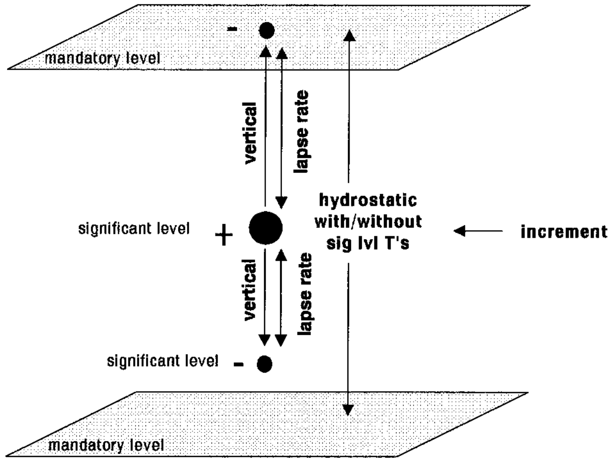

FIG. 11. Arrangement of variables for checks at significant levels.

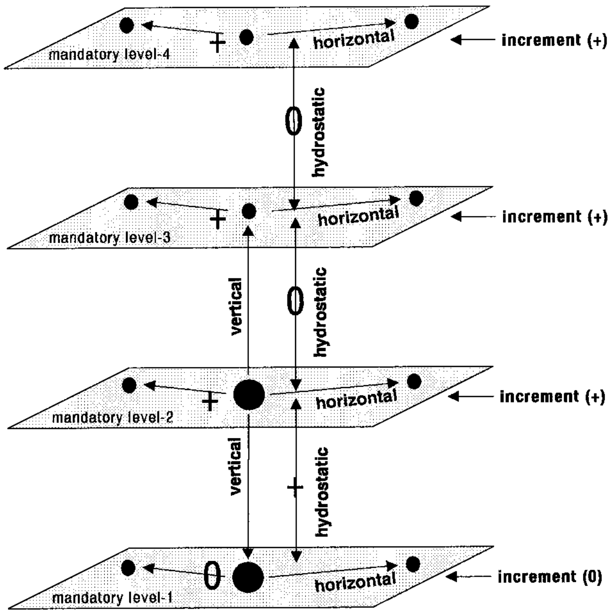

FIG. 12. Residuals when there is a computation error between levels 1 and 2. Note that all levels 2 and above are in error by the same amount.

neighboring levels. No horizontal check is available at significant levels. While hydrostatic checks cannot be made between this significant level and mandatory levels above or below, a hydrostatic check can be made that includes the level. Such a hydrostatic residual will be affected by any communication error at this significant level and may give good evidence of such an error, with the magnitude of the influence depending strongly upon the thickness of the layer, which includes this level and extends to the next temperature data above and below. Thus, even a large temperature communication error may have an insignificant effect for a thin layer, placing a severe limitation on the identification of temperature communication errors at significant levels by use of the hydrostatic residuals.

Figure 12 shows the effect of a height computation error upon various residuals. The vertical checks immediately above and below the data error level are affected by the computation error, but the magnitude of these vertical residuals cannot be used to determine the magnitude of the error, and the vertical checks will not be further considered for this kind of error. Rather, for the layer where the error occurs, the hydrostatic residual has the magnitude of the error. At levels below the error, hydrostatic residuals, increments, and horizontal residuals are unaffected, and at all levels above the error, the increments and horizontal residuals have (roughly) the magnitude of the error. A correction will modify all heights above the layer of the error by the same amount.

The usefulness of each check for error determination may be measured by its mean and standard deviation for data with no error. Long-term averages of these statistics are used in setting limits for the decisions. Figures 8 and 9 show the check means for height and temperature, calculated from mandatory level data at all stations reporting for 81 data times from January to March 1999. Figures 5 and 6 show the corresponding check standard deviations. The hydrostatic check has the smallest standard deviation, followed by the vertical, horizontal, and increment checks. The temperature standard deviations vary little with pressure, while the height standard deviations grow for smaller pressure. The height check means also grow with elevation, while the temperature check means are mostly small. The use of a long-term average of these statistics for error determination needs to be reviewed periodically, especially as changes are made to the model used for the 6-h forecast values.

5. The DMA and the correction of errors

The DMA considers the reported radiosonde levels from the lowest level upward. Whenever a correction is made at a particular level, the DMA then returns immediately to the lowest level, looking for additional corrections. It does not stop until the top level is reached without making any further changes below. A penultimate pass through the data searches for individual observation errors (for which no corrections are made), and a final pass looks for continuing temperature errors at the upper levels of the data profile. Such a general procedure is needed in the presence of multiple errors, as suggested by the various influences of each error upon the several checks (illustrated in section 4).

The potential availability of residuals is determined by the circumstances of a given level. For example, the horizontal residual is only available on mandatory levels; a vertical check is generally available at all levels, and a hydrostatic residual is only available between mandatory levels with complete data. Therefore, the DMA begins by determining the “surface type” for each level. Table

TABLE 2. Surface types and the residuals that may be available for each type. Hydrostatic residuals may be available for the layer beginning at the data level to the level above, below, or both above and below. There is no correction made at some level types, even if some residuals are available.

Description	Residuals				
	Hydrostatic	Baseline	Increment	Vertical	Horizontal
Mandatory, below			No correction		
Mandatory, first above ground	Above	x	x	x	x
Mandatory, first above ground, lower hole boundary	—	x	x	x	x
Mandatory, middle	Both	—	x	x	x
Mandatory, middle, lower hole boundary	Below	—	x	x	x
Mandatory, middle, upper hole boundary			No correction		
Mandatory, middle, isolated	No correction		x	—	x
Mandatory, top	Below	—	x	x	x
Mandatory, top, upper hole boundary			No correction		
Mandatory, incomplete	—	—	x	x	x
Significant, middle or top	—	—	x	x	x
Significant, middle or top, above top mandatory level			No correction		
Surface	—	x	x	—	—

2 gives a classification of the levels and lists the check residuals that may be available. Each surface type will have a specific, and in most cases unique, error routine that is called to deal with possible errors. For some reports, there is a series of mandatory pressure levels for which there are no available data. When this condition happens, such a series of pressure levels is referred to as a data ‘‘hole,’’ and the error routines treat the lower boundary of the hole as if it were the top of a profile and the upper boundary of the hole as if it were the lowest reported level. The complex of hydrostatic residuals forms the basis for most error correction. This fact is true for two reasons: first, with rare exceptions, all rough errors create large hydrostatic residuals, and second, the hydrostatic redundancy of heights and temperatures at mandatory levels gives by far the most powerful and accurate method for error correction.

TABLE 3. CQCHT error types and their description.

Type	Description
	Communication errors
1	Single height, interior level
2	Single temperature, interior level
3	Height and temperature at same level, interior level
5	Height, temperature, or both at top level
7	Height at two adjacent interior levels
8	Temperature at two adjacent interior levels
9	Height at lower and temperature at upper of two adjacent interior levels
10	Temperature at lower and height at upper of two adjacent interior levels
20	Significant-level temperature
21–25	Noncorrectable significant-level temperature
100	Surface pressure communication error
102	Surface temperature error
105	Likely surface temperature error, too small to correct
	Undetermined error(s), possible in surface pressure
106	Surface pressure observation error
	Computation errors
6	Error in the computation of mandatory-level heights
	Observation errors
30–35	Temperature observation errors, rejected or used with reduced weight
36–37	Height observation errors, rejected or used with reduced weight
40	Persistent temperature errors at top of profile

Each error correction routine, determined by the corresponding surface type, follows much the same pattern. Each routine decides which hydrostatic residuals are appropriate to use and then determines which, if any, are large. Those that are large will determine which error type is most likely: error(s) at a single level of height, temperature, or both; computation error between levels; error of variables at adjacent levels; error at the top level; significant level error; or observation error. The error kinds are listed in Table 3 along with a number for the error, which is convenient to use in referring to each error. Details of the treatment by the DMA for each of the surface types is contained in Collins (1998b). That paper also contains the details for the application of each elemental correction that may be applied to several of the error types shown in Table 3. Table 4 shows the errors that can be detected and/or corrected for each surface type. Note that, for some surface types, no correction is possible, and only observation errors may be detected. For examples of the CQCHT error detection and correction and results from the application of the CQC over a full year, see Collins (2001, this issue).

6. Summary

This paper reiterates the principles of CQC and describes their implementation in NCEP’s CQCHT operational QC code for radiosonde heights and temperatures. This new code is designed to examine mandatory and significant-level data simultaneously. It also affords the opportunity to make complicated corrections in some cases of multiple errors. Although no QC code can make perfect decisions, especially one that makes corrections, experience shows this algorithm to perform

TABLE 4. Errors possible for each surface type.*

	Error/correction types									
Level type	Obs	z, T	Multi-level	Comp	Ps-comm	Ps-obs	T_s	z_s	Other	Comments
Mand, below ground	x									No corr
Mand, 1st above ground	x	x	x	x						
Mand, 1st above ground, lower hole boundary	x	x								
Mand, middle	x	x	x	x						
Mand, middle, lower hole boundary	x	x								
Mand, middle, upper hole boundary	x									No corr
Mand, middle, isolated	x									No corr
Mand, top	x	x								
Mand, top, upper hole boundary	x									No corr
Mand, incomplete	x	T								
Significant, middle or top	x	T								
Significant, middle or top, above top mandatory level	x									No corr
Surface					x	x	x	x	x	

* Abbreviations used: Obs = observation, Multilevel = errors at two adjacent levels, Comp = computation, Ps-comm = surface pressure communication error, Ps-obs = surface pressure observation error, T_s = surface temperature, z_s = station elevation, Mand = mandatory, corr = correction, x = error/correction type is possible for this level type, and T = error/correction type is possible for temperature.

well under a wide range of circumstances. Its greatest vulnerability, perhaps, is in its heavy reliance on a 6-h forecast for the detection of observation errors. However, with the recognition that each forecast model can only make use of data that are representative to it, and with the continued increase in forecast skill, this vulnerability is steadily reduced. It is reiterated that the statistics on the residuals underlying the QC decisions must be developed specifically with the forecast model in which the data are to be used, having been used to give the background for the residuals. It is necessary to revise these statistics whenever significant changes are made to the forecast model.

Acknowledgments. The first 10 years of development of CQC at NCEP/EMC were guided by Lev Gandin. Daily discussions were of the utmost importance in the direction taken in the development and refinement of the codes. The debt to him cannot be overstated.

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APPENDIX

List of Variables and Symbols

Variables:

$A_{l1,l2}$	Term in barometric formula; converting from use of temperature in Kelvins to degrees Celsius
$B_{l1,l2}$	Normalized pressure thickness of layer $l1$ to $l2$
c_a	Fitting constant for vertical correlation functions of height and temperature
$d_{i,j}$	Spherical distance between points i and j
g	Acceleration of gravity or 6-h forecast value (guess)
i	Increment; difference between observation and 6-h forecast value
l	Level in the vertical
o	Observed value
p_l	Pressure at level l
p_s	Pressure at the earth's surface
r	Rough error
$r_{i,j}$	Increment correlation between points or levels i and j
R	Gas constant for dry air
s^b	Baseline residual; the difference between the station elevation, given by the report or the NCEP dictionary, and the hydrostatically determined height at the surface pressure
s_l^h	Horizontal residual at point l
$s_{l1,l2}^m$	Hydrostatic residual between mandatory levels $l1$ and $l2$, utilizing only mandatory level heights and virtual temperatures (s^n for regular temperature)
s^p	Surface pressure residual; the difference between the reported surface pressure and the hydrostatically determined surface pressure
$s_{l1,l2}^s$	Hydrostatic residual between mandatory levels $l1$ and $l2$, utilizing mandatory level heights and virtual temperatures at all available intermediate levels
s_l^v	Vertical residual at level l
t_i'	Temperature error at level i
t_i	Temperature at level i
T_l	Temperature or virtual temperature at level l
T_s	Temperature at the earth's surface
T_0	Temperature of 0°C = 273.15 K
w_i	Analysis weight contribution at point or level i

x_{ij}	Hydrostatic residual in terms of temperature $\equiv S_{ij}/B_{ij}$
z_l	Geopotential height at level l
z_s	Station elevation
ε	Ratio of 6- observation error variance to forecast error variance

Symbols:

$\hat{x}$	True value (of variable x)
x'	Error contribution (of variable x)
$\overline{x}$	Statistical average (of variable x)

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The Operational Complex Quality Control of Radiosonde Heights and Temperatures at the National Centers for Environmental Prediction. Part II: Examples of Error Diagnosis and Correction from Operational Use

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ABSTRACT

The method of complex quality control of radiosonde heights and temperatures (CQCHT) has been under continuous development and improvement at the National Centers for Environmental Prediction since 1988. Part I of this paper gives the background for the method and details for the currently operational version of the code, which contains significant improvements over previous versions. Part II shows a number of interesting examples of operation of the algorithm and gives statistics on its performance during the first year of operation, September 1997 through August 1998. In a few examples, it is seen how even complicated errors may be corrected. The statistics show that of the 5700 hydrostatically detected errors each month, 77% were corrected. There is a great variation in the geographical distribution of errors, but it is found that a majority of all stations have at least one hydrostatically suspected error during a month's time. In addition to hydrostatically detected errors, the CQCHT detects almost 16 000 so-called observation errors in height and temperature each month.

1. Introduction

Part I of this paper (Collins 2001, this issue) gives the principles of complex quality control (CQC) following Gandin (1988) and describes the implementation of these principles for the complex quality control of radiosonde heights and temperatures (CQCHT) at the National Centers for Environmental Prediction (NCEP). Early versions of CQC at NCEP were reported in Collins and Gandin (1990) and Gandin et al. (1993). An outline of the major changes in the NCEP global model and data assimilation system since 1985, including CQCHT, can be found in Kalnay et al. (1998). In Part I, the scientific and technical aspects of the CQCHT were emphasized, including a full description of the improved strategies for error correction; here in Part II, examples are given of the application of the CQCHT in actual cases, and performance statistics for identifying and correcting errors for the 1-yr period from September 1997 through August 1998 are presented.

Fundamental to CQC philosophy is that all information pertaining to a datum will be collected or computed prior to any decision regarding it. This information should be in quantitative form rather than qualitative (e.g., pass/fail) for a particular datum check. The decisions are made by the decision-making algorithm (DMA), which considers all quantitative information from the available and appropriate checks. CQCHT includes checks on increment value, (difference between observation and 6-h forecast) consistency of horizontal and vertical optimal interpolation for each increment, vertical lapse rate, consistency of heights and temperatures at lowest levels (the baseline checks), and hydrostatic consistency. Part I described all checks in detail and the methods employed by the DMA. It is especially noteworthy that the CQCHT not only identifies bad data but corrects much of it when an error has led to large hydrostatic residuals.

A few words about the data processing at NCEP are appropriate. The various real-time data transmissions, received around the clock, are decoded and collected into daily Binary Universal Form for Data Representation (BUFR) ‘‘tank’’ files, which are updated every 2 min. From these tanks, the data to be used in each assimilation/forecast system are selected. The data are put into an assimilation-oriented BUFR format, with each datum associated with its 6-h forecast value. Part of this file contains the upper-air radiosonde data, which form the input for the CQCHT. Dropsonde data are not quality controlled with CQCHT because of the potentially highly sensitive nature of these data and their procedural differences from other radiosondes. Prior to running each assimilation/forecast model, the CQCHT is run to provide radiosonde height and temperature data as input in which errors are corrected when possible or marked

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TABLE 1. CQCHT error types and their description.

Type	Description
	Communication errors
1	Single height, interior level
2	Single temperature, interior level
3	Height and temperature at same level, interior level
5	Height, temperature, or both at top level
7	Height at two adjacent interior levels
8	Temperature at two adjacent interior levels
9	Height at lower and temperature at upper of two adjacent interior levels
10	Temperature at lower and height at upper of two adjacent interior levels
20	Significant-level temperature
21–25	Noncorrectable significant-level temperature
100	Surface pressure communication error
102	Surface temperature error
105	Likely surface temperature error, too small to correct Undetermined error(s), possibly in surface pressure
106	Surface pressure observation error
	Computation errors
6	Error in the computation of mandatory-level heights
	Observation errors
30–35	Temperature observation errors, rejected or used with reduced weight
36–37	Height observation errors, rejected or used with reduced weight
40	Persistent temperature errors at top of profile

as bad when appropriate. For global data, on a Cray YMP computer, the code runs in under 100 s.

Many examples of CQCHT operation are available from operational runs. Section 2 of this paper presents a selection of interesting examples of the major kinds of errors encountered in radiosonde heights and temperatures and describes the actions taken by the CQCHT. For this purpose, it is convenient to introduce a shorthand notation for each error type considered (Table 1, which is reproduced from Part I). Corrections may be made to computation errors and to any of the communication errors except Nos. 21–25, 105, and 106; corrections are never made to observation errors.

As CQCHT is run, it collects its own performance statistics, which are routinely compiled into monthly summaries. Section 3 shows statistics regarding the receipt of data, the error diagnosis, and the error corrections for the 1-yr period from September 1997 through August 1998. The paper concludes with a summary of statistics of the CQCHT performance at NCEP.

2. Examples of errors in radiosonde heights and temperatures

As discussed fully in Part I, errors are conveniently divided into three groups: communication, computation, and observation. The term ‘‘observation error’’ is often used to refer strictly to an instrument or measurement error, but the term's meaning is extended here to include any difference between the true value of a measured parameter (e.g., temperature) and that used in its subsequent processing, once recorded on the ground at the observation station. In the parameters considered, namely geopotential heights and temperatures, strictly speaking, only temperatures can exhibit observation errors. However, the terminology is also loosely applied to heights hydrostatically computed from temperatures that contain observation errors. Note that observation errors do not result in hydrostatic inconsistencies between the heights and temperatures. Communication and computation errors, on the other hand, will almost always result in hydrostatic inconsistencies. These inconsistencies are determined from the complex of hydrostatic residuals, which are computed as the difference between

TABLE 2. Example 1: error to single height (type 1).

STN ID: 43311 LAT: 11.12 LON: 72.73 STN HT: 4.
DATE/TIME: 98032412 DHOUR: 0.0 SCAN: 1 INST TYPE: 20
SURFACE PRESS: 1007.0 PIS: −1.6 PSINC: 6.6 BASRES: −58.

	Height				Hydr Res		Temperature				
PRESS	ZOB	ZI	ZV	ZH	HYDS	HYDN	TOB	TI	TV	TH	X
1007.0	4.	−14.					29.3	−2.1			
1000.0	**8.**	**−72.**	**−66.**		**60.**	**65.**	28.6	−2.3	−1.3		56.7
962.0							25.8	−1.7	−0.6		
925.0	757.	−9.	22.		0.	4.	24.8	−0.6	0.1		3.6

Error diagnosis:

PRESSURE	VAR	IETYP	QMARK	ORIG-VAL	COR	NEW-VAL
1000.0	Z	1	1.	8.0	**60.0**	68.0

SURFACE PRESS: 1007.0 PIS: −1.6 PSINC: −0.2 BASRES: **2.**

	Height				Hydr Res		Temperature				
PRESS	ZOB	ZI	ZV	ZH	HYDS	HYDN	TOB	TI	TV	TH	X
1007.0	4.	−14.					29.3	−2.1			
1000.0	**68.**	**−12.**	**−6.**		**0.**	**5.**	28.6	−2.3	−1.3		4.2
962.0							25.8	−1.7	−0.6		
925.0	757.	−9.	−2.		0.	4.	24.8	−0.6	0.1		3.6

TABLE 3. Example 2: error to single height (type 1) and error at the top level (type 5).

STN ID: 97372 LAT: −10.17 LON: 123.67 STN HT: 138.
DATE/TIME: 98051812 DHOUR: 0.0 SCAN: 1 INST TYPE: 10
SURFACE PRESS: 997.0 PIS: 1.5 PSINC: 0.1 BASRES: −1.

	Height				Hydr Res		Temperature				
PRESS	ZOB	ZI	ZV	ZH	HYDS	HYDN	TOB	TI	TV	TH	X
500.0	5920.	21.	5.		−1.	1.	−3.1	−0.6	0.2		0.4
400.0	7650.	18.	637.		**−1795.**	**−1791.**	−13.9	−0.6	−0.5		−425.3
386.0							−15.1	0.0	0.3		
300.0	**7980.**	**−1777.**	**−1792.**		**1804.**	**1804.**	−28.7	0.0	0.5		676.2
250.0	11 060.	22.	878.		−15.	−17.	−39.5	−1.6	−0.5		−2.2
248.0							−40.1	−1.8	−0.9		
150.0	14 350.	6.	218.		**−598.**	**−613.**	−64.5	1.9	0.7		−103.3
144.0							−66.1	2.3	1.4		
118.0							−76.7	−0.3	−1.1		
100.0	**16 120.**	**−578.**	**−581.**				−80.2	0.6	1.2		
94.7							−81.7	−1.2	−1.4		
76.3							−79.7	−0.6	−0.2		

Error Diagnosis:

PRESSURE	VAR	IETYP	QMARK	ORIG-VAL	COR	NEW-VAL
300.0	Z	1	1.	7980.0	**1800.0**	9780.0
100.0	Z	5	1.	16 120.0	**600.0**	16 720.0

	Height				Hydr Res		Temperature				
PRESS	ZOB	ZI	ZV	ZH	HYDS	HYDN	TOB	TI	TV	TH	X
500.0	5920.	21.	5.		−1.	1.	−3.1	−0.6	0.2		0.4
400.0	7650.	18.	1.		**5.**	**9.**	−13.9	−0.6	−0.5		2.2
386.0							−15.1	0.0	0.3		
300.0	**9780.**	**23.**	**8.**		**4.**	**4.**	−28.7	0.0	0.5		1.6
250.0	11 060.	22.	9.		−15.	−17.	−39.5	−1.6	−0.5		−2.2
248.0							−40.1	−1.8	−0.9		
150.0	14 350.	6.	−9.		**2.**	**−13.**	−64.5	1.9	0.7		−2.2
144.0							−66.1	2.3	1.4		
118.0							−76.7	−0.3	−1.1		
100.0	**16 720.**	**22.**	**19.**				−80.2	0.6	1.2		
94.7							−81.7	−1.2	−1.4		
76.3							−79.7	−0.6	−0.2		

the thickness from one mandatory level to the next as given by the reported heights and as computed from the report temperatures (and moisture). It is only communication and computation errors that are correctable; for that purpose, the complex of hydrostatic residuals is critical. Some details of the method of error detection and correction was expounded in Part I, and complete details can be found in Collins (1998).

Most communication and computation errors are created by faulty human action. As such, they tend to be ‘‘simple’’ in the sense that a single digit is corrupted, the sign is wrong, or digits are interchanged. These particular error types are specifically sought in the CQCHT error correction. When appropriate, the use of a simple correction will be noted in the examples. Another characteristic of human error is that it usually affects a single datum, thus often allowing easy identification and correction. The error types 1, 2, 5, 20, 100, and 102 result in most cases from a single human mistake.

Error detection begins with the computation of the various check residuals: increments, horizontal residuals, vertical residuals, baseline residuals, hydrostatic residual, and lapse-rate classes. Each profile is considered from the lowest level to the highest, and errors with possible corrections are considered first. If any correction is made at a particular level, below the top level, then all residuals are recomputed and the profile is reexamined from the lowest level. In this way, sometimes multiple complicated corrections may be made that otherwise would be missed. A few examples of these dependent corrections will be given later. The majority of corrections, however, are at an isolated level.

The examples will first consider errors to a single variable, height, or temperature. Next, multiple errors will be considered, both at a single level and at adjacent levels. Examples containing computation errors will be shown. Then, errors of surface pressure and surface temperature will be given, followed by an example of correction of a bad significant level temperature. Last, observation errors will be discussed.

a. Single errors

Isolated temperature or height errors are the most common communication errors. Example 1 (Table 2) shows the error and correction to a 1000-hPa height. The fol-

TABLE 4. Example 3: type-6 correction—computation error.

STN ID: 42369 LAT: 26.75 LON: 80.88 STN HT: 122.
DATE/TIME: 98042212 DHOUR: −1.0 SCAN: 1 INST TYPE: 20
SURFACE PRESS: 989.0 PIS: 1.1 PSINC: 1.5 BASRES: −14.

	Height				Hydr Res		Temperature				
PRESS	ZOB	ZI	ZV	ZH	HYDS	HYDN	TOB	TI	TV	TH	X
1000.0	14.	3.	10.								
989.0	122.	10.					36.0	−3.8			
850.0	1459.	−11.	−7.		3.	3.	24.3	−2.4	−2.4		1.0
700.0	3114.	−14.	34.	−12.	**−134.**	**−134.**	10.8	0.0	0.5	0.5	−27.2
500.0	**5680.**	**−135.**	−77.	−136.	2.	2.	−8.8	1.1	1.0	0.1	0.7
400.0	**7370.**	**−127.**	−32.	−142.	8.	8.	−20.7	0.5	−0.2	0.6	1.9
300.0	**9440.**	**−113.**	−31.	−124.	5.	5.	−35.9	2.0	0.9	1.7	1.8
250.0	**10 690.**	**−92.**	−18.	−107.	−3.	−3.	−43.7	3.3	2.4	4.0	−0.8
200.0	**12 160.**	**−76.**	−13.	−89.	1.	1.	−51.7	1.5	0.7	1.4	0.3
150.0	**13 990.**	**−72.**	−31.	−88.			−60.3	−0.3	−0.7	−0.4	

Error diagnosis:

PRESSURE	VAR	IETYP	QMARK	ORIG-VAL	COR	NEW-VAL
500.0	Z	6	1.	5680.0	**130.0**	5810.0
400.0	Z	6	1.	7370.0	**130.0**	7500.0
300.0	Z	6	1.	9440.0	**130.0**	9570.0
250.0	Z	6	1.	10 690.0	**130.0**	10 820.0
200.0	Z	6	1.	12 160.0	**130.0**	12 290.0
150.0	Z	6	1.	13 990.0	**130.0**	14 120.0

	Height				Hydr Res		Temperature				
PRESS	ZOB	ZI	ZV	ZH	HYDS	HYDN	TOB	TI	TV	TH	X
1000.0	14.	3.	10.								
989.0	122.	10.					36.0	−3.8			
850.0	1459.	−11.	−7.		3.	3.	24.3	−2.4	−2.4		1.0
700.0	3114.	−14.	−8.	−12.	**−4.**	**−4.**	10.8	0.0	0.5	0.5	−0.8
500.0	**5810.**	**−5.**	−2.	−6.	2.	2.	−8.8	1.1	1.0	0.1	0.7
400.0	**7500.**	**3.**	−1.	−12.	8.	8.	−20.7	0.5	−0.2	0.6	1.9
300.0	**9570.**	**17.**	0.	6.	5.	5.	−35.9	2.0	0.9	1.7	1.8
250.0	**10 820.**	**38.**	11.	23.	−3.	−3.	−43.7	3.3	2.4	4.0	−0.8
200.0	**12 290.**	**54.**	18.	41.	1.	1.	−51.7	1.5	0.7	1.4	0.3
150.0	**14 120.**	**58.**	29.	42.			−60.3	−0.3	−0.7	−0.4	

lowing information is shown for the example: the first line identifies the station by its World Meteorological Organization (WMO) block and station number and gives the station latitude, longitude, and elevation in meters above sea level. In the third line, PIS is the surface pressure increment (hPa), BASRES is the baseline residual (m), and PSINC is the baseline residual in terms of pressure. The lower portion of the table is separated into parts pertaining to height, hydrostatic residuals, and temperature. The column headings have the following meanings: PRESS is pressure, ZOB is the observed height, ZI is the height increment, ZV is the vertical height residual, ZH is the horizontal height residual, HYDS is the hydrostatic residual computed using significant as well as mandatory level information, HYDN is the hydrostatic residual computed using only mandatory level information, TOB is the observed temperature, TI is the temperature increment, TV is the vertical temperature residual, TH is the horizontal temperature residual, and X is hydrostatic residual divided by the logarithm of the layer pressure thickness (this makes HYDN have units of temperature). Any errors that are suspected and any residuals that are large are printed in bold in the data that follow. Only the range of levels that are relevant to the error diagnosis is displayed in the examples. Note that the hydrostatic residuals are for a layer but are displayed at a particular (mandatory) level. They apply to the layer from the level where they are displayed to the next higher (in height) mandatory level. The amount of information in this part of the examples is large, and it takes some work to digest and appreciate it all. This information reflects a selection of that information operationally available for monitoring of all CQCHT decisions.

Next, is the error diagnosis section. It lists any error determination and any corrections to the data. The column headings are PRESSURE, the pressure; VAR, the variable (height or temperature: z or T); QMARK, the quality mark (1. = corrected, 3. = questionable quality, 13. = bad quality); ORIG-VAL, the value before correction; COR, the correction; and NEW-VAL, the value after correction. In this case, QMARK = 1., indicating that a correction was made. The value of the correction in this example is seen to be 60 m. Note that this is a simple correction, the change of one digit. A correction of approximately 60 m is first suggested by the complex of the hydrostatic residual for 1000–925 hPa and the baseline residual. This result is confirmed by the incre-

TABLE 5. Example 4: single level temperature communication error—type-2 correction and computation error correction between the surface and the first mandatory level above.

STN ID: 46780 LAT: 22.68 LON: 121.50 STN HT: 280.
DATE/TIME: 98042212 DHOUR: 0.0 SCAN: 1 INST TYPE: 9
SURFACE PRESS: 982.0 PIS: 0.8 PSINC: 20.0 BASRES: **−180.**

	Height				Hydr Res		Temperature				
PRESS	ZOB	ZI	ZV	ZH	HYDS	HYDN	TOB	TI	TV	TH	X
1000.0	116.	3.	115.	7.							
982.0	280.	7.					25.6	−2.2			
925.0	**619.**	**−177.**	−109.	−174.	**39.**	**43.**	21.3	−2.9	11.4	−1.0	**34.4**
850.0	**1351.**	**−176.**	−41.	−174.	**86.**	**92.**	**−10.5**	**−30.2**	**−29.0**	**−29.3**	**32.4**
700.0	**2999.**	**−166.**	−38.	−167.	3.	16.	11.8	0.3	9.3	0.8	3.3
500.0	**5730.**	**−160.**	−35.	−162.	−8.	−6.	−6.8	−1.1	−1.2	0.0	−1.9
400.0	**7430.**	**−166.**	−44.	−168.	5.	5.	−17.1	0.3	0.6	0.3	1.3
300.0	**9530.**	**−162.**	−40.	−163.	−2.	−2.	−31.7	0.1	0.1	0.2	−0.3
200.0	**12 260.**	**−167.**	−48.	−157.	3.	3.	−54.3	−0.4	−0.5	0.8	0.6
150.0	**14 060.**	**−161.**	−46.	−147.	1.	1.	−65.1	0.3	0.1	−0.1	0.1
100.0	**16 470.**	**−144.**	−66.	−137.			−75.2	1.7	1.6	1.9	

Error diagnosis:

PRESSURE	VAR	IETYP	QMARK	ORIG-VAL	COR	NEW-VAL
850.0	T	2	1.	−10.5	**31.0**	20.5
925.0	Z	6	1.	619.0	**180.0**	799.0
850.0	Z	6	1.	1351.0	**180.0**	1531.0
700.0	Z	6	1.	2999.0	**180.0**	3179.0
500.0	Z	6	1.	5730.0	**180.0**	5910.0
400.0	Z	6	1.	7430.0	**180.0**	7610.0
300.0	Z	6	1.	9530.0	**180.0**	9710.0
200.0	Z	6	1.	12 260.0	**180.0**	12 440.0
150.0	Z	6	1.	14 060.0	**180.0**	14 240.0
100.0	Z	6	1.	16 470.0	**180.0**	16 650.0

SURFACE PRESS: 982.0 PIS: 0.8 PSINC: 0.0 BASRES: **0.**

	Height				Hydr Res		Temperature				
PRESS	ZOB	ZI	ZV	ZH	HYDS	HYDN	TOB	TI	TV	TH	X
1000.0	116.	3.	1.	7.							
982.0	280.	7.					25.6	−2.2			
925.0	**799.**	**3.**	0.	6.	**1.**	**4.**	21.3	−2.9	−3.3	−1.0	**3.4**
850.0	**1531.**	**4.**	−2.	6.	**−2.**	**4.**	**20.5**	**0.8**	**2.0**	**1.7**	**1.4**
700.0	**3179.**	**14.**	6.	13.	3.	16.	11.8	0.3	0.3	0.8	3.3
500.0	**5910.**	**20.**	9.	18.	−8.	−6.	−6.8	−1.1	−1.2	0.0	−1.9
400.0	**7610.**	**14.**	0.	12.	5.	5.	−17.1	0.3	0.6	0.3	1.3
300.0	**9710.**	**18.**	8.	17.	−2.	−2.	−31.7	0.1	0.1	0.2	−0.3
200.0	**12 440.**	**13.**	−1.	23.	3.	3.	−54.3	−0.4	−0.5	0.8	0.6
150.0	**14 240.**	**19.**	2.	33.	1.	1.	−65.1	0.3	0.1	−0.1	0.1
100.0	**16 650.**	**36.**	27.	43.			−75.2	1.7	1.6	1.9	

ment and vertical residuals, and a simple correction is sought and found: namely, 60 m.

The last section repeats the profile but with any corrections made and the residuals recomputed, showing, in this case, that the changes have made them acceptable. Note that in this case the horizontal check residuals were not available but a correction was still made.

Multiple errors sufficiently isolated from each other may occur within a profile in such a way that the identification of these errors and any correction proceed as if the errors occurred in complete isolation. Example 2 (Table 3) shows two height errors and corrections, one at 300 hPa and the other at 100 hPa, the top mandatory level. The complex of hydrostatic residuals for 400–300 and 300–250 hPa suggests a correction of about 1800 m, which is confirmed by the other residuals. The correction of the 100-hPa height is not as direct. An error is diagnosed by the large 150–100-hPa hydrostatic residual, but it cannot determine by itself whether the error is to the height, the temperature, or both. However, the magnitude of the height increment and height vertical residual and the smallness of the temperature residuals confirm that there is only a height error and that its magnitude is about 600 m. The simple corrections of 1800 and 600 m are applied, with the result seen in the last part of the example. All resulting residuals are small after the corrections.

b. *Computation error*

When there is an error in the computation of the height of a particular mandatory level, then all heights above this level are also in error by the same amount.

Table 6. Example 5: multiple errors, including error to height and temperature at the same level (type 3) with dependent corrections.

STN ID: 60760 LAT: 33.92 LON: 8.17 STN HT: 97.
DATE/TIME: 98042612 DHOUR: −1.0 SCAN: 1 INST TYPE: 61
SURFACE PRESS: 1005.0 PIS: 0.3 PSINC: 0.3 BASRES: −2.

	Height				Hydr Res		Temperature				
PRESS	ZOB	ZI	ZV	ZH	HYDS	HYDN	TOB	TI	TV	TH	X
850.0	1518.	−9.	−3.	−17.	1.	2.	10.0	−2.8	−0.5	−2.4	0.7
809.0							7.3	−2.8	−1.1		
797.0							7.6	−1.8	−0.1		
700.0	3112.	−13.	57.	−22.	**−294.**	**−318.**	4.0	−0.4	−2.5	−0.8	−64.6
545.0							**5.0**	**14.0**	2.2		
500.0	**5570.**	**−204.**	**−202.**	**−216.**	**187.**	**114.**	**13.4**	**27.5**	**23.3**	**27.1**	34.9
481.0							−15.9	0.5	−14.1		
403.0							−24.7	1.4	0.5		
400.0	7430.	6.	87.	−6.	−3.	−5.	−25.1	1.4	0.3	1.7	−1.1
379.0							−27.5	1.6	0.5		
373.0							−28.5	1.4	0.5		
342.0							−33.7	0.3	0.2		
313.0							−39.1	−1.1	−1.1		
300.0	9450.	6.	48.	−7.	**−108.**	**−107.**	−40.3	−0.1	0.2	0.2	−39.9
285.0							−42.5	0.5	0.6		
250.0	**10 560.**	**−102.**	**−106.**	**−105.**	**106.**	**106.**	−50.1	−0.2	0.0	0.1	32.6
200.0	12 090.	3.	43.	−4.	−11.	−11.	−60.3	−1.5	−1.8	−0.7	−2.5
150.0	13 870.	4.	2.	−8.			−60.7	1.9	2.3	1.7	

Error diagnosis:

PRESSURE	VAR	IETYP	QMARK	ORIG-VAL	COR	NEW-VAL	SCAN
545.0	T	24	3.	5.0	**0.0**	5.0	1
500.0	Z	3	1.	5570.0	**200.0**	5770.0	2
500.0	T	3	1.	13.4	**−26.8**	−13.4	2
545.0	T	20	1.	5.0	**−14.0**	−9.0	3
250.0	Z	1	1.	10 560.0	**100.0**	10 660.0	4

	Height				Hydr Res		Temperature				
PRESS	ZOB	ZI	ZV	ZH	HYDS	HYDN	TOB	TI	TV	TH	X
850.0	1518.	−9.	−3.	−17.	1.	2.	10.0	−2.8	−0.5	−2.4	0.7
809.0							7.3	−2.8	−1.1		
797.0							7.6	−1.8	−0.1		
700.0	3112.	−13.	−8.	−22.	**13.**	**14.**	4.0	−0.4	0.2	−0.8	2.9
545.0							−9.0	0.0	−0.2		
500.0	**5770.**	**−4.**	**−2.**	**−16.**	**3.**	**2.**	**−13.4**	**0.7**	**0.5**	**0.3**	0.5
481.0							−15.9	0.5	−0.1		
403.0							−24.7	1.4	0.5		
400.0	7430.	6.	6.	−6.	−3.	−5.	−25.1	1.4	0.3	1.7	−1.1
379.0							−27.5	1.6	0.5		
373.0							−28.5	1.4	0.5		
342.0							−33.7	0.3	0.2		
313.0							−39.1	−1.1	−1.1		
300.0	9450.	6.	5.	−7.	**−8.**	**−7.**	−40.3	−0.1	0.2	0.2	−2.4
285.0							−42.5	0.5	0.6		
250.0	**10 660.**	**−2.**	**−6.**	**−5.**	**6.**	**6.**	−50.1	−0.2	0.0	0.1	2.0
200.0	12 090.	3.	2.	−4.	−11.	−11.	−60.3	−1.5	−1.8	−0.7	−2.5
150.0	13 870.	4.	2.	−8.			−60.7	1.9	2.3	1.7	

Therefore, such errors are identified by a single large hydrostatic residual, accompanied by a change in the value of height increments between adjacent vertical levels, and horizontal residuals of approximately the same magnitude persisting aloft. Example 3 (Table 4) shows a case in which there is a hydrostatic residual of −134 m between 500 and 400 hPa, accompanied by height increments and horizontal residuals of approximately the same magnitude at 500 hPa and above. A correction of 130 m produces a clean radiosonde profile.

Example 4 (Table 5) is more complex because it combines a height computation error, in this case between the surface and the first mandatory level above, with an isolated temperature error at 850 hPa. The original pattern of hydrostatic residuals does not fit that for a computation error, so that error is not corrected first. Rather, the temperature error at 850 hPa is first identified. The pair of hydrostatic residuals, in terms of temperature (*X*), indicate a temperature error of about 33°. The final correction, from −10.5 to 20.5, is simple: a sign and one digit change.

TABLE 7. Example 6: corrections of types 1, 2, 5, and 7.

STN ID: 97072 LAT: −0.68 LON: 119.73 STN HT: 86.
DATE/TIME: 98031400 DHOUR: 0.0 SCAN: 1 INST TYPE: 9
SURFACE PRESS: 1003.0 PIS: 0.9 PSINC: −0.3 BASRES: 3.

	Height				Hydr Res		Temperature				
PRESS	ZOB	ZI	ZV	ZH	HYDS	HYDN	TOB	TI	TV	TH	X
1003.0	86.	8.					26.8	−4.1			
1000.0	115.	10.	4.	8.	11.	**61.**	26.8	−3.9	−3.2	−1.6	**53.5**
941.0							25.4	−1.3	24.4		
925.0	802.	9.	0.	8.	**62.**	**66.**	**−24.5**	**−50.2**	**−49.4**	**−48.9**	**52.9**
850.0	1538.	12.	−67.	11.	**202.**	**214.**	20.0	−0.5	14.7	0.3	75.4
811.0							17.4	−0.3	−0.2		
771.0							15.3	0.3	1.0		
712.0							9.6	−1.8	−1.2		
700.0	**3388.**	**224.**	**208.**	**222.**	**−197.**	**−184.**	9.3	−1.4	−0.4	−0.8	−37.3
674.0							8.4	−0.6	0.2		
637.0							6.0	−0.7	−0.4		
567.0							1.8	−0.1	−0.1		
542.0							0.0	0.3	0.1		
525.0							−1.5	0.6	0.3		
500.0	5920.	32.	−57.	31.	−5.	−7.	−4.1	0.5	0.1	0.9	−2.0
469.0							−7.3	0.6	0.8		
444.0							−11.5	−1.0	−2.0		
424.0							−10.8	1.9	1.9		
400.0	7640.	34.	31.	32.	**−60.**	**−58.**	−13.5	1.2	0.1	0.8	−13.8
389.0							−14.8	1.0	0.3		
317.0							−26.7	0.0	−0.3		
300.0	**9700.**	**−27.**	238.	**−27.**	**−621.**	**−621.**	−29.7	0.2	0.2	0.2	−232.7
250.0	**10 350.**	**−647.**	−650.	**−645.**	**685.**	**685.**	−40.3	0.2	0.2	0.7	209.8
200.0	12 520.	38.	285.	42.	2.	2.	−51.3	−0.4	−0.5	−0.1	0.6
178.0							−56.9	0.1	−0.7		
172.0							−56.9	1.8	1.3		
150.0	14 340.	45.	334.	49.	**−1007.**	**−1015.**	−63.3	2.1	0.5	1.9	−171.0
148.0							−63.9	2.2	0.6		
120.0							−73.5	2.4	0.8		
100.0	**15 720.**	**−930.**	**−999.**	**−930.**	**1009.**	**1001.**	−79.4	3.6	2.3	3.6	191.8
94.1							−81.2	1.7	−1.1		
72.6							−73.9	6.6	4.0		
70.0	18 770.	143.	427.		−5.	−37.	−74.4	4.3	1.7		−7.6
56.2							−76.5	−6.4	−8.5		
51.3							−66.1	3.0	3.3		
50.0	20 730.	134.	34.		10.	−15.	−66.3	2.6	1.1		−2.0
34.9							−67.6	−2.6	−3.1		
30.0	23 830.	137.	1567.		**−4149.**	**−4488.**	−63.3	0.4	0.7		−756.4
27.3							−60.5	0.9	0.0		
21.4							−49.9	3.8	−30.5		
20.0	**22 330.**	**−3892.**	**−3959.**				**20.6**	**72.8**	**71.0**		
14.4							−46.3	−0.4	−16.0		

Error diagnosis:

PRESSURE	VAR	IETYP	QMARK	ORIG-VAL	COR	NEW-VAL
925.0	T	2	1.	−24.5	**53.0**	28.5
700.0	Z	1	1.	3388.0	**−200.0**	3188.0
300.0	Z	7	1.	9700.0	**60.0**	9760.0
250.0	Z	7	1.	10 350.0	**680.0**	11 030.0
100.0	Z	1	1.	15 720.0	**1000.0**	16 720.0
20.0	Z	5	1.	22 330.0	**3930.0**	26 260.0
20.0	T	5	13.	20.6	**0.0**	20.6

	Height				Hydr Res		Temperature				
PRESS	ZOB	ZI	ZV	ZH	HYDS	HYDN	TOB	TI	TV	TH	X
1003.0	86.	8.					26.8	−4.1			
1000.0	115.	10.	4.	8.	−18.	**1.**	26.8	−3.9	−3.2	−1.6	**0.5**
941.0							25.4	−1.3	−1.6		
925.0	802.	9.	0.	8.	−79.	**0.**	**28.5**	**2.8**	**3.6**	**4.1**	**−0.1**
850.0	1538.	12.	0.	11.	**2.**	**14.**	20.0	−0.5	−1.2	0.3	5.1
811.0							17.4	−0.3	−0.2		

TABLE 7. (*Continued*)

	Height				Hydr Res		Temperature				
PRESS	ZOB	ZI	ZV	ZH	HYDS	HYDN	TOB	TI	TV	TH	X
771.0							15.3	0.3	1.0		
712.0							9.6	−1.8	−1.2		
700.0	**3188.**	**24.**	**8.**	**22.**	**3.**	**16.**	9.3	−1.4	−0.4	−0.8	3.3
674.0							8.4	−0.6	0.2		
637.0							6.0	−0.7	−0.4		
567.0							1.8	−0.1	−0.1		
542.0							0.0	0.3	0.1		
525.0							−1.5	0.6	0.3		
500.0	5920.	32.	10.	31.	−5.	−7.	−4.1	0.5	0.1	0.9	−2.0
469.0							−7.3	0.6	0.8		
444.0							−11.5	−1.0	−2.0		
424.0							−10.8	1.9	1.9		
400.0	7640.	34.	9.	32.	**0.**	**2.**	−13.5	1.2	0.1	0.8	0.4
389.0							−14.8	1.0	0.3		
317.0							−26.7	0.0	−0.3		
300.0	**9760.**	**33.**	7.	**33.**	−**1.**	−**1.**	−29.7	0.2	0.2	0.2	−0.4
250.0	**11 030.**	**33.**	6.	**35.**	**5.**	**5.**	−40.3	0.2	0.2	0.7	1.5
200.0	12 520.	38.	9.	42.	2.	2.	−51.3	−0.4	−0.5	−0.1	0.6
178.0							−56.9	0.1	−0.7		
172.0							−56.9	1.8	1.3		
150.0	14340.	45.	7.	49.	−**7.**	−**15.**	−63.3	2.1	0.5	1.9	−2.5
148.0							−63.9	2.2	0.6		
120.0							−73.5	2.4	0.8		
100.0	**16 720.**	**70.**	**1.**	**70.**	**9.**	**1.**	−79.4	3.6	2.3	3.6	0.2
94.1							−81.2	1.7	−1.1		
72.6							−73.9	6.6	4.0		
70.0	18 770.	143.	68.		−5.	−37.	−74.4	4.3	1.7		−7.6
56.2							−76.5	−6.4	−8.5		
51.3							−66.1	3.0	3.3		
50.0	20 730.	134.	34.		10.	−15.	−66.3	2.6	1.1		−2.0
34.9							−67.6	−2.6	−3.1		
30.0	23 830.	137.	80.		−**219.**	−**558.**	−63.3	0.4	0.7		−94.1
27.3							−60.5	0.9	0.0		
21.4							−49.9	3.8	−30.5		
20.0	**26 260.**	**38.**	−**29.**				**20.6**	**72.8**	**71.0**		
14.4							−46.3	−0.4	−16.0		

Once the temperature is corrected, then the 925–850- and 850–700-hPa hydrostatic residuals, when recomputed, are small, allowing the computation error between the surface, 982 hPa, and the first mandatory level above (925 hPa) to be identified. The correction amount, −180 m, is given by the baseline residual, which agrees well with the height increments and horizontal residuals before correction. After all corrections are made, the residuals all become small.

c. Multiple corrections, including correction to height and temperature at the same level (type-3 error)

The next example (Table 6), in fact, shows much more than just a correction to a height and temperature at the same level. It is necessary to follow carefully the sequence of error diagnosis and correction. For this purpose, a separate column is added to the error diagnosis section of the example: namely, SCAN. The scan number tells on which vertical sweep through the data a particular diagnosis and/or correction was made.

On scan 1, the temperature at the 545-hPa significant level is identified as questionable the quality mark 3 is assigned. On the second scan, a type-3 correction—correction to both height and temperature at the same level—is applied at 500 hPa. This error is identified by the complex of hydrostatic residuals for 700–500 and 500–400 hPa, which are large. The height residuals of −202 to −216 m and the temperature residuals of 23.3 to 27.5 K agree acceptably with the corrections of 200 m and −26.8 K. Both corrections are simple: a change of one digit for height and a sign change for the temperature.

These changes at 500 hPa allow the bad temperature at 545 hPa and height at 250 hPa to be corrected on scans 3 and 4. The 100-m correction is simple. The final set of values and residuals is displayed below, and all residuals are seen to be acceptable.

d. Errors at adjacent levels

When errors at adjacent levels are otherwise sufficiently isolated and are well defined, they may be automatically identified and corrected. There are special routines to locate error of types 7–10, as identified in

TABLE 8. Example 7: Type-102 correction—surface temperature communication error.

STN ID: 52323 LAT: 41.63 LON: 96.88 STN HT: 1764.
DATE/TIME: 983031300 DHOUR: −1.0 SCAN: 1 INST TYPE: 32
SURFACE PRESS: 823.0 PIS: 0.9 PSINC: −2.1 BASRES: **20.**

	Height				Hydr Res		Temperature				
PRESS	ZOB	ZI	ZV	ZH	HYDS	HYDN	TOB	TI	TV	TH	X
823.0	1764.	8.					**−9.5**	**−5.1**			
700.0	3035.	13.	−8.	21.	3.	4.	−9.1	1.0	0.9	0.8	0.8

Error diagnosis:

PRESSURE	VAR	IETYP	QMARK	ORIG-VAL	COR	NEW-VAL
823.0	T	102	1.	−9.5	**7.0**	−2.5

	Height				Hydr Res		Temperature				
PRESS	ZOB	ZI	ZV	ZH	HYDS	HYDN	TOB	TI	TV	TH	X
823.0	1764.	8.					**−2.5**	**1.9**			
700.0	3035.	13.	−8.	21.	3.	4.	−9.1	1.0	0.9	0.8	0.8

Table 1. Example 6 (Table 7) shows corrections of type 7—error in the height at adjacent levels. In this example, there are also other errors that are also corrected. Some problems with the diagnosis and corrections are noted.

The sequence of error diagnosis and correction for this example proceeds without interruption from the lowest to the highest level. The 925-hPa temperature is first corrected from −24.5° to 28.5°C, a simple correction (sign and one digit). Next, the 700-hPa height is corrected from 3388 to 3188 m, also a simple correction. Note the triplet of large hydrostatic residuals for 400–300, 300–250, and 250–200 hPa. These are used to make the type-7 correction of 60 m to the 300-hPa height and 680 m to the 250-hPa height. Note, for instance, that the 400-hPa height increment before the correction is not 60 m, but the *change* in increment between 400 and 500 hPa *is* approximately 60 m. Therefore, the correction brings the increments more in line with each other even though they may not become much smaller. This is automatically accounted for by the DMA. The next correction is a 1000-h change to the 100-hPa height, a simple correction. The final correction is to change the 20-hPa height by 3930 m. The 20-hPa temperature is not corrected, but rather is given a quality mark of 13., indicating that it should be rejected.

The corrections in general lead to residuals that are much improved from the originals. However, there are some difficulties to be noted for this example. The hydrostatic residuals using significant as well as mandatory level data, HYDS, for the layers 1000–925 and 925–850 hPa, become larger after the correction to the 925-hPa temperature than they were before. Note, however, that the HYDN values do become smaller. The reason that HYDS becomes larger is that its computation uses not only the significant level temperatures but also the moisture data, and, in this case, the dewpoint temperature at 925 hPa has a large error. The CQCHT has properly decided to use the HYDN values rather than the HYDS values to make the correction.

The other difficulty concerns the diagnosis and correction at 20 hPa. It would appear that a correction to 26 360 m would be better, giving a *larger* height increment of 138 m and perhaps allowing the temperature also to be corrected.

e. Surface temperature correction

A communication error in the surface temperature will give a large baseline residual without affecting other residuals. Example 7 (Table 8) shows the diagnosis and correction of a surface temperature communication error. The baseline residual is 20 m, leading to a correction of 7°C to the 823-hPa temperature. The baseline residual after the correction is 2 m, and the temperature increment is also improved.

f. Significant-level temperature communication error (type-20 error)

The communication error in significant-level temperatures is perhaps most easily identified by a large temperature increment and vertical residual, with possibly only small influence on the layer hydrostatic residual, including the significant level. This is necessarily true, because the spacing of significant levels can be very tight, and errors may have very small influence on the hydrostatic residual. However, a communication error in a significant-level temperature should have some influence on the layer hydrostatic residual, HYDS, and so no correction is made by the CQCHT unless this influence is identified. Otherwise, even a large significant-level temperature error is identified as an observation error and is not corrected.

Example 8 (Table 9) shows the correction to the 211-hPa temperature from 62.4 to −62.4°C, a simple correction. In this case, the influence upon the hydrostatic

TABLE 9. Example 8: significant-level temperature correction (type 20).

STN ID: 62010 LAT: 32.68 LON: 13.17 STN HT: 80.
DATE/TIME: 98032412 DHOUR: −2.0 SCAN: 1 INST TYPE: 60
SURFACE PRESS: 1006.0 PIS: 1.6 PSINC: −0.2 BASRES: 2.

	Height				Hydr Res		Temperature				
PRESS	ZOB	ZI	ZV	ZH	HYDS	HYDN	TOB	TI	TV	TH	X
300.0	9250.	17.	10.	14.	−4.	−4.	−47.7	−0.4	0.6	−0.3	−1.4
250.0	10 420.	4.	−1.	5.	**−404.**	−3.	−58.7	−3.4	−38.5		−0.9
211.0							**62.4**	**122.6**	**123.6**		
200.0	11 810.	−5.	−9.		−1.	−1.	−61.1	−0.7	−63.7		−0.2

Error diagnosis:

PRESSURE	VAR	IETYP	QMARK	ORIG-VAL	COR	NEW-VAL
211.0	T	20	1.	62.4	**−124.8**	−62.4

	Height				Hydr Res		Temperature				
PRESS	ZOB	ZI	ZV	ZH	HYDS	HYDN	TOB	TI	TV	TH	X
300.0	9250.	17.	10.	14.	−4.	−4.	−47.7	−0.4	0.6	−0.3	−1.4
250.0	10 420.	4.	−1.	5.	**3.**	−3.	−58.7	−3.4	−2.7		−0.9
211.0							**−62.4**	**−2.2**	**−1.2**		
200.0	11 810.	−5.	−9.		−1.	−1.	−61.1	−0.7	0.1		−0.2

residual, HYDS, from 250 to 200 hPa is large (−404 m). Note that the error has no influence upon the hydrostatic residual calculated exclusively from mandatory level data, HYDN. After the correction, all residuals are acceptable.

g. Observation errors

Errors, called observation errors in this paper, have multiple causes; they may be due to large, random measurement error or to rough, nonrandom error. The diagnosis of observation errors by automated quality control (QC) is difficult. The main reason is that they originate prior to calculation of geopotential heights and therefore do not cause any large hydrostatic residuals, making them nearly impossible to distinguish from background errors unless they are much larger than possible forecast errors. The CQC strategy, by using all available checks, can minimize the required magnitude for observation error detection, but the limit is still larger than that for communication and computation errors. By comparing the increment with the horizontal and vertical residuals (for single-level errors), the CQCHT can usually be confident in the identification of moderately large observation errors. Its largest difficulty is with temperatures near the surface, especially for strong nighttime winter inversions. Even with these limitations, the number of observation errors detected is large, as shown in section 3.

Recently, the DMA was extended to identify multilevel observation errors. When a temperature sensor fails at some point in a sonde ascent or begins to deviate from a proper temperature, then such a failure or deviation is likely to persist for much of the rest of the ascent. Such an occurrence will, through the hydrostatic relation, lead to heights that are bad for all levels above the level of temperature sensor failure. In the tests, each radiosonde height and temperature profile is examined to see if there is such a level of failure. If found, then all heights and temperatures are rejected at and above this level. Testing shows some measure of success, but more development is needed for general use. This error analysis, however, was implemented in December 1998 for Indian data, because it was found to be of great value there.

Observation errors come in many flavors, but only a single example will be shown. Often, a single temperature is suspected, with only a moderate increment. Frequently, the top level will have a bad temperature. At other times, there will be several suspected temperatures at consecutive levels, with the magnitude of the increments in these cases usually between 5° and 10°. At levels both above and below those suspected to have observation errors, the increments and horizontal residuals may be close to the limit for suspicion; it is here that a QC specialist's help is needed to make a definitive decision on data quality. Example 9 (Table 10) shows an example of observation errors detected at several levels with increments of moderate magnitude. A QC specialist may change the determination from being questionable quality (QMARK = 3.) to being reject (QMARK = 13.). The specialist may also include an additional level or two, or it might be that comparison with other data types (note that the horizontal residuals are not available) would indicate that all the observations are correct. It is noted that observation errors are sought only after all possible communication and computation errors have been handled.

3. Statistics from one year of use of CQCHT

While CQCHT is running routinely in operations it keeps track of the numbers of reports from the various WMO blocks and generates various statistics on the

TABLE 10. Example 9: observation errors at several levels.

STN ID: 89611 LAT: −66.25 LON: 110.53 STN HT: 41.
DATE/TIME: 1998010100 DHOUR: 0.0 SCAN: 2 INST TYPE: 37
SURFACE PRESS: 989.0 PIS: 1.1 PSINC: 0.4 BASRES: −4.

	Height				Hydr Res		Temperature				
PRESS	ZOB	ZI	ZV	ZH	HYDS	HYDN	TOB	TI	TV	TH	X
1000.0	−52.	5.	0.								
989.0	41.	9.					3.3	1.1			
981.0							3.3	1.5	1.2		
925.0	576.	8.	3.		0.	1.	−0.3	0.6	0.2		0.7
911.0							−1.5	−0.1	0.2		
850.0	1244.	7.	11.		0.	−5.	−6.9	−2.4	−0.3		−1.7
771.0							**−13.8**	**−6.5**	**−2.5**		
726.0							**−16.9**	**−7.9**	**−2.9**		
712.0							**−16.1**	**−6.5**	**−0.8**		
700.0	2724.	−23.	−7.		5.	10.	**−16.9**	**−6.6**	**−1.7**		2.1
663.0							**−18.1**	**−5.9**	**−1.2**		
633.0							**−20.1**	**−5.8**	**−1.7**		
583.0							−23.9	−5.2	−2.4		
559.0							−23.7	−2.4	0.0		
535.0							−25.1	−1.1	−0.1		
528.0							−25.5	−0.6	0.0		
500.0	5200.	−58.	−24.		1.	−1.	−28.7	−0.2	0.4		−0.3

Error diagnosis:

PRESSURE	VAR	IETYP	QMARK	ORIG-VAL	COR	NEW-VAL
771.0	T	31	**3.**	−13.8	0.0	−13.8
726.0	T	30	**3.**	−16.9	0.0	−16.9
712.0	T	31	**3.**	−16.1	0.0	−16.1
700.0	T	31	**3.**	−16.9	0.0	−16.9
663.0	T	31	**3.**	−18.1	0.0	−18.1
633.0	T	31	**3.**	−20.1	0.0	−20.1
583.0	T	31	**3.**	−23.9	0.0	−23.9

errors themselves: numbers diagnosed, numbers corrected, pressure level of errors, geographic distribution, and so on. All these aspects will be considered in the sections to follow.

a. Numbers of reports received

Figure 1 shows the overall numbers of reports available to NCEP operations, by month, from September 1997 to August 1998. For direct comparison between months, the values are normalized to a 30-day month. The total per month is between 35 000 and 40 000. Small numbers of reports are observed at 0600 and 1800 UTC, and nearly equal numbers of reports are received at 0000 and 1200 UTC. However, there are some stations that report only at 0000 UTC, and others report only at 1200 UTC. The pattern is erratic, but the following WMO blocks may have the largest number of stations reporting only once per day: 12–15, 17–41, 43, 44, 48, 60–68, and 76–98. For comparison with the period of this study, Figs. 2 and 3 show the total data counts by month (not normalized) for 0000 UTC and 1200 UTC for the 40-yr period ending with August 1997. These counts show what was available to the NCEP–National Center for Atmospheric Research 40-Year Reanalysis (Kalnay et al. 1996). These figures show that the last 10 years have been a period of decline in the number of radiosonde reports, largely directly or indirectly associated with the breakup of the former Union of Soviet Socialist Republics (USSR). However, numbers recently may have stabilized.

Regional data counts are displayed in Table 11 as the average number of reports for the region per day for the study period. The regions are chosen to be contig-

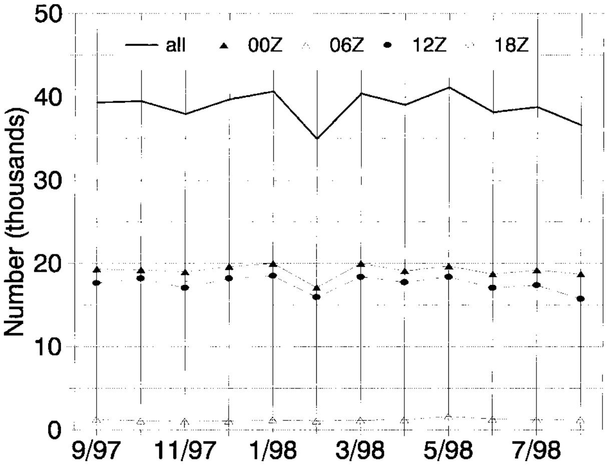

FIG. 1. Numbers of reports available to NCEP operations by month, from Sep 1997 to Aug 1998, shown individually for 0000, 0600, 1200, and 1800 UTC and overall.

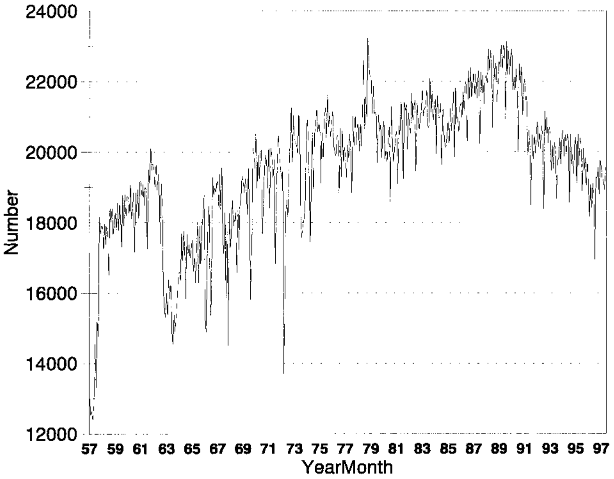

FIG. 2. Total data counts by month (not normalized) for 0000 UTC for the 40-yr period ending with Aug 1997.

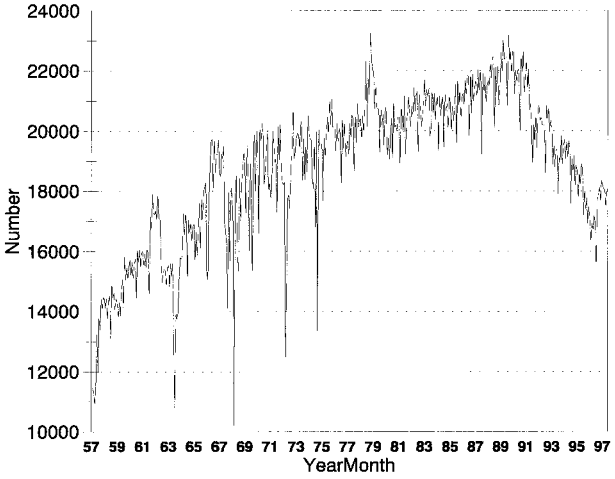

FIG. 3. Same as Fig. 2 but for 1200 UTC.

uous and largely homogeneous in data quality. A more complete rationale for the region choices is given in Gandin et al. (1993, referred to subsequently as G93). The largest numbers of reports are received from China, western Europe, the United States, and the former USSR, with significant numbers also from Canada, India, the Pacific as a whole, and Australia. Since the G93 study, which reports on an early version of CQC for radiosonde heights and temperatures for the period from May 1989 to April 1991, there have been some significant regional changes in data receipt. The number from eastern Europe is down, the number from the former USSR is less than one-half of what it was, and the number from Mongolia is one-quarter of what it was. Most regional data counts have been constant, but the count from India has increased.

b. Errors detected by CQCHT

The average number of stations with at least one hydrostatic suspicion (i.e., communication or computation error suspicion) per month by large region is displayed in the column labeled ''Avg Stns'' in Table 12. A comparison of Table 12 with Table 11 shows that the average number of stations reporting in each block is roughly the same as the number of stations with at least one hydrostatic suspicion for many blocks. However, this does not give a good idea of the quantity of hydrostatic errors for each station by large region. Rather, that can be obtained in a rough way by dividing the total number of errors in a large region by the number of stations with at least one hydrostatic suspicion. The result is displayed in the column labeled ''Avg Susp/Stn'' in Table 12, where it is seen that some regions produce a much larger normalized number of hydrostatic errors,

TABLE 11. Average number of reports per day by large region for Sep 1997 to Aug 1998.

Area	Abbreviation	WMO block Nos.	Average Daily	 0000 UTC	 1200 UTC
Western Europe	WEur	1–8, 10, 16	187	66	71
Eastern Europe	EEur	9, 11–15, 17	36	18	14
Former USSR	USSR	20–38	144	85	58
Western Asia	WAs	40–41	31	17	13
India, Ceylon	Ind	42–43	61	31	30
Mongolia	Mong	44	3.5	1.5	1.3
Taiwan, Korea, Japan	TKJ	45–47	63	30	28
Indochina, Malaysia	Indo	48	20	12	5
China	Chin	50–59	234	118	115
North and Central Africa	NAfr	60–65, 67	45	18	27
South Africa	SAfr	68	22	11	11
United States	US	70, 72, 74	180	85	87
Canada	Can	71	62	30	31
Central America	CAm	76, 78	30	12	17
South America	SAm	80–88	30	9	21
Antarctica	Ant	89	16	9	7
Pacific	Pac	91, 96–98	52	33	18
Australia, New Zealand	Aust	93–94	48	34	12

TABLE 12. Average number of stations with at least one hydrostatic suspicion per month and average number of hydrostatic suspicions per station with at least one hydrostatic suspicion by large region for Sep 1997 to Aug 1998.

Area	Abbreviation	WMO block Nos.	Avg stations	Avg suspicion/station
Western Europe	WEur	1–8, 10, 16	64	2.4
Eastern Europe	EEur	9, 11–15, 17	20	4.3
Former USSR	USSR	20–38	108	5.3
Western Asia	WAs	40–41	27	8.6
India, Ceylon	Ind	42–43	33	24.2
Mongolia	Mong	44	4	14.4
Taiwan, Korea, Japan	TKJ	45–47	29	8.6
Indochina, Malaysia	Indo	48	13	13.6
China	Chin	50–59	112	7.5
North and Central Africa	NAfr	60–65, 67	36	10.1
South Africa	SAfr	68	12	6.4
United States	US	70, 72, 74	81	2.2
Canada	Can	71	29	0.8
Central America	CAm	76, 78	23	11.0
South America	SAm	80–88	26	16.9
Antarctica	Ant	89	12	11.4
Pacific	Pac	91, 96–98	33	13.7
Australia, New Zealand	Aust	93–94	29	1.0

particularly India, South and Central America, Mongolia, Indochina and Malaysia, North and Central Africa, Antarctica, and the Pacific. Regions with small normalized numbers of errors include western and eastern Europe, the former USSR, the United States, Canada, and Australia.

Not only does the average number of hydrostatic errors per error-producing station vary greatly from region to region, but the number of error suspicions varies within each region from month to month, as illustrated in Table 13. At times, the reason for an increase in error suspicion counts may be known, but such is not the case for any of the changes seen during this time period. The peaks in error production do not correspond for the various regions, suggesting that they are due to local effects and not to processing changes at NCEP.

The number of errors for each error type varies with pressure in its own characteristic way. Figures 4 and 5 show the variation of the average count per major observation time by pressure of the most common error types: single height error, single temperature error, error in height and temperature at the same level, error at the top level, and computation error. Figure 4 shows the average number of error suspicions; Fig. 5 shows the average number of error corrections.

Height errors at a single level—type 1—have two peaks: 925 and 400 hPa. The cause of the peak at 925 hPa is unknown, but often the 925-hPa pressure level is the first mandatory level above the ground, suggesting possible procedural difficulties at some stations. At the highest levels, the number of errors is reduced simply because few reports reach these levels. The pattern of single level temperature errors—type 2—closely follows that for heights but with somewhat smaller numbers and without the sharp peak at 925 hPa.

The number of height and temperature errors at the same level—type 3—is slightly less than for types 1 and 2. There is a peak in the number of suspicions at 700 hPa, but the number of corrections varies little from 850 to 70 hPa, about 25 per major observation time. The number of error suspicions for the top level—type

TABLE 13. Count of hydrostatic suspicions for each month by large region (9/97 is Sep 1997, etc.).

	Large region																	
	WEur	EEur	USSR	WAs	Ind	Mong	TKJ	Indo	Chin	NAfr	SAfr	US	Can	CAm	SAm	Ant	Pac	Aust
9/97	179	265	584	278	1031	52	212	260	993	840	88	384	50	238	672	359	719	18
10/97	174	179	779	305	1177	11	205	172	979	622	137	323	57	365	386	353	694	13
11/97	187	91	765	505	950	20	158	134	1137	412	188	438	18	347	471	314	690	85
12/97	120	104	617	200	906	27	89	127	1121	330	176	117	24	240	480	119	498	57
1/98	143	106	750	201	873	90	199	114	1419	419	132	179	17	193	416	226	383	32
2/98	129	97	625	195	749	80	112	101	873	285	117	122	31	179	394	77	403	21
3/98	142	67	601	232	795	72	571	100	770	404	95	121	5	179	483	89	401	21
4/98	124	52	598	253	853	84	580	226	815	308	29	110	8	274	499	84	379	16
5/98	94	46	557	199	805	85	675	480	840	318	29	145	16	764	451	32	526	15
6/98	132	47	534	195	863	83	156	247	765	274	25	103	30	349	487	31	429	15
7/98	288	44	621	268	869	51	132	112	821	370	41	161	29	153	545	33	444	13
8/98	250	55	454	186	721	39	200	137	618	315	23	156	18	173	454	28	487	5

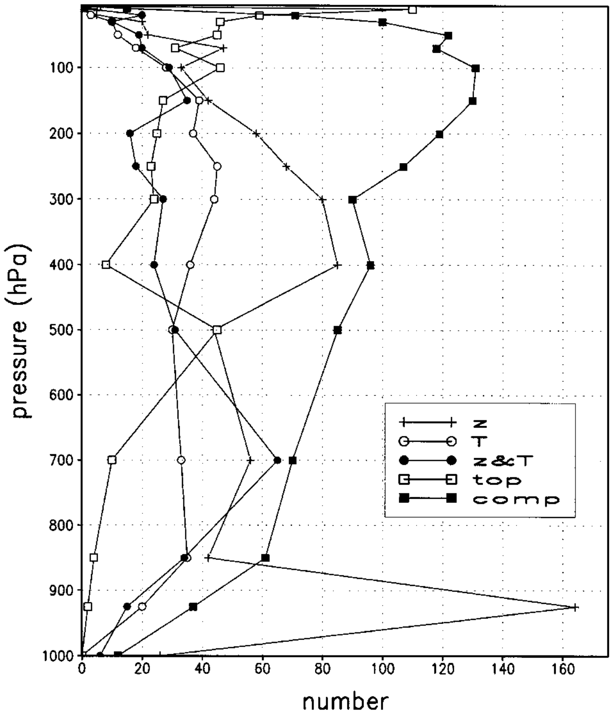

FIG. 4. The average number of error suspicions for error types: single level height (*z*), single level temperature (*T*), height and temperature at the same level (*z*&*T*), top level (top), and computation (comp).

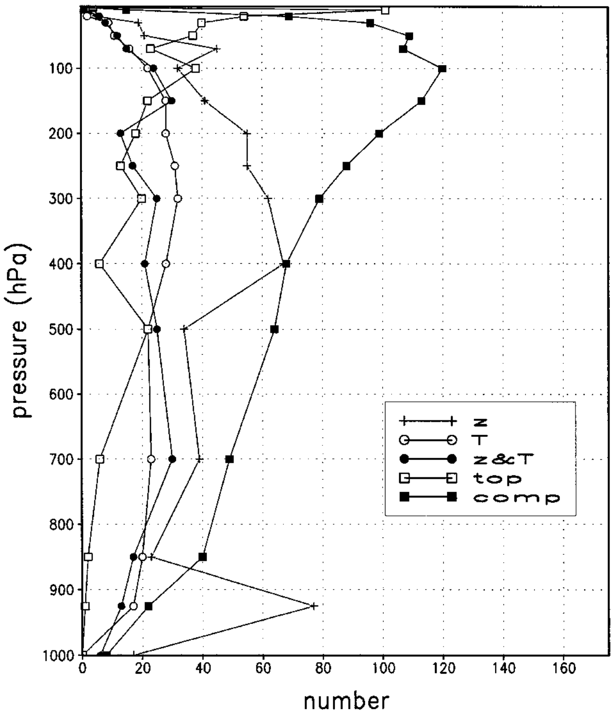

FIG. 5. Same as Fig. 4 but for error corrections.

5—naturally increases upward, reaching a maximum number of suspicions of about 110 at 10 hPa.

Computation errors—type 6—are counted differently. There is a type-6 error associated with every level changed by a single computation error. Type-6 suspicions that are rejected for correction, on the other hand, are reported only at the single level above the isolated large hydrostatic residual that leads to such a suspicion. This situation leads to the fact that the number of computation error suspicions—type 6—surpasses other hydrostatic error types, reaching a broad maximum of about 130 at 100 hPa. Because the rejected suspicions count so much less than the suspicions that are corrected, the number of type-6 corrections is nearly equal to the number of suspicions, peaking at 100 hPa with about 120 corrections. From the information available, it would be difficult to get an accurate count, but the total number of actual computation error suspicions, for all levels, is estimated to be about 150.

The percent of hydrostatic error suspicions that is corrected is fairly high, as shown in Fig. 6, varying generally above 70% for pressures from 500 to 30 hPa. For 1000 to 700 hPa, the correction percent drops to about 50% for most error types. Above 30 hPa, the counts are so low that the averages are unreliable. The general picture is that the percent of corrections increases with elevation, up to 30 hPa. As explained in Part I of this paper, type-2 temperature corrections

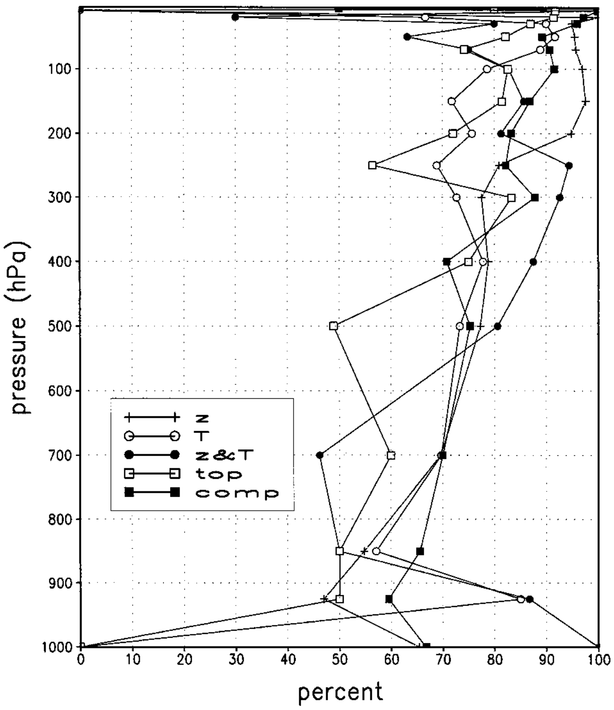

FIG. 6. The percent of hydrostatic error suspicions that are corrected for error types 1, 2, 3, 5, and 6.

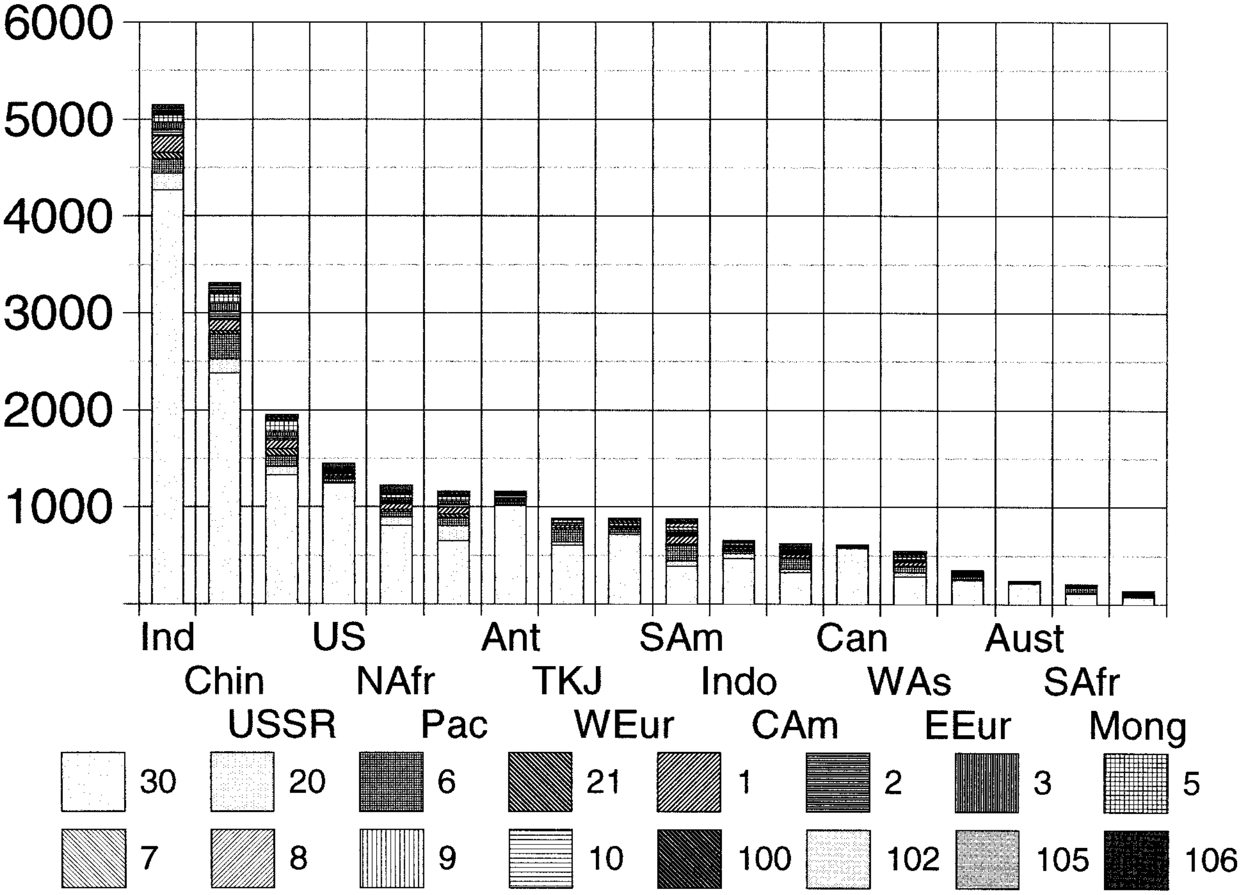

FIG. 7. Cumulative counts of error suspicions by type for each large region, sorted by total error suspicion counts. Type "30" includes all observation errors, types 30–37. An explanation of the error types is contained in Table 1, and specification of the large regions and their abbreviations is given in Tables 11 and 12.

should be most confident for thick (with respect to logarithm of pressure) layers. Because the logarithm of pressure thickness of the layers (between successive mandatory levels) does show a general increase upward, this may be a partial reason for the correction percent of errors of types 2 and 3 to increase upward. For other error types, other factors must be operating, probably including the greater general variability of the atmosphere at lower elevations.

The discussion on error counts has so far not concentrated on observation errors, largely because they have never been the main focus of CQCHT and can never be corrected. However, their numbers are very large. Figure 7 shows cumulative counts of error suspicions by type for each large region, sorted by total error suspicion counts. The lowest part of each bar is for observation errors and dominates for all regions. Overall, 74% of the error suspicions are for observation errors. However, only 20% of the data suspected of observation error are rejected; the other 80% are given the status of questionable quality.

The distribution of error suspicions, other than for observation errors, is given in Fig. 8. The large regions are sorted by total average monthly numbers of error suspicions. The first bar segment is for significant-level temperature error suspicions and represents a reasonably large fraction of the total for most regions. Other significant contributions are given by computation errors, errors to a single height, errors to a single temperature, errors to both height and temperature at the same level, and errors at the top level.

4. Summary

The CQC for radiosonde heights and temperatures has undergone development at NCEP for more than a decade. Part I of this paper reported on the scientific and technical aspects of the culmination of that development: CQCHT. Part II gives examples of representative types of errors encountered and some more-complicated examples that illustrate the power of the algorithm. Although the computer code that implements the CQC reasoning is sequential, the effect is similar to human reasoning, which may first accumulate all avail-

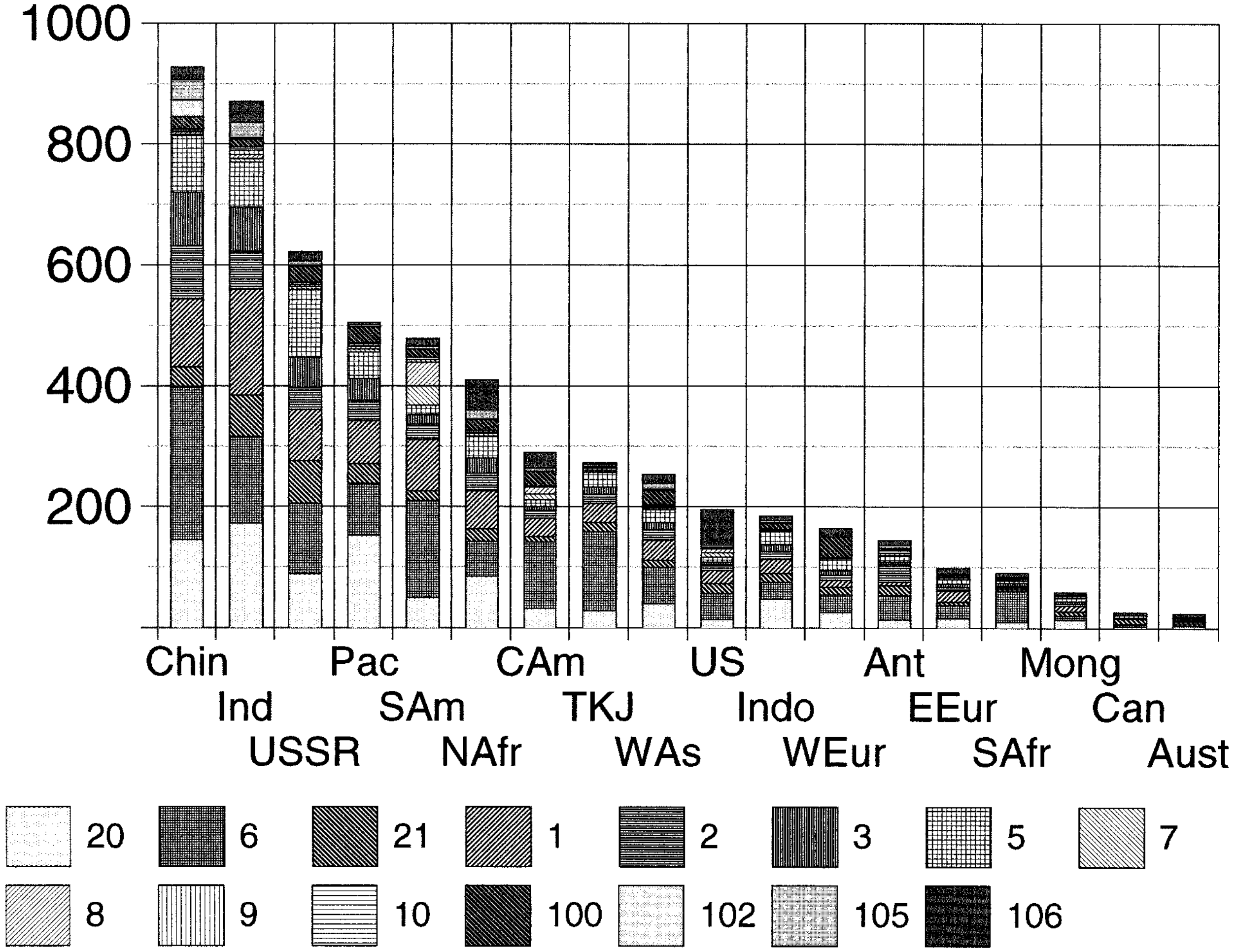

FIG. 8. The distribution of error suspicions, other than for observation errors, allowing the number of other error types to be distinguished more easily.

able knowledge before making a decision—a fact that is borne out by the successful correction of errors of different types and complexity.

The latter part of this paper shows the performance of the CQCHT over a 1-yr period of operation. On average, 1277 reports were considered by CQCHT each day (at 0000, 0600, 1200, and 1800 UTC). During each month, there was an average of 756 stations with at least one hydrostatically suspected error, producing an average of 5624 hydrostatically suspected errors each month. In addition, the CQCHT suspected an average of 15 979 observation errors each month, 20% of which were marked for rejection. Of the hydrostatically suspected errors, 77% were corrected.

The hydrostatic redundancy in radiosonde heights and temperatures leads to the rather unique opportunity for their correction. Although CQC methods have been developed, both at NCEP and elsewhere, for the quality controlling of other data types, the correction, and even error detection, opportunities are more limited. It is probably true that the best QC for any observation would require a method designed in some way specifically for it. However, this approach would lead to a great code maintenance problem and may not be much more productive than a unified approach. With that in mind, perhaps, several centers have adopted QC approaches that are not variable specific. At NCEP, in addition to specific QC procedures for radiosondes, Doppler profilers, velocity azimuth display wind reports from the Weather Surveillance Radars-1988 Doppler, and unautomated aircraft reports, there is a unified optimal interpolation QC that checks all data types for the global data assimilation system. This paper has reported on the one place where the CQC approach, including data correction, is likely to have the greatest positive effect.

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