Complex Quality Control of Significant Level Rawinsonde Temperatures

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ABSTRACT

Rawinsonde heights and temperatures have been quality controlled using complex quality control at the National Centers for Atmospheric Prediction since December 1988 when an algorithm using only hydrostatic checking was introduced for the checking of mandatory level heights and temperatures. The quality control of significant level temperatures was added to the hydrostatic code in April 1990. In November 1991, the mandatory level checking was greatly expanded and improved by the inclusion of additional checks: increment (observation minus 6-h forecast), horizontal, and vertical. This paper describes a major improvement to the significant level quality control, introduced in May 1994, using complex quality control techniques. The philosophy of the method and the various checks are described. The principles of the decision-making algorithm are stated, examples are shown, and some statistics of the use of the significant level checking are presented.

1. Introduction

Quality control (qc) of upper-air data has traditionally had the primary purpose of removing erroneous data from use by analysis–forecasting systems. Complex quality control (cqc), on the other hand, has the additional goal of correcting as many errors in the data as possible (Gandin 1988). This goal is reasonable because of the errors found in upper-air data, a large percentage are of ‘‘human’’ origin. That is to say that they are introduced by a specific human action: incorrect transcription of data, incorrect typing of data, incorrect computation, incorrect coding of the data, etc. These errors will henceforth be called communication or computation errors as appropriate.

Processing of rawinsonde data is partially or nearly completely automated for many national upper-air networks. When a sounding is computed automatically, then computation errors are not possible, and when the data are entered into the communication network automatically, then most sources of communication errors are also eliminated. Unfortunately, there remain many regions where a human is involved in the calculation of heights from temperatures and humidity, where significant levels are determined manually and where data are entered manually into the communication network. It is primarily these stations that display what are referred to as communication and computation errors.

Other errors, including instrument errors, calibration errors, errors of representativeness, and any other error introduced into the data before use at the observation station, are called observation errors. Because these errors are introduced prior to the hydrostatic computation of mandatory level heights, they cannot cause hydrostatic inconsistencies in the final (mandatory level) heights and temperatures. Observation errors can be detected only if they are sufficiently large against the background of random errors. Their determination with complex quality control of heights and temperatures (CQCHT) is discussed by Collins (1996). The background of more or less random errors can be determined by statistics of the various checks when all known errors are eliminated. As a group, these communication, computation, and large observation errors are called rough errors to distinguish them from (generally) small random instrument and other errors.

The cqc of upper-air rawinsonde mandatory level heights and temperatures has been performed at the National Centers for Environmental Prediction (NCEP, formerly the National Meteorological Center) since 1988 (Collins and Gandin 1990) when a check using only the hydrostatic check was introduced. It is referred to as the comprehensive hydrostatic quality control (CHQC) algorithm. That code allowed the detection of many communication and computation errors. The qc of significant level temperatures was added to the hydrostatic code in April 1990 (Collins 1990). In November 1991, mandatory level checking of heights and temperatures was greatly expanded and improved by the inclusion of additional checks: increment check (observation minus 6-h forecast value), horizontal optimal interpolation (OI) check of increments, and vertical OI check of increments. The mandatory level checking is part of the CQCHT algorithm. It was at this point that observation

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Outline of steps of CQCHT:

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Input mandatory level data for all stations.
Do mandatory level qc in 2 scans:
        Calculate residuals:
                hydrostatic
                baseline
                increment
                horizontal
                OI of increments
                horizontal OI of msl pressure increments
                vertical OI of increments
                temporal (for retrospective qc only)
        Decision Making Algorithm for mandatory levels
                make corrections when possible, generally decide data quality
                determine observation errors on scan 2
        Update values used internally by the program
Perform quality control of significant level temperatures. For each station:
        Read (reread) data
        Check all changed mandatory level temperatures for resulting superadiabatic
        lapse rates.
        Resolve temperatures at coincident mandatory and significant levels.
        Calculate significant level residuals:
                increment
                vertical OI
                hydrostatic
                T*
        Decision Making Algorithm for significant levels
                make corrections and diagnose errors
        Write new data values and qc results for both mandatory and significant levels to
        BUFR data file.
End of program
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FIG. 1. Steps in the operation of CQCHT.

errors could first be detected. Details of the mandatory level part of CQCHT may be found in Collins and Gandin (1992), and a description of its operation over a 2-yr period is given in Gandin et al. (1993).

The cqc of significant level temperatures, introduced in 1990, did not include the use of forecast temperatures for any of its checks and made no use of lapse rate checks. It used only hydrostatic and vertical checks. Since all levels of temperature data are used now in NCEP's global data assimilation procedures, a good qc for temperatures is required. This paper discusses the scientific basis, some details, and some results from a much improved qc for rawinsonde significant level temperatures. This algorithm was introduced into operations as a part of CQCHT in May 1994.

To correct data, cqc must determine the generic cause of each error. The CQCHT algorithm uses a powerful set of checks to that end. Each check is performed independently and only then are the results combined to make the data quality decision and to make a correction where possible.

As far as mandatory heights and temperatures are concerned, there is an especially powerful mechanism for correction of communication and computation errors. Because both heights and temperatures are reported in the meteorological messages, any communication or computation error leads to a hydrostatic inconsistency between the reported heights and temperatures (except in some special situations of multiple errors). Observation errors, on the other hand, do not lead to a hydrostatic inconsistency since such temperatures with error are used to calculate the heights that will also be in error but hydrostatically consistent. It is seen that the hydrostatic check can, generally, by itself be used to distinguish communication and computation from observation errors.

As indicated in the historical development of the cqc of upper-air data at the NCEP, there is now a single algorithm that deals with both mandatory and significant level heights and temperatures, namely, CQCHT. Because of the powerful tools for performing the qc at mandatory levels and because the significant level qc relies heavily on the mandatory level data that it uses being accurate, the mandatory level qc is completed first, and then the qc for significant level temperatures is performed. These steps are illustrated in Fig. 1, where the calculations in the first box are made for each of the two mandatory level scans for the qc of heights and temperatures, while the calculations in the second box are for the qc of significant level temperatures, which are performed layer by layer.

The mandatory level qc for rawinsonde heights and temperatures is accomplished in two scans, with most corrections made on the first scan and observation errors identified on the second. There are several checks used, including increment, horizontal OI on increments, and vertical OI on increments, but the most important checks are the hydrostatic checks.

The checks for the significant levels' cqc include increment, hydrostatic, vertical, and lapse rate checks. After all check results are computed, the decision-making algorithm (DMA) is called upon to diagnose observation errors and correct communication errors where possible. Noncorrectable errors are also identified. The profile is considered in pieces, from one mandatory level with nonmissing height and temperature of good quality to the next.

Most accurate for the checking of significant level temperatures is the vertical check. However, if adjacent levels have bad data, then this check cannot be used. Therefore, the qc of significant levels is most accurate and most able to make corrections when only vertically isolated temperatures are bad. The checking is also less certain when several levels of a profile, usually near the surface, are significantly different from the 6-h forecast, that is, nonrepresentative. The details of the checks are contained in section 2, and the details of the DMA are in section 3.

Examples of operation of the significant level checking are contained in section 4, while some statistics of operation may be found in section 5.

2. The checks and preliminary tests

The mandatory level checking is performed almost entirely without reference to the significant level temperatures, following the usual cqc practice of performing qc sequentially on various classes of data—first on the most accurate variables where the most sensitive checks can be used. The possibility of using the hydrostatic check, in combination with other checks, with the potential for correcting most communication and computation errors, led to the decision to qc the mandatory level temperatures (and heights) before the significant level temperatures. Even though they have not yet been quality controlled, the significant level temperatures are used to check the lapse rates that result from correcting a mandatory level temperature.

Another matter relating to mandatory levels is that frequently there is a significant level that is at a mandatory level pressure. Naturally, the temperatures should agree. The temperatures do not always agree and this situation must be resolved. These topics are discussed in the next few sections, followed by a discussion of the performance of the various checks.

A note on terminology is appropriate. The term ''increment'' was introduced by Thiebaux and Pedder in 1987 to denote an observed value of a parameter minus its background value, where the background could be climatology or forecast. In this context, the increment may be of either sign. This practice has been followed uniformly at NCEP for quality control, even though other terms are used elsewhere. The results of other checks are referred to as residuals, for example, vertical residual or horizontal residual. However, when the results of all checks are referred to as a group, then ''residuals'' are meant to also include the increment.

a. Lapse rate check of mandatory levels

For the reasons already given, the mandatory level data are quality controlled before the significant level data. It is important for the cqc of significant level temperatures that the mandatory level temperatures be without error. There are rare cases where bad corrections are made to mandatory level temperatures, and also some cases where the correction is slightly inaccurate. For this reason, any corrected mandatory level temperature is checked for superadiabatic lapse rate with its nearest significant level temperature or mandatory level neighbors (if any are close enough). Since it is extremely rare that both a mandatory level temperature and an adjoining significant level temperature contain a communication error, the possible influence of a bad significant level temperature on this check is minimal. (If the number of errors that are observed was randomly distributed among the stations and their levels, then the chances of a bad significant level temperature being used in the check of a mandatory level temperature correction would be about 3×10^{-6}. Since the errors are not randomly distributed and some bad significant level temperatures remain undetected, the occurrence is higher.)

b. Combination of mandatory and significant level data into a single array

The significant level checking is performed between mandatory levels containing both height and temperature with values of good quality. In this paper, such levels are referred to as ''complete'' mandatory levels. As a preliminary step in the qc, a single profile of heights and temperatures is created containing all available levels. At the same time a level type is assigned to each level, which aids in the decision process. The level types distinguish between significant and mandatory levels and the data (temperature and/or height) that are available and good.

c. Coincidence check of significant and mandatory levels

Occasionally a mandatory level and significant level are at the same pressure. In these cases, it is necessary to guarantee that the temperatures are identical. This function is performed by the significant level temperature qc. The following rules are for making the temperatures the same, when they are different.

1) If the mandatory level temperature has been corrected, and this temperature is within ±2.0 K of the significant level temperature, set it equal to the significant level temperature.
2) Otherwise, give precedence to the mandatory level temperature.

(a) If the mandatory level temperature is not missing, set the significant level temperature equal to it.

(b) But if the mandatory level temperature is missing and the significant level temperature is not missing, set the mandatory level temperature equal to it.

d. Temperature increments on significant levels

The temperature increment i_l is defined as the observed value minus the 6-h forecast value interpolated horizontally and vertically to the observation location:

$$i_l = o_l - g_l, \tag{1}$$

where i_l is the increment, o_l is the observed value, and g_l is the forecast value, all at level l. The forecast values are first interpolated bilinearly from the forecast grid points to the observation latitude and longitude and then interpolated vertically with respect to the logarithm of pressure to the observation pressure. The increment check is an effective check for significant level errors. Its greatest limitation is that it depends upon the accuracy of the forecast model providing the forecast value for its usefulness. When the forecast is accurate, the increment check is very powerful for determining the presence of an error, but if the value were ‘‘corrected’’ to the forecast value, then this value would provide no independent information to the subsequent analysis. Therefore, other independent information must be used, in most cases, in addition to the increment, in determining a correction value.

e. Vertical residuals

The vertical residual is the difference between the observed temperature and the temperature interpolated vertically to the observed temperature level from neighboring levels. Figure 2 schematically shows the relationship between the mandatory and significant levels and vertical residuals calculated at level l. The vertical interpolation of temperature for comparison with the observation is linear with respect to the logarithm of pressure. Two different vertical residuals are obtained when the required information are available. One, v_l^m, is obtained using the nearest mandatory level neighbors. The other vertical residual, v_l^a, uses the nearest neighboring levels whether they are significant or mandatory. The advantage of v_l^m is that its value is not sensitive to multiple errors in significant level temperature. However, if there is a single error, then v_l^a gives a better measure of that error.

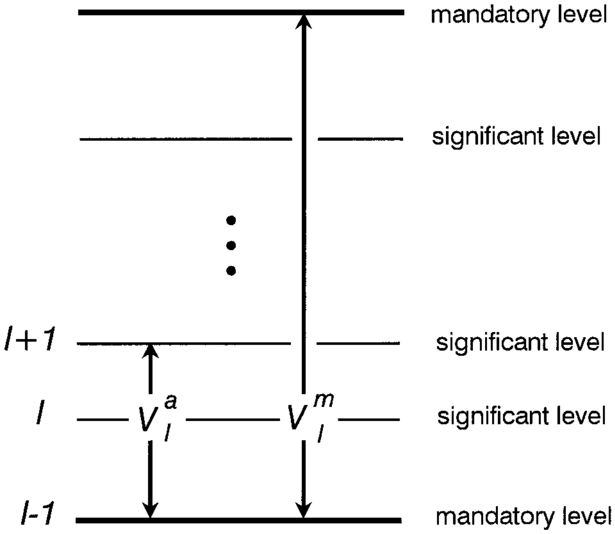

FIG. 2. Schematic of arrangement of mandatory and significant level relative to the vertical check with nearest neighbors v^a and with nearest mandatory levels v^m. The check is performed at the level l.

Each of the vertical residuals may be written as the difference between the observed value and a weighted average of adjacent observation values:

$$v^m l = o_l - w_{l-1}^m o_{l-1}^m - w_{l+1}^m o_{l+1}^m \tag{2}$$

and

$$v_l^a = o_l - w_{l-1}^a o_{l-1}^a - w_{l+1}^a o_{l+1}^a, \tag{3}$$

with weights w determined from linear interpolation with respect to the logarithm of pressure, where the superscript m refers to values at mandatory levels, while the superscript a refers to values at the nearest levels. In (2), the subscripts $l-1$ and $l+1$ refer to the next complete levels below or above, while in (3), the subscripts $l-1$ and $l+1$ refer to the next level below and above. Note that the vertical residual is independent of the forecast.

f. Hydrostatic residuals

The hydrostatic residual $s_{l1,l2}^a$ is calculated between ‘‘complete’’ mandatory levels $l1$ and $l2$. It uses both mandatory and all significant level temperatures and is given by

$$s_{l1,l2}^a = z_{l2} - z_{l1} - A_{l1,l2} - \sum_{i=l1}^{l2-1} B_{i,i+1}(T_i + T_{i+1}), \tag{4}$$

where

$$A_{l1,l2} = \frac{RT_o}{g} \ln\left(\frac{p_{l1}}{p_{l2}}\right) \tag{5}$$

and

$$B_{i,i+1} = \frac{R}{2g} \ln\left(\frac{p_i}{p_{i+1}}\right). \tag{6}$$

In these equations, $R = 287.05$ J kg^{-1} K^{-1} is the dry air gas constant, $g = 9.80665$ m s^{-2} is the acceleration

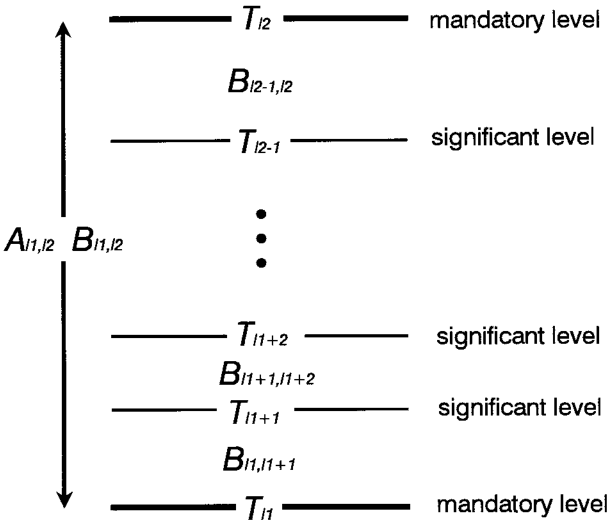

FIG. 3. Schematic of arrangement of mandatory and significant levels relative to the hydrostatic checks, which apply between the mandatory levels $l1$ and $l2$.

of gravity, and $T_0 = 273.15°\text{C}$. Figure 3 shows the arrangement of levels and temperatures, as well as A's and B's.

Strictly speaking, the temperatures in (4) should be virtual temperatures, but the effect of moisture is neglected because the moisture has not been quality checked and its effect is less than the magnitude of the rough errors that are diagnosed by CQCHT. A sample of several observation times shows the global average of the effect of moisture on the hydrostatic residual for the lowest six mandatory layers to be 3.7, 3.4, 5.0, 4.6, 12, and 0.6 m, whereas the smallest height corrections in CQCHT are about 40 m and the smallest temperature corrections are about 6°C.

After the initial checking and possible correction of mandatory level heights and temperatures, the hydrostatic residual $s^m_{l1,l2}$, using only the mandatory level data at levels $l1$ and $l2$, is generally small. It is given by

$$s^m_{l1,l2} = z_{l2} - z_{l1} - A_{l1,l2} - B_{l1,l2}(T_{l1} + T_{l2}), \qquad (7)$$

where

$$B_{l1,l2} = \frac{R}{2g} \ln\left(\frac{p_{l1}}{p_{l2}}\right). \qquad (8)$$

Following the correction to any communication errors in the layer the hydrostatic residual, $s^a_{l1,l2}$ in (4), should also become small. This condition must be satisfied before any potential corrections are accepted.

g. The T* values

A value, T^*, is calculated to aid in the correction of erroneous significant level temperatures. It is a hydrostatic estimate of the necessary correction, which is good when there is a single significant level temperature error. Here, T^* is calculated as the magnitude of temperature change that must be made to an individual significant level temperature in order to make $s^a_{l1,l2}$ equal zero. If there are multiple communication errors, then T^* is not useful.

It is calculated as

$$T^*_j = (B_{j-1,j} + B_{j,j+1})^{-1}\left[z_{l2} - z_{l1} - A_{l2,l1} - T_{l1}B_{l1,l1+1} - T_{l2}B_{l2-l,l2} - \sum_{\substack{i=l1+1\\ i\neq j}}^{l2-1} T_i(B_{i-1,i} + B_{i,i+1})\right]$$

$$\text{for } j = I1+1, I1+2, \ldots, I2-2, I2-1. \qquad (9)$$

3. The decision-making algorithm

After the mandatory and significant level data have been combined into arrays ordered by decreasing pressure, lapse rates for corrected mandatory level temperatures have been checked, temperature differences at coincident mandatory and significant levels have been resolved, and all the check residuals and T^* have been calculated, then the DMA is called. Based upon check results, including the increment vertical residuals, hydrostatic residuals, and T^*, the DMA decides which data, if any, are in error and which to correct, and decision values are assigned reflecting its judgment. Other programs use these decision values as flags to determine how, if at all, the data are to be used. The usual practice at NCEP is that questionable data are used with diminished weight in data assimilation, while data identified as bad are not used at all. In this section, the general strategies and some detail for the DMA will be given.

As the cqc method is designed to diagnose the presence of rough errors and to correct those that it can, and since it uses the residuals to perform this task, it is necessary to understand the statistical character of the residuals *in the absence of rough errors.* A sample from January to June 1994 was used to produce means, standard deviations, and higher moments. Except for the increment, which is directly dependent upon the forecast model quality, Fig. 4 shows that the means for all re-

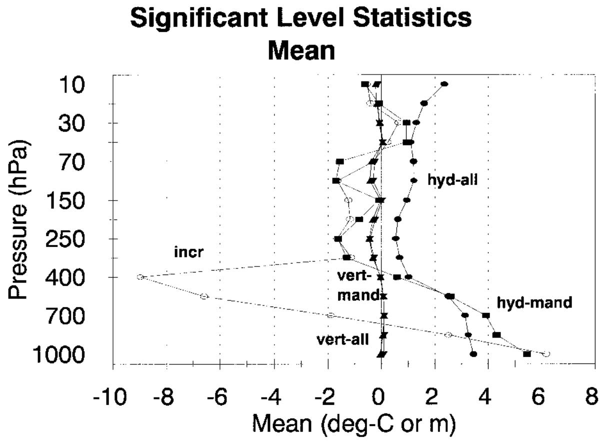

FIG. 4. Mean for increment (incr), vertical residual using mandatory levels only (vert-mand), vertical residual using all levels (vert-all), and hydrostatic residuals (hyd-mand and hyd-all) for January–June 1994.

siduals are small, and Fig. 5 shows the standard deviation as a function of pressure. The DMA uses the residuals divided by these standard deviations in its decisions. This makes the residuals comparable to each other. The decisions consider a normalized value of 3.0 for a check residual to be large (except at the tropopause where a larger value is used), while values of residuals less than 3.0 standard deviations from their normal value are considered to be small. The value used to separate small residuals from large is determined experimentally by the performance of the qc. Therefore, the exact value of the different residuals is of much less importance than a good general idea of their vertical variation and the relative magnitude for the various checks. Spot checks have shown these factors to remain relatively constant. It is convenient to introduce a shorthand notation for the residual values, divided by their long-term standard deviations (in the absence of rough errors). These symbols are shown in Table 1.

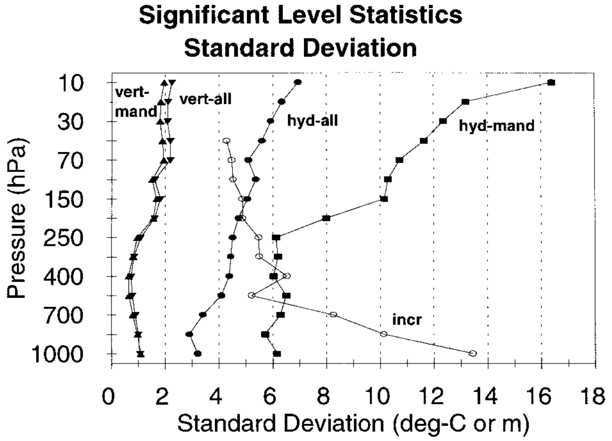

FIG. 5. Standard deviations for increment (incr), vertical residual using mandatory levels only (vert-mand), vertical residual using all levels (vert-all), and hydrostatic residuals (hyd-mand and hyd-all): average for January–June 1994.

TABLE 1. Shorthand notation for the residuals and normalized residuals.

Normalized	Nonnormalized	Residual
[i]	i	Increment
[v^m]	v^m	Vertical, using only mandatory levels
[v^a]	v^a	Vertical, using all levels
[s^a]	s^a	Hydrostatic, using all levels
	s^m	Hydrostatic, using only mandatory levels
	$T*$	Temperature change needed to give $s^a = 0$.

There are five possible outcomes to each decision, as summarized in Table 2. Also, a number of error types are determined, as shown in Table 3. The rest of this section will be devoted to giving the principles used in the DMA decisions.

An observation error in significant level temperature always leads to a large increment and vertical residual with surrounding mandatory levels, but affects the layer hydrostatic residual. A correction can be made only when the layer hydrostatic residual is large and there is sufficient agreement between the other relevant residuals. These rules are expanded and made more concrete in the following principles of the DMA.

1) Residuals, normalized by their long-term standard deviation in cases without rough error, are used in all decisions.
2) Two of the check residual values are not influenced by multiple errors in significant level temperatures, namely, the increment i and the vertical check with mandatory levels v^m. Therefore, these two checks can be used to identify all levels with suspect temperatures.
3) If i and v^m are small, then the algorithm considers there to be no errors.
4) Observation errors have large i and v^m, but small s^a. Observation errors are further diagnosed by examining the lapse rates between the data level and the levels above and below.
5) (Only) communication errors cause s^a to be large.
6) Corrections are made only when the relevant residuals (i and v^m, and possibly others, as discussed below) agree sufficiently well with each other, both in value and sign.
7) Proposed corrections, which are only possible for

TABLE 2. Data decisions.

Decision	Meaning
0	Good
1	Corrected
2	Initially suspected; found to be good
3	Questionable
4	Bad

TABLE 3. Error types.

Error type	Description
0	No error. Decision 0.
2xx	Found only at mandatory levels. The temperature correction of type xx was rejected because of lapse rate check results. Decision 3 or 4, depending upon the size of i. See Gandin et al. (1992) for a description of these correction types.
500	No error after checking (i, v^m large). Decision 2.
501	i, v^m large, s^a small; superadiabatic lapse rate. Decision 4.
502	Data corrected. i, v^m, s^a large. Decision 1.
503	Correction type 502 rejected; i, v^m, s^a large. Decision 3 or 4, depending upon the size of i, v^m.
504	Correction type 502 rejected since recomputed s^a remains large. Decision 3 or 4, depending upon the size of i, v^m.
505	Correction type 502 rejected since the correction was too small. Decision 3 or 4, depending upon the size of i, v^m.
506	Correction type 502 rejected since corrected temperature would lead to superadiabatic lapse rate. Decision 4.

communication errors, are formed from an average of the available i and v^m. If T^* is close to this average, this is an indication that there is a single communication error, and T^* and v^a, if they are available, are then also used in the average. While the value of the temperature for an observation error could be changed to make the residuals smaller, the new value would not provide independent information for a subsequent analysis and forecast. A communication error, on the other hand, since it leads to a hydrostatic inconsistency due to the redundancy of reported heights and temperatures at mandatory levels, can be corrected to a value that will likely provide independent information.

8) Since all corrections are for communication errors, generally caused by direct wrong action by a person, a "simple" correction is sought and used if found. A simple correction is one that corrects an error in sign, an error to a single digit, or an error of transposition of two or more digits, or an error in sign in combination with a single digit or transposition of digits. First, a proposed correction is obtained as outlined above. Then a simple correction is looked for within specified limits of the proposed correction. The simple correction closest to the proposed correction is tested for acceptability, if any is found. Examination of the significant level qc results shows that somewhat over 40% of the corrections are simple.

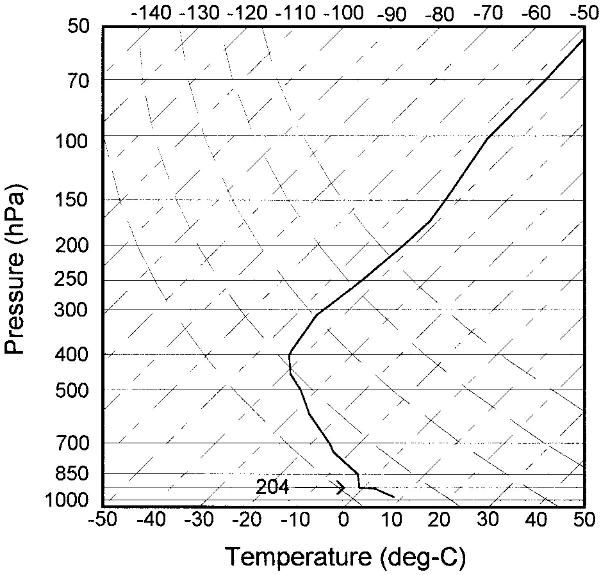

FIG. 6. Example of mandatory level correction rejected by lapse rate check with significant level adjacent temperature. The case is 1200 UTC 27 May 1996, station 24507, Tura, Russia, 64.28°N, 100.23°E.

4. Examples

Examples are shown that typify the kinds of errors and some of the complicating circumstances encountered while quality controlling the significant level temperatures. There are four categories of simple situations: 1) a mandatory level correction is rejected by the significant level checking; 2) an error is suspected, but then rejected; 3) an error is detected, but no correction is possible; and 4) an error is detected and corrected. The following sections will further describe these error types and give one or more examples. Some complicating factors will also be explained.

a. Mandatory level correction rejected

Of the mandatory level temperatures that are corrected by CQCHT, about 6% are rejected by the lapse rate check using adjoining significant level temperatures. When this happens, examination often shows that the temperature correction was much better than the original, but not quite good enough. This happens most frequently for temperatures at thin layer boundaries, for example, 1000–925 hPa or 925–850 hPa, where the mandatory level temperature correction, which makes use of the hydrostatic residual, is very sensitive to random errors in height. Figure 6 shows a rejected mandatory level correction at 925 hPa. The case is 1200 UTC 27 May 1996, station 24507, Tura, Russia, at 64.28°N, 100.23°E. The figure uses skewed temperature and logarithm of pressure scales, with the pressures ruled at the mandatory levels for easy reference. The dry adiabats between 0° and 80°C are also shown at a 20° interval. The lapse is superadiabatic between 934 and 925 hPa and so the 925-hPa temperature is rejected.

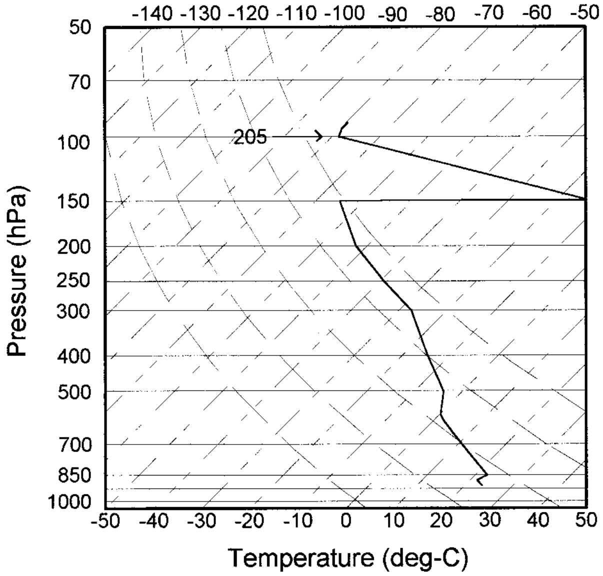

FIG. 7. Example of bad rejection of mandatory level correction because of bad significant level temperature. The case is 0000 UTC 24 May 1996, station 43295, Bangalore, India, 12.97°N, 77.58°E.

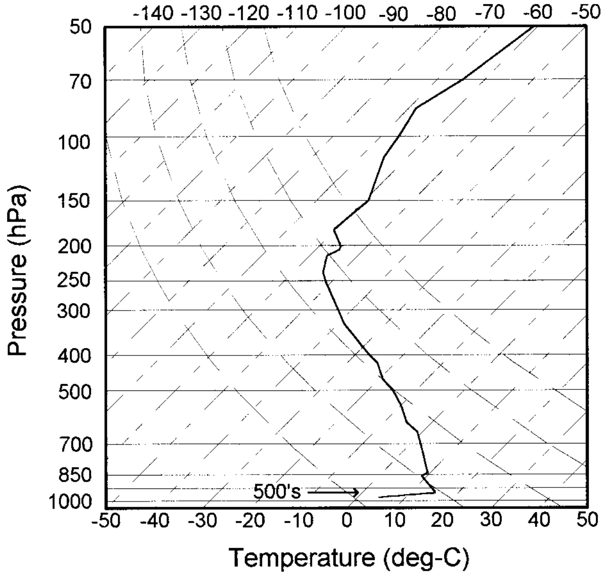

FIG. 8. Example of type 500 diagnoses. Temperatures at 954 and 949 hPa are suspected to have error, but they are decided to be good. The case is 0000 UTC 29 May 1996, station 94637, Kalgorlie, Australia, 30.77°S, 121.45°E.

Very rarely the mandatory level temperature correction may be rejected because it is checked against a bad significant level temperature that results in a superadiabatic lapse rate. Figure 7 shows an example containing a bad significant level temperature at 149 hPa. The case is 0000 UTC 24 May 1996, station 43295, Bangalore, India, at 12.97°N, 77.58°E. This erroneous diagnosis leads to the rejection of the good corrected temperature at 100 hPa.

b. No error

There are primarily two locations where initial error suspicions are made when in fact there is no error: 1) at the top of the boundary layer and 2) near the tropopause. At both locations the temperature profile is very nonlinear, leading to a poor result from the vertical checks. In these cases, other checks are used to show that the reported temperatures are actually good. Suspicion is made because the i and v^m residuals are large, but since s^a is small and there is no superadiabatic lapse rate, a type 500 is assigned. There are a rather large number of type 500 suspicions, which is evidence that the full complex of checks must be used for a correct diagnosis of many temperatures.

Figure 8 shows an example of type 500 diagnoses at 954 and 949 hPa. The case is 0000 UTC 29 May 1996, station 94637, Kalgoorlie, Australia, at 30.77°S, 121.45°E. The vertical residuals at the two levels are 9.7° and 9.6°C (large), leading to the error suspicion. However, the hydrostatic residual s^a for the layer containing these levels is 9.5 m (small). All temperatures are believed to be good.

Figure 9 shows an example of type 500 diagnoses at and above the tropopause at the pressures 127, 119, and 110 hPa. The case is 0000 UTC 29 May 1996, station 47909, Naze, Amamio Island, at 28.38°N, 129.55°E. The temperatures are initially suspected by vertical residuals v^m of $-8.7°$, $-6.3°$, and $-8.0°$C (all large), but the hydrostatic residuals s^a for the layer is 5.3 m. They are therefore assigned the type 500.

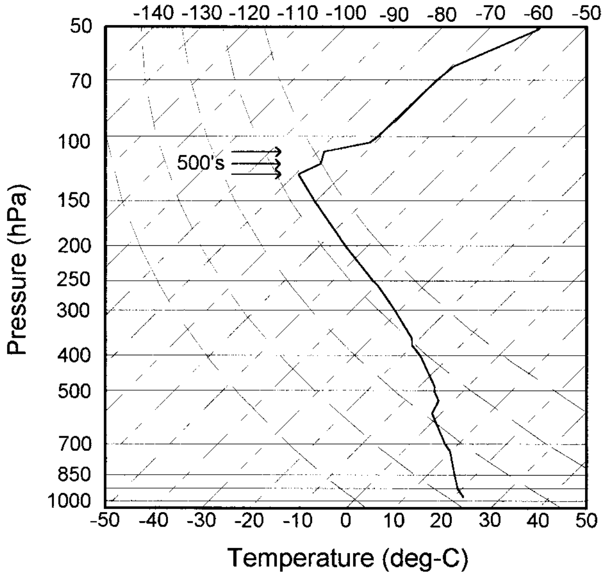

FIG. 9. An example of type 500 diagnoses near the tropopause The case is 0000 UTC 29 May 1996, station 47909, Naze, Amamis Island (Japan), 28.38°N, 129.55°E.

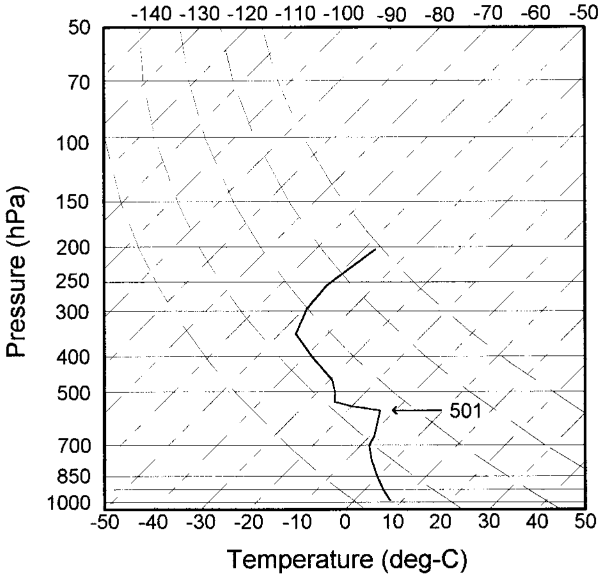

FIG. 10. Example of type 501 diagnosis. Residuals i and v^m are large and the lapse is superadiabatic, but s^a is small. The case is 0000 UTC 28 May 1996, station 22845, Kargopol, Russia, 61.50°N, 38.93°E.

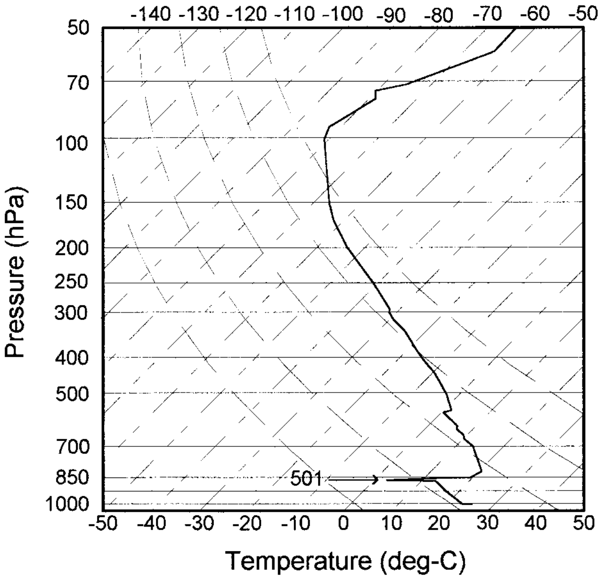

FIG. 11. Another example of type 501 diagnosis, illustrating the particular difficulties with thin layers. The case is 0000 UTC 28 May 1996, station 76723, Isla Socorra, Columbia, 18.72°N, 110.95°W.

c. Errors detected, no correction

Table 3 showed a classification of the possible significant level temperature diagnoses. There are several types, namely, 501, 503, 504, 505, and 506 for which the temperature is in error but no correction is possible. The reason why no correction is possible differs from one type to another, as illustrated for most of the types by the following examples.

Figure 10 shows an example of error type 501. The case is 0000 UTC 28 May 1996, station 22845, Kargopol, Russia, at 61.50°N, 38.93°E. At 561 hPa the increment i is 6.2°C and v^m is 7.0°C, both large. In addition, the lapse rate between 561 and 546 hPa is superadiabatic. However, the hydrostatic residual s^a has the small value of -5.2 m and therefore no hydrostatic correction is possible, leading to the type 501 diagnosis. The temperature is marked as bad.

Even a large error in a significant level temperature may not lead to the hydrostatic residual s^a becoming large. An example is provided in Fig. 11 for 0000 UTC 28 May 1996, station 76723, Isla Socorra, Columbia, at 18.72°N, 110.95°W. At 864 hPa, the level of the bad temperature, the residuals are as follows: $i = -18.8$°C, $v^m = -16.3$°C, $v^a = -12.0$°C, $s^m = -3.1$ m, and $s^a = 7.7$ m. In addition, the lapse rate between 864 and 851 hPa is superadiabatic. The large error has only influenced the hydrostatic residual by about 11 m because of the thin layers in which it is embedded. (The neighbors are at 869 and 851 hPa.) No correction is advisable in such a situation, and a type 501 is assigned, with the temperature marked as bad.

For an error type 503, several residuals, including the hydrostatic residual, are large, but they are inconsistent and so no correction can be made. An example is shown in Fig. 12 for 1200 UTC 28 May 1996, station 47420, Nemuro, Japan, at 43.33°N, 145.58°E. At 989 hPa the residuals are as follows: $i = -0.9$°C, $v^m = 7.4$°C, $v^a = 7.0$°C, $T^* = 16.7$°C, $s^m = 23.8$ m, and $s^a = 14.9$ m. The temperature in this case is likely bad, but the nature of the problem is difficult to determine. The 989-hPa temperature is marked as bad without attempting a correction.

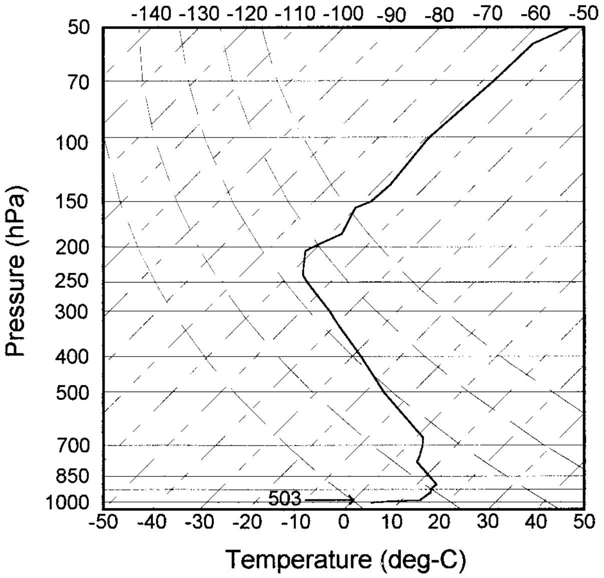

FIG. 12. Example of type 503 diagnosis: large, inconsistent residuals. The case is 1200 UTC 28 May 1996, station 47420, Nemuro, Japan, 43.33°N, 145.58°E.

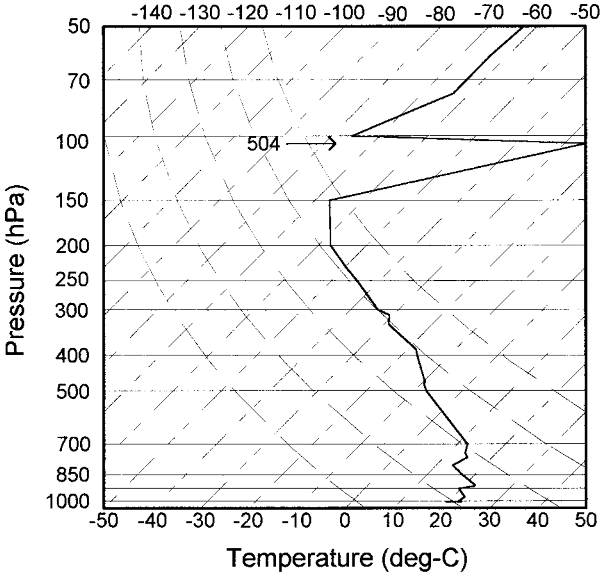

FIG. 13. Example of type 504 diagnosis: the proposed correction does not reduce s^a to an acceptable level. The case is 1200 UTC 28 May 1996, station 76256, Empalme, Mexico, 27.95°N, 110.80°W.

One condition for the acceptance of a significant level temperature correction is that the corrected temperature must lead to a recomputed hydrostatic residual s^a that is small. Type 504 is used to denote that all conditions for a correction are met except that the recomputed s^a remains large. An example is given in Fig. 13 for 1200 UTC 28 May 1996, station 76256, Empalme, Mexico, at 27.95°N, 110.80°W. All residuals are large and there is no question that the reported temperature is bad. But the increment is 54.2°C, while T^* is -63.3°C. Normally, these two residuals will be close in absolute value and of opposite sign for a good correction. That they differ so much is an indication that the recomputed s^a will be large. In this case, the temperature is marked as bad.

d. Corrections made

There are more corrections than all the other types of detected errors combined (see Table 4 in section 5 for the statistics). (Remember that there is no error for Type 500.) A few examples will be given that typify these cases. The first example, Fig. 14, shows corrections at two levels. The case is for 0000 UTC 29 May 1996, station 94044, Momote, New Guinea (Admiralty Island), at 2.07°S, 147.43°E. The original temperature profile, including the erroneous temperatures, is plotted with the corrected temperatures marked as dots. The 255-hPa temperature is corrected from -28.9° to -38.9°C and the 207-hPa temperature is corrected from 10.2° to -50.1°C. Both of these are "simple" corrections, found not by accident, but by searching for them in the vicinity of the correction proposed as a linear combination of the appropriate residuals.

Another example of a simple correction is provided in Fig. 15 for 0000 UTC 28 May 1996, station 67964, Goetz, Obs., Zimbabwe, at 20.1 5°S, 28.62°E. The temperature at 491 hPa is corrected from 15.0° to -14.9°C, which is a sign correction (the tenth place is made odd to agree with the usual coding convention).

TABLE 4. Summary of significant level checking for 1995.

Description	Number per month	Number per observation time
Type 2xx	96	1.6
Type 502	852	14
Type 500	2406	40
Type 501	153	2.6
Type 503	42	0.7
Type 504	169	2.8
Type 505	83	1.4
Type 506	148	2.5
Type 501, 503–506	595	9.9

The final example, Fig. 16, illustrates the difficulty in making corrections when there are multiple significant level temperature errors between adjacent mandatory levels. The case is 1200 UTC 28 May 1996, station 46747, Tungkong, Taiwan, at 22.47°N, 120.43°E. The temperature at 644 hPa is corrected from 13.8° to 7.4°C, while the temperature at 598 hPa cannot be corrected. For multiple errors the error types are not too informative but, in this case, the proposed correction would lead to a superadiabatic lapse rate, so type 506 was assigned and the 589-hPa temperature was marked for rejection.

5. Summary and conclusions

Significant level temperatures have been checked and occasionally corrected for some years at the NCEP. In

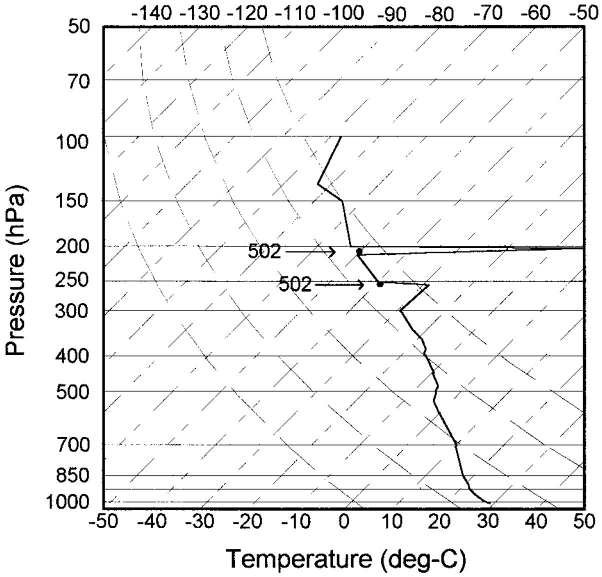

FIG. 14. Simple significant level corrections at two levels. The case is 0000 UTC 29 May 1996, station 94044, Momote, New Guinea, 2.07°S, 147.43°E.

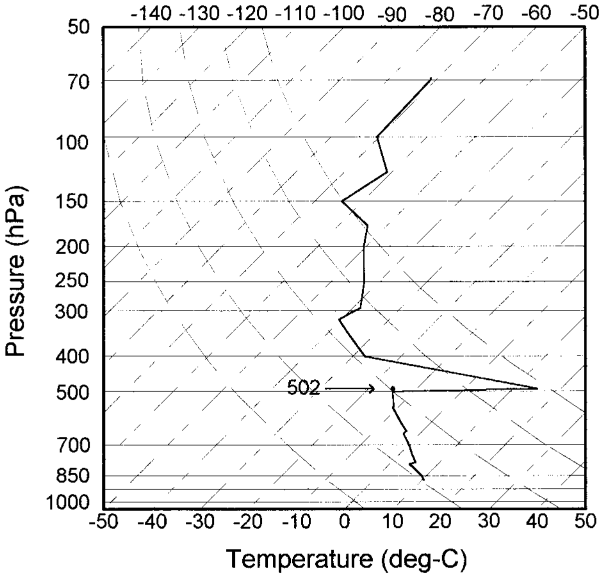

FIG. 15. Sign correction for significant level temperature at 491 hPa. The case is 0000 UTC 28 May 1996, station 67964, Goetz, Obs., Zimbabwe, 20.15°S, 28.62°E.

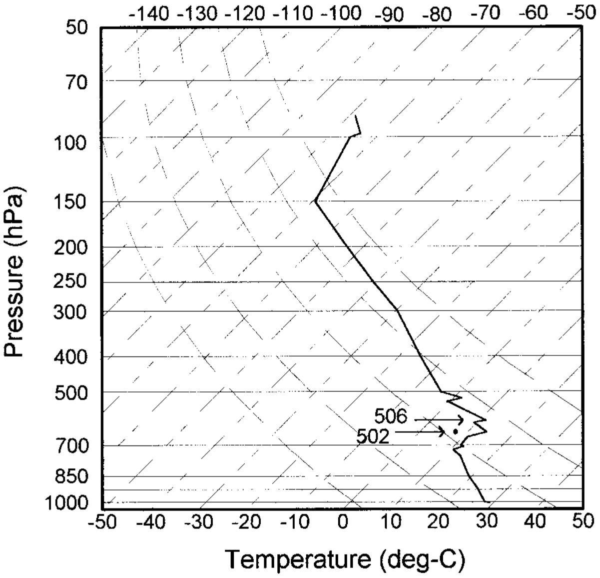

FIG. 16. Example of multiple errors in significant level temperatures between a pair of mandatory levels. One temperature is corrected while a second is rejected. The case is 1200 UTC 28 May 1996, station 46747, Tungkong, Taiwan, 22.47°N, 120.43°E.

May 1994, the checking was completely changed, resulting in much better diagnosis and correction. This paper discusses the new algorithm. As a further improvement to significant level checking, a completely rewritten cqc was implemented at NCEP in April 1997 that combines mandatory and significant level quality control.

The result of the significant level checking is summarized monthly. The average statistics for 1995 are given in Table 4. A large number of suspicions are rescinded by additional checking (type 500). This is to be expected from the way that significant level temperatures are defined, being in a sense outliers in the profile of observed temperatures. The most usual situations for type 500 diagnosis are near the surface and tropopause. Most of these situations are correctly identified, allowing the temperatures to be used in the NCEP assimilation. The number of corrections (type 502) is somewhat larger than the overall number of rejections and questionable quality diagnosis (types 501, 503–506). The previous significant level temperature qc algorithm averaged about 20 corrections each observation time and another one to two diagnoses of questionable data. The corrections were made without the aid of the forecast and there was no lapse rate check to verify that they were reasonable. While the current algorithm provides fewer corrections, those that it makes are more reliable. The decisions for questionable quality and rejections, types 501, 503–506, are vastly improved over the previous version.

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