Determination of Radiosonde Station Elevation from Observational Data

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ABSTRACT

Correct radiosonde station elevation (balloon release height) is important in quality control of radiosonde soundings. Incorrect heights introduce errors in calculated temperature trends and numerical forecasts. Radiosonde metadata frequently contain erroneous information regarding station elevations. Soundings are produced at the station using the correct station elevation and the hydrostatic equation to determine the height of each pressure level in the sounding. It is easy to do a reverse calculation using the soundings to calculate the station elevation (release point). From a time series of calculated station elevations, the change dates and station elevations can be determined for individual stations. A method was developed to calculate station elevation and change dates automatically from time series of calculated station elevations.

1. Introduction

Correct radiosonde station elevation (balloon release site) is important for many meteorological tasks. For example, undocumented station relocations or incorrect changes in station elevation produce noise in time series of radiosonde data. An undocumented change of station elevation of, say, 30 m above the previous level will introduce a negative contribution to the temperature trend at the station. In the troposphere, assuming a lapse rate of 6.5°C km^{-1}, an undocumented change of height of 30 m produces an apparent temperature change of 0.2°C at all elevations above the surface [see Parker and Cox (1995) for more examples]. This noise interferes with climate trend detection and reduces the accuracy of numerical forecasts. Also, changes in station elevation often indicate a change of station location and an accompanying change of ground equipment and/or radiosonde models. Hence, elevation change dates often correspond to dates of inhomogeneities in time series of upper-air observations.

Station elevation is not transmitted with the upper-air sounding and must be obtained from other sources. Almost all metadata sources contain some incorrect stations coordinates and elevations. There are many reasons for these errors, but they consist primarily of data-entry errors, out-of-date changes to the metadata, and loss of station history information. Sources of current stations elevations contain errors [for example, the World Meteorological Organization's (WMO) *WMO Catalogue of Radiosondes and Upper-Air Wind Systems in Use by Members* (available, at the time of writing, online at http://www.wmo.ch/web/ddbs/jen/Radiosondes/index.html), which is updated on a regular basis]. Historical upper-air metadata of station elevations contain errors and do not agree with each other. If station elevation data of current stations contain errors that are not detected or corrected by groups such as the National Centers for Environmental Prediction (NCEP), then it is almost impossible to detect and correct elevation errors in historical data because of unrecoverable loss of information in the original records.

NCEP, like the National Climatic Data Center (NCDC), depends on the U.S. Air Force master station catalog, the WMO catalog, and the National Weather Service (NWS) for station locations. NCEP performs sporadic studies to detect station elevation using the hydrostatic equation (B. Ballish 2001, personal communication). If a large and consistent difference exists between the first guess and an observation, the station elevation will be investigated. Hence, it is possible and likely for elevation errors of up to 100 m to exist in their database for months, if not years.

Because of the errors in station elevation metadata, an independent determination of station elevation data is required. Using time series of observational data at each upper-air station, it is possible to determine periods of constant station elevation and changes in station elevation with a high degree of accuracy. The high ac-

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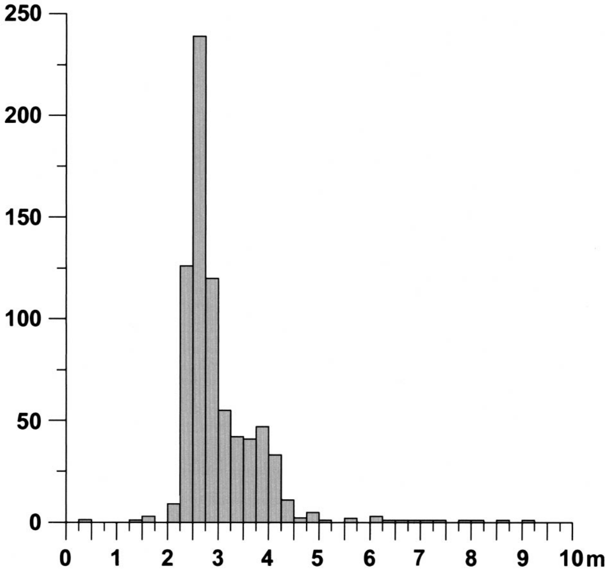

FIG. 1. Distribution of the standard deviation $\overline{\mathrm{SD}}_{\hat{H}}$ calculated from 752 stations.

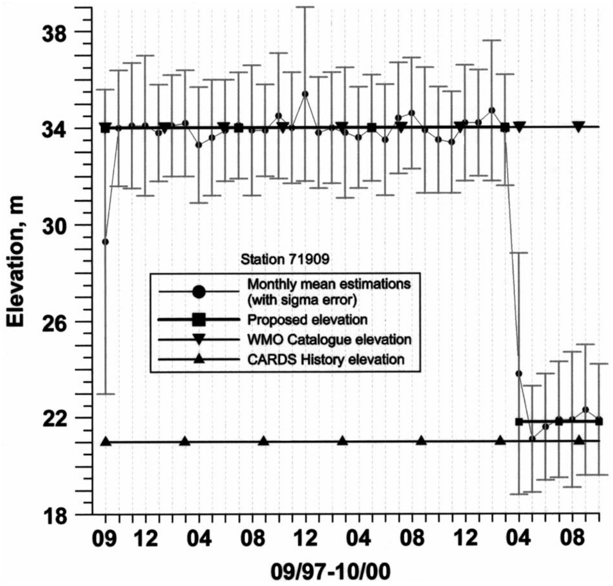

FIG. 2. Calculated station elevations for Iqaluit (71909) from Sep 1997 to Oct 2000.

curacy follows from the fact that the original soundings are developed using the hydrostatic equation and correct station elevation. The accuracy of the reverse calculation depends on the resolution of the soundings in the database and variability of the observed variables. With detailed soundings, the surface elevation can be determined to within centimeters for long time series.

2. Method

If a sounding contains pressure P_0, temperature T_0, and humidity at the surface level and P_1, T_1, humidity, and geopotential height H_1 at a nearby level, then the height H_0 of the surface can be estimated from

$$\hat{H}_0 = H_1 - \frac{(T_{v0} + T_{v1})}{2}\frac{R}{g}\ln\frac{P_0}{P_1}. \qquad (1)$$

which is derived by integration of the hydrostatic equation,

$$\frac{\partial H}{\partial P} = -\frac{RT_v}{gP}, \qquad (2)$$

from P_0 to P_1, assuming a linear change of virtual temperature T_v. Here R is the gas constant for dry air, g is the acceleration due to gravity, and $\hat{H}_0$ is the calculated surface elevation.

Calculated elevations are approximations of the true height H_0 due to observational errors in H, T, P, and humidity; small computational errors made in producing the sounding; and the departure of the actual profile of T_v from the assumed linear profile. The variance of the calculated surface elevations about the true elevation is usually small, however. Figure 1 shows the distribution of standard deviations $\overline{\mathrm{SD}}_{\hat{H}}$ about the monthly mean of the calculated elevations for 752 stations from September of 1997 to October of 2000. Most radiosonde stations in this sample have standard deviations in the range of 2–5 m, and a few have standard deviations that exceed 9 m (see Fig. 1).

The distance between the surface level and the first significant level or mandatory level is clearly an important factor in the minimization of $\overline{\mathrm{SD}}_{\hat{H}}$. This result is demonstrated in section 3. For a majority of stations, this value is in the range 60–150 m (America and Europe), but for some stations (Africa and Asia) it exceeds 1000 m.

The true elevation of a station or change in elevation can be determined by analyzing a time series of calculated surface elevation. Periods of stable station elevation and changes in elevation can be detected visually in a time series plot of calculated station heights (see Fig. 2). The following method was developed to determine station elevation and change dates for NCDC's worldwide radiosonde database (more than 2000 stations).

Assuming that a time series consists of n ($1 \leq n \leq N$) time intervals, each of which has a constant elevation, the problem is solved by minimization of the function

$$F(n, t_2, \ldots, t_n, H_{01}, \ldots, H_{0n}) = \sum_{i=1}^{n}\sum_{j=t_i}^{t_{i+1}}(\overline{\hat{H}}_{0j} - H_{0i})^2 \rightarrow \min, \qquad (3)$$

subject to the inequality constraints

$$t_i < t_{i+1}, \quad \forall\, i = 1, \ldots, n, \qquad (4)$$

where $\overline{\hat{H}}_{0j}$ is the calculated monthly mean station ele-

TABLE 1. List of stations with height difference $|HP - H_0|$ of 10 m or more between WMO reported elevation HP and calculated elevation $\overline{H}_0$. Here, S_H is the std dev of H_0 w.r.t. the monthly mean values $\hat{H}_{0j}$.

WMO No.	HP (m)	H_0 (m)	S_H (m)	$\lvert HP - H_0\rvert$ (m)
31004	79	679.9	1.0	600.9
57816	1014	1223.3	0.6	209.3
36870	851	659.4	1.0	191.6
33946	181	282.6	0.9	101.6
62053	132	38.1	0.7	93.9
97072	6	84.0	0.8	78.0
72662	965	1029.9	0.8	64.9
42182	216	274.1	2.6	58.1
37549	427	481.1	0.9	54.1
59431	74	126.4	2.3	52.4
68032	900	951.0	1.4	51.0
60571	773	809.7	2.2	36.7
91217	111	76.5	3.4	34.5
71815	26	60.0	0.4	34.0
29634	176	142.3	2.7	33.7
97372	108	141.3	1.2	33.3
78016	6	37.5	0.6	31.5
33658	246	215.2	1.2	30.8
70350	34	3.7	0.4	30.3
58725	192	221.4	1.4	29.4
17280	677	648.0	0.8	29.0
96315	15	43.0	0.4	28.0
37789	1113	1140.9	1.6	27.9
89662	81	53.4	0.6	27.6
47936	53	27.0	0.6	26.0
60630	293	267.0	0.9	26.0
71203	430	455.9	0.4	25.9
68110	1700	1725.6	1.3	25.6
89050	16	39.7	0.7	23.7
33791	124	100.6	1.0	23.4
89592	30	52.7	0.5	22.7
54511	55	33.0	1.0	22.0
21946	61	39.2	0.9	21.8
24507	168	189.6	1.1	21.6
57447	438	459.3	0.7	21.3
72393	121	99.9	0.6	21.1
52836	3192	3212.7	4.9	20.7
24125	220	200.9	2.0	19.1
43150	66	47.1	2.7	18.9
56146	3394	3412.7	5.7	18.7
02185	34	15.4	1.9	18.6
56137	3307	3325.5	4.2	18.5
31369	68	49.6	0.7	18.4
41780	22	40.4	1.7	18.4
04202	77	59.0	0.4	18.0
01400	29	46.9	0.6	17.9
68461	1678	1695.8	4.2	17.8
80241	167	184.7	1.7	17.7
71907	6	23.7	0.4	17.7
63612	515	498.3	0.6	16.7
60680	1378	1361.7	0.6	16.3
91592	72	55.9	1.1	16.1
48455	20	3.9	0.5	16.1

vation, i denotes the time interval, and j is a time point in the ith interval.

Function (3) depends only on the $n - 1$ time variables t_i, $i = 2, \ldots, n$, because, for any value of t_i, $i = 2, \ldots, n$, the value of H_{0i}, $i = 1, \ldots, n$, is determined by

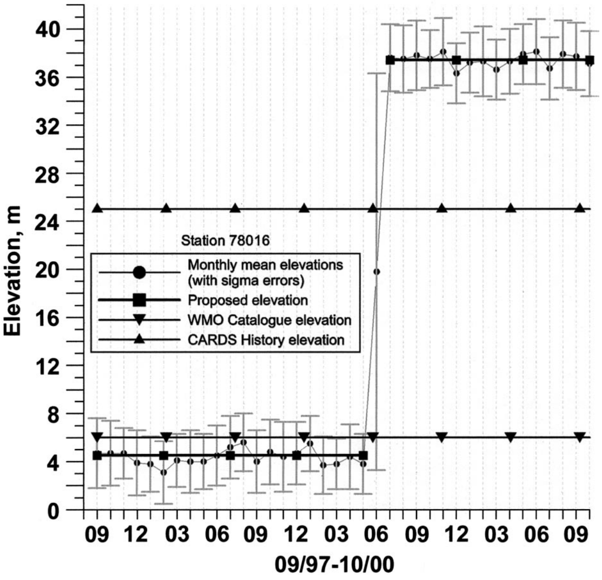

FIG. 3. Calculated station elevations for Bermuda (78016) from Sep 1997 to Oct 2000.

$$H_{0i} = \sum_{j=t_i}^{t_{i+1}} \overline{\hat{H}}_{0j} w_j \Big/ \sum_{j=t_i}^{t_{i+1}} w_j. \qquad (5)$$

The weights w_j are proportional to number of data points used to calculate the monthly mean elevations $\overline{\hat{H}}_{0j}$ and are inversely proportional to the standard deviations $SD_{\hat{H}j}$ of $\hat{H}_0$ with respect to $\overline{\hat{H}}_{0j}$. The weightings in (5) are used instead of simple averaging to reduce the influence of monthly averaged values based on few data points and elevations with a large standard deviation.

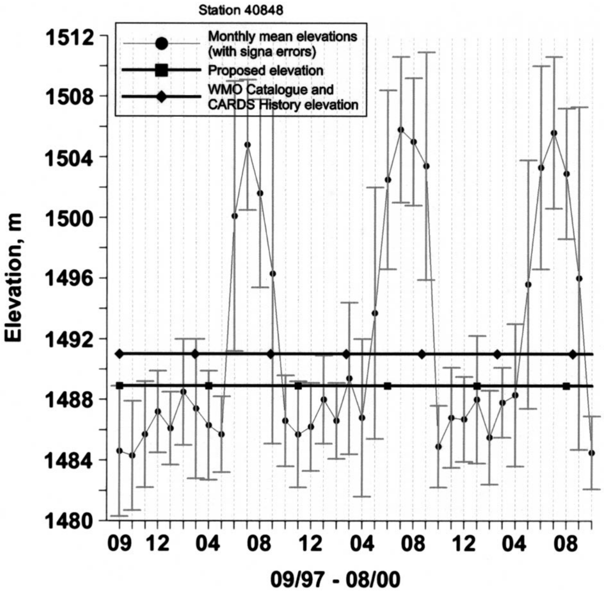

FIG. 4. Calculated station elevations for Shiraz (40848) from Sep 1997 to Oct 2000.

TABLE 2. List of U.S. military ships determined to have small standard deviations of $\hat{H}_0$ (N is the number of observations).

CARDS No.	Ship name	Period	N	$\overline{\mathrm{SD}}_{\hat{H}}$ (m)	S_H (m)	H_0 (m)
99302	USS *Coral Sea*	Apr 1972–Jun 1989	1159	0.35	0.25	12.6
99320	USS *Oriskany*	Jan 1973–Feb 1976	267	0.33	0.18	15.7
99334	USS *Okinawa*	Apr 1972–Oct 1985	273	0.33	0.25	19.7
99382	USS *Belleau Wood*	Oct 1978–May 1989	298	0.34	0.22	20.6
99321	USS *Ranger*	Nov 1972–Jun 1989	500	0.34	0.22	15.6
99333	USS *Constellation*	Jun 1972–Apr 1980	576	0.31	0.23	18.6
		May 1980–May 1989				13.7
99332	USS *Enterprise*	Oct 1971–Jul 1987	1588	0.36	0.23	10.6
99369	USS *Nimitz*	Jun 1975–Apr 1989	758	0.36	0.32	10.7
99306	USS *Independence*	Sep 1975–Sep 1988	496	0.39	0.28	10.7
99329	USS *Kitty Hawk*	Feb 1972–Jun 1984	487	0.38	0.20	18.7
99312	USS *Midway*	Jun 1972–Mar 1989	1246	0.34	0.24	14.6
99341	USS *Blue Ridge*	Mar 1973–Nov 1980	315	0.39	0.24	18.6
		Dec 1981–Oct 1984				9.6

If the monthly mean elevations are relatively error free, then F is concave upward and has a minimum. Hence, (3) can be solved, for example, by the method of gradients [also termed the method of steepest descent; see Ketter and Prawel (1969)]. The equation is solved iteratively starting from $n = 1$ and proceeding until $F(n + 1)$ is greater than $F(n)$. Then, if neighboring station elevations H_{0i} are too close to each other (within 2–3 m), the number n is decreased until an optimum is found.

3. Results

The method was applied to radiosonde data transmitted via the global telecommunications system (GTS) from September of 1997 to October of 2000 to demonstrate the effectiveness of the method. The results show that, for the majority of radiosonde stations in the WMO catalog of aerological stations, the calculated elevations and the reported elevations HP are nearly iden-

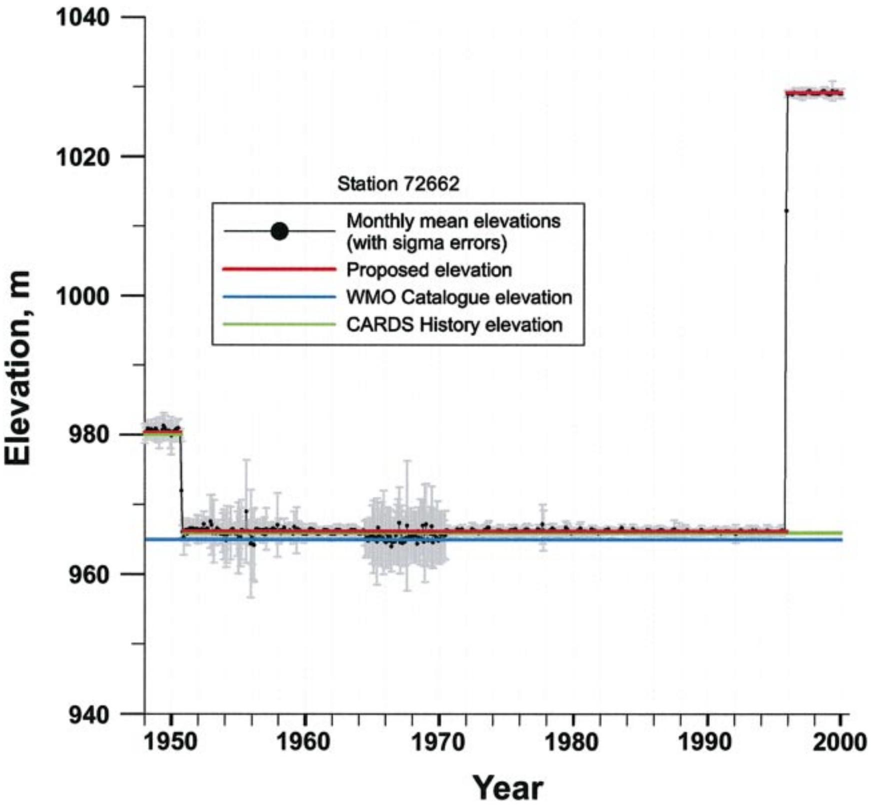

FIG. 5. Calculated station elevations for Rapid City (72662) from Jan 1948 to Dec 1999.

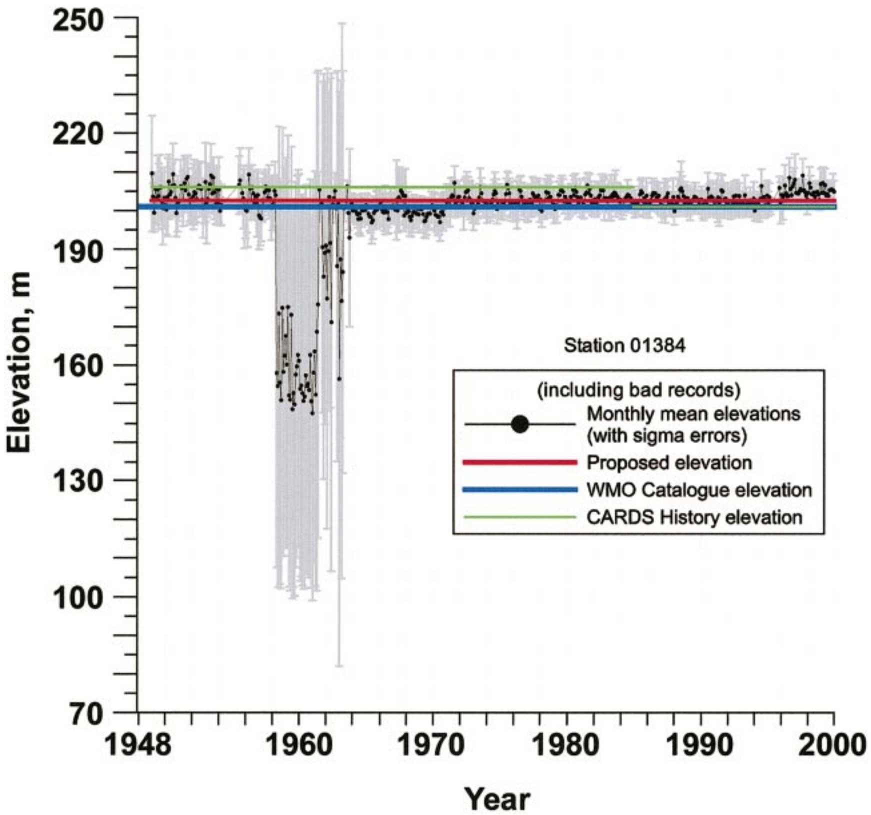

FIG. 6. Calculated station elevations for Oslo/Gardermoen (01384) from Jan 1949 to Dec 1999 from CARDS.

tical. Four hundred ninety stations have a difference of less than 2 m, or

$$|\mathrm{HP} - H_0| \le 2.5S_H, \qquad (6)$$

where S_H is standard deviation of monthly means $\overline{\hat{H}}_{0j}$ for the 1997–2000 period.

There are stations for which the WMO catalog elevations differ greatly from the calculated elevations (up to several hundred meters). Two hundred fifty-six stations were found to have differences greater than 2 m and

$$|\mathrm{HP} - H_0| > 2.5S_H. \qquad (7)$$

Table 1 lists 53 upper-air stations at which the calculated and WMO elevation differ by more than 16 m (the limit 16 m is chosen to give a reasonable table size). If the elevation changed between 1997 and 2000, only the last elevation H_{0i} is given in the table. Undocumented station elevation changes were detected at several stations. Fig. 2 shows that in April of 2000 the elevation at Iqaluit, Northwest Territories, Canada, WMO station 71909, changed from 34 to 21.8 m. The WMO catalog and NCDC's Comprehensive Aerological Reference Dataset (CARDS) documented no such change, and it is clear the station relocated to 21.8 m. Similar, the Bermuda Naval Air Station, WMO 78016 (see Fig. 3), moved from an elevation of 4.5 to 37.5 m in July of 1999. Again, the WMO catalog and CARDS document no such change in elevation. As a final example, the Vandenberg Air Force Base WMO (72393) elevation is 121 m according to the WMO catalog. The elevation was calculated to be 99.8 m, however. CARDS station history has 100 m for most of the period of observation but contains the erroneous information that the elevation was 63 m from 1967 to 1970.

Most stations do not exhibit seasonal variations in calculated station elevations; there are exceptions, however. Figure 4 is a plot of the results for Shiraz, Iran. There is a remarkable repetition of summer peaks with departures from the weighted elevation of 15–16 m. There are two possible causes of these seasonal variations: large seasonal departures of the atmospheric temperature profile from the assumed linear profile (e.g., deep temperature inversion), and inadequate resolution in the sounding near the surface. It was found that in January the height of the first level averaged 65 m above the surface; in July the averaged height of the first level above the surface was 1314 m. This station's calculated station elevations are complex, but the calculated value of 1489. 1 m is very close to the value in the WMO catalog.

The calculated elevations for 614 CARDS stations were almost identical to both the WMO catalog and CARDS station history files (i.e., the differences are less than 2 m). In contrast, the calculated elevations at 901 stations differed by more than 2 m from the official elevation.

Figure 5 shows the calculated station elevations for Rapid City, South Dakota (WMO 72662), which is an example of an elevation change that is not documented. Analysis of the station elevation time series indicates two changes of elevation occurred from 1948 to 1999. The first station elevation change occurred in November of 1950. This change (from 982.3 to 966.2 m) is found in the CARDS history files (from 980 to 966 m). The second change (from 966.2 to 1029.1 m) occurs near November of 1995. CARDS metadata do not contain this information and the WMO catalog for July of 2000 has 965 m for the station elevation. The *Federal Meteorological Handbook* (NWS 1997) printed in 1997 has the station elevation as 966 m.

Upper-air observations performed at U.S. military ships are high-quality observations by many criteria. These observations usually have very small variation of estimated station elevation $\hat{H}_0$. The height of the release point can be estimated to within inches (see Table 2). It was determined that 2 of the 12 listed ships have changed the launch point. Note that the current practice is to use an elevation of 0.0 m for all ships. The last column in Table 2 shows the systematic error from the hydrostatic equation for upper-air observations from these ships, assuming a launch height of 0.0 m.

Method (3) also can be used to provide quality control of observations at a station. It may be used not only to correct station elevation, but as a check to eliminate incorrectly identified soundings (wrong WMO number) in a time series for that station. Figure 6 shows the calculated station elevations for Oslo/Gardermoen, Norway. There clearly is a problem with the data from May of 1958 to June of 1964. It was determined that all 1200 UTC observations from May of 1958 to April of 1961 have an averaged surface elevation of 104 m, and 1200 UTC observations from May of 1961 to April of 1963 have an averaged elevation of 35 m. All 0000 UTC observations from May of 1958 to June of 1964 have an elevation of 202 m, however. The most reasonable explanation is that 1200 UTC data are from stations that have been misidentified as Oslo. The data are reasonable after excluding the 1200 UTC soundings (results not shown).

4. Conclusions

Metadata for upper-air stations contain incorrect station elevations for many upper-air stations. These incorrect station elevations are a source of noise in upper-air data and reduce the reliability of the data.

This paper presents a method to check station elevations in the metadata for accuracy. From long historical time series of radiosonde soundings, correct station elevations and change dates can be identified. The method developed in this paper will enable the various meteorological data centers to determine rapidly when station elevations have changed and then make nearly real time modifications to the metadata. It should lead to improvement of upper-air data quality.

The files with detected elevations for the CARDS dataset and for current upper-air data may be requested from the authors by e-mail.

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