SOLA, 2009, Vol. 5, 109−112, doi:10.2151/sola.2009−028

Correction of Radiosonde Pressure and Temperature Measurements Using Simultaneous GPS Height Data

Yoichi Inai[1], Fumio Hasebe[2], Kensaku Shimizu[1], and Masatomo Fujiwara[2]
[1]*Graduate School of Environmental Science, Hokkaido University, Sapporo, Japan*
[2]*Faculty of Environmental Earth Science, Hokkaido University, Sapporo, Japan*

Abstract

A method of correction for radiosonde pressure and temperature data by using simultaneous global positioning system (GPS) ellipsoidal height (z_{GPS}) is proposed. The correction is made by adjusting the observed pressure and temperature so that the ellipsoidal height (z_{PTU}) calculated from integrating the hypsometric equation by using the latitude- and altitude-dependent gravity together with the observed pressure, temperature and humidity (PTU) agrees with z_{GPS}. The temperature bias is assumed to arise only from inaccurate radiation correction so that there is no temperature bias in the nighttime data. Under this assumption, the deviations of z_{PTU} from z_{GPS} in the nighttime data result only from observational errors in pressure. The pressure adjustment required to remove these deviations is applied also to the daytime data. The daytime temperature bias can then be estimated from the difference between z_{PTU} and z_{GPS} during the day. The biases in Vaisala RS80 pressure and temperature measurements are estimated using the Soundings of Ozone and Water in the Equatorial Region campaign data. The estimated pressure bias is positive below ~7 km and negative above it. The bias above 15 km is statistically significant. The daytime temperature bias lacks statistical significance due to fluctuations in the results.

1. Introduction

Radiosonde data have been conveniently used for evaluating remote sensing data. On the other hand, the validation of themselves has been made by conducting comprehensive intercomparisons using multiple cross-platform datasets (e.g., Nash et al. 2006; Haimberger et al. 2008; Yoneyama et al. 2008).

The Vaisala RS80 radiosonde system, widely used as a standard operational radiosonde but was replaced by RS92 in the early 21st century, is still used for research purposes. The geopotential heights are repeatable within ±10 and ±50 m (1σ) at 100 and 10 hPa, respectively, for RS92, and within ±40 and ±500 m for RS80 observations (Steinbrecht et al. 2008). On the other hand, the radiosondes have become equipped with the global positioning system (GPS), which gives accurate height above ellipsoid, i.e., ellipsoidal height (z_{GPS}) achieving the accuracy of within ±20 m from surface to 34 km (Nash et al. 2006).

The Soundings of Ozone and Water in the Equatorial Region (SOWER) campaigns have been conducted in every boreal winter since December 2004 in the tropical western Pacific/Indonesian region. Cryogenic Frostpoint Hygrometers (CFH; Vömel et al. 2007a) (frostpoint and z_{GPS}) equipped with RS80 (temperature and pressure) radiosondes have been launched. After screening noisy profiles judged by the representativeness of population (see Section 3.2), 17 daytime, 4 nighttime, and 5 twilight observations are found suitable for the analysis (Table 1). The main purpose of these campaigns is to quantify the dehydration amount associated with the quasi isentropic advection in the tropical tropopause layer (TTL). For this purpose, the isentropic coordinate system is conveniently used (e.g., Hasebe et al. 2007) because the air parcels stay on an isentrope even when they are displaced by small scale transient waves. Therefore, it is important to estimate the pressure and temperature errors in radiosonde data. In the SOWER campaigns, pre-launch calibrations, the so-called ground checks, of RS80 pressure, temperature and humidity measurements have not been conducted. Some systematic biases that might affect individual data cannot be adjusted after the launch. Nevertheless, the systematic errors could be identified by investigating the statistical properties of post-launch radiosonde data. In this paper, a method for correcting the radiosonde pressure and temperature data is proposed by taking the advantage of simultaneous GPS measurements. As the sample size of our data is rather small, the statistical significance derived by applying t-tests will be indicated for the practical purpose, although there is clearly a limitation for its interpretation.

2. Possible biases in radiosonde data

The RS80 temperature sensor is composed of thermistor speck, lead wire and mount. All these parts have a very low emissivity and low solar absorptivity as they are coated by aluminum. Thus, this sensor is virtually unaffected by incoming infrared radiation and cooling by its own emission, making it an excellent sensor during the nighttime. However, the absorbed solar energy must be dissipated by air-cooling during the daytime. This introduces the temperature sensor some sensitivity to the balloon rise rate (Luers and Eskridge 1998) making an accurate radiation correction difficult.

The manufacturer's algorithm for removing the effect of solar radiation is recently reported to have caused an overcorrection (Steinbrecht et al. 2008). They also discussed that the pressure sensor has the negative bias in the stratosphere and positive bias in the troposphere leading to the negative bias below 30 hPa and the positive bias above it in the geopotential height (Z) field.

Figure 1 shows the vertical profiles of the difference between Z and z_{GPS} obtained from the daytime and nighttime sonde observations at Biak, Indonesia. While Z is defined by integrating the hypsometric equation with the constant standard gravity ($g_s = 9.80665$, e.g., Fleagle and Businger 1980), the use of latitude- and height-dependent gravity

---

Corresponding author: Yoichi Inai, Graduate School of Environmental Science, Hokkaido University, Kita 10 Nishi 5 Kita-ku, Sapporo 060-0810, Japan. E-mail: wwyoww@ees.hokudai.ac.jp.

Table 1. The number of simultaneous observations of RS80 and GPS categorized by the daytime (the launch time 06:00–16:30 LT), the nighttime (18:00–04:30 LT) and the twilight (04:30–06:00 and 16:30–18:00 LT) condition for each location during the SOWER campaigns in the western Pacific.

Obs. Station (code)	Location (lon., lat.)	Day obs.	Night obs.	Twilight obs.
Biak (BI)	(136.06, −1.17)	5	4	3
Bandung (BD)	(107.59, −6.89)	1	0	0
Kototabang (KT)	(100.32, −0.20)	4	0	2
Tarawa (TR)	(172.92, 1.35)	1	0	0
Ha Noi (HN)	(105.80, 21.01)	6	0	0

$$g\,(\varphi, r) = \frac{GM}{r^2} - \Omega^2\, r \cos^2\varphi, \tag{1}$$

in the integration will yield ellipsoidal height (z_{PTU}) comparable with z_{GPS}, given some reference height at some point. Here, φ is latitude, r is the distance from the center of gravity of the earth, G is universal gravitational constant (6.673×10^{-11} [m^3 s^{-2} kg^{-1}]), M is mass of the earth (5.988×10^{24} [kg]) and Ω is angular speed of the earth (7.292×10^{-5} [rad s^{-1}]). With the approximation of ellipsoid for the earth, r is calculated by

$$r\,(\varphi, z) = \frac{ab}{\sqrt{b^2 \cos^2\varphi + a^2 \sin^2\varphi}} + z, \tag{2}$$

where a is equatorial radius of the earth (6.378×10^6 [m]), b is polar radius of the earth (6.357×10^6 [m]) and z is the ellipsoidal height [m]. Then, under the approximation of hydrostatic equilibrium (safely assumed for the SOWER data) and ideal gas law, z_{PTU} is calculated from

$$z_{\mathrm{PTU}}\,(p) = -\int_{p_0}^{p} \frac{R^*}{gM_d}\,\frac{T}{p' + p_w\left(\dfrac{M_w - M_d}{M_d}\right)}\,dp' + z_{\mathrm{GPS}\,0}, \tag{3}$$

where R^* is universal gas constant (8314.51 [J K^{-1} kmol^{-1}]), M_d is molecular weight of dry air (28.96 [kg kmol^{-1}]), M_w is that of water vapor (18.015 [kg kmol^{-1}]), T is absolute temperature [K], p is pressure [N m^{-2}], and p_w is pressure of water vapor [N m^{-2}], which could be estimated from relative humidity observations by using the Goff-Gratch equation (Goff and Gratch 1946). Here p_0 and z_{GPS0} are the pressure and GPS height, respectively, at 70 seconds after the launch when stable GPS records become available. The red dashed lines in Fig. 1 indicate the vertical profiles of $Z - z_{\mathrm{PTU}}$ thus obtained. The black lines ($Z - z_{\mathrm{GPS}}$) should follow the red dashed lines ($Z - z_{\mathrm{PTU}}$) if z_{PTU} is correct. The fact that they deviate from each other suggests that there must be some systematic errors in the pressure and/or temperature measurements in RS80. This is commonly observed independent from the batches of RS80 and the locations of observational stations. The similarity between the features of daytime and nighttime data suggests that the systematic errors in z_{PTU} are not due to inaccurate radiation correction but to pressure biases common to day and night.

The comparison between Z and z_{GPS} in RS80 data in midlatitude (Steinbrecht et al. 2008) shows similar features as depicted in Fig. 1 irrespective of local time. This is another indication of the importance of the pressure bias as the temperature structure is much different between the tropics and extratropics. Those values of $Z - z_{\mathrm{GPS}}$ during the night have a tendency to show slightly smaller values than those during the day. The detailed comparison between daytime and nighttime results could be used to separate the contribution of solar radiation on z_{PTU}.

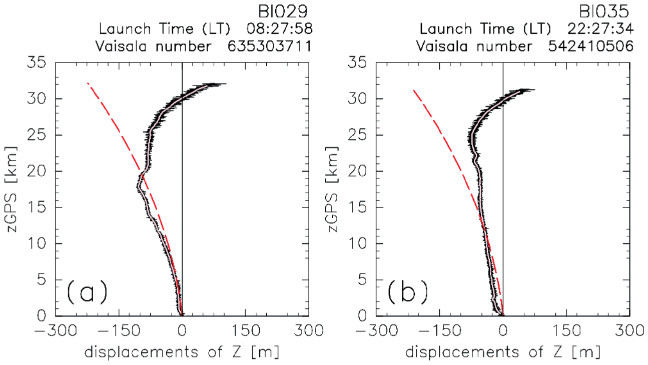

Fig. 1. (a) Daytime and (b) nighttime profiles of $Z - z_{\mathrm{GPS}}$ (raw data in black and ±60 second running mean in light pink) and $Z - z_{\mathrm{PTU}}$ (red dashed line) plotted against ellipsoidal height by GPS.

3. The method of correction

The systematic errors in the sonde data revealed in Fig. 1 can be estimated and corrected statistically by adjusting the observed pressure and temperature so that z_{PTU} and z_{GPS} agree with each other. However, some assumptions are necessary since z_{PTU} depends on three variables such as pressure, temperature and water vapor amount while only one variable z_{GPS} is given. A method of correction is proposed in the following.

3.1 Pressure data

The dependence of z_{PTU} on p_w is quite small as p_w/p is less than 1×10^{-2}. The humidity data by RS80 Humicap is, therefore, safely assumed to cause no error in z_{PTU}. The temperature bias of nighttime observations is neglected for RS80 because it is considered much smaller than that of inaccurate radiation correction during the day (Luers and Eskridge 1998; Steinbrecht et al. 2008). Under these assumptions, the pressure bias in the nighttime data can be uniquely determined by the comparison between z_{PTU} and z_{GPS} observed during the night.

Figure 2 shows the vertical profiles of the differences between z_{PTU} and z_{GPS} ($z_{\mathrm{PTU}} - z_{\mathrm{GPS}}$; blue) for four nighttime observations (all at Biak). The estimation of z_{PTU} has been made by using the differential form of Eq. (3) incorporated with the linearization with respect to p_w/p:

$$\frac{dz}{d \ln p} = \frac{-R^*T}{gM_d}\left(1 - \frac{p_w}{p}\,\frac{M_w - M_d}{M_d}\right). \tag{4}$$

The observed values of $\ln p$, T and relative humidity are smoothed by applying ±60 s running mean before the conversion to p_w and substituting them into Eq. (4) in the finite difference form.

The correction of the pressure data is made by adjusting the observed pressure so that the systematic displacement of the blue lines seen in Fig. 2 is eliminated. The adjusted pressures p_i^* (i = 1, 2, …) being consistent with the observed values of z_{GPS}, T and p_w are recursively obtained once p_0^*, the adjusted pressure at the bottom, is given:

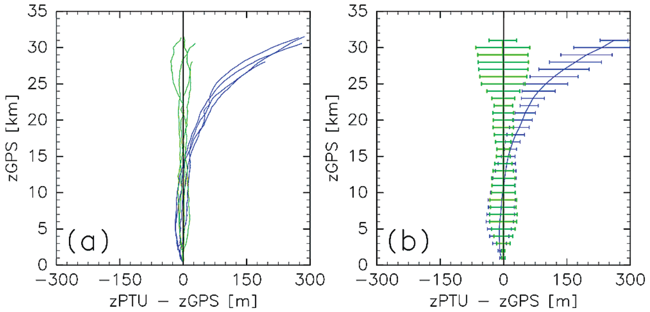

Fig. 2. The differences $z_{PTU} - z_{GPS}$ (blue) and those after the pressure-correction (green) for four nighttime observations. (a): individual observations and (b): average with the 95% confidence intervals for the mean.

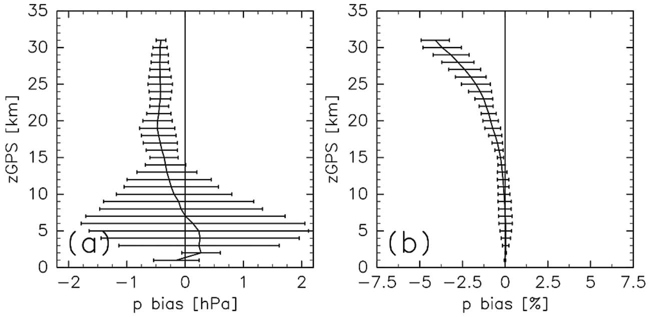

Fig. 3. Pressure bias estimated by nighttime observations: (a) mean bias and (b) that in %. Horizontal bars are the 95% confidence intervals.

$$p_1^* = p_0^* \exp\left(\frac{(z_{GPS1} - z_{GPS0})}{\frac{-R^*T_0}{g_0 M_d}\left\{1 - \frac{p_{w0}}{p_0^*}\left(\frac{M_w - M_d}{M_d}\right)\right\}}\right), \qquad (5)$$

$$p_{i+1}^* = p_{i-1}^* \exp\left(\frac{(z_{GPS\,i+1} - z_{GPS\,i-1})}{\frac{-R^*T_i}{g_i M_d}\left\{1 - \frac{p_{wi}}{p_i^*}\left(\frac{M_w - M_d}{M_d}\right)\right\}}\right) \qquad (i \geq 1). \qquad (6)$$

Here p_0^* is empirically determined as a common value for all nighttime soundings by minimizing the mean squared difference $\delta p_i \equiv p_i - p_i^*$ in the whole observation range. The initial level ($i = 0$) is chosen to that at 70 s after the launch as noted in Section 2. The last 60 s before the balloon burst do not give values of δp due to the lack of smoothing data for 60 s. In this way, the value of 0.71 hPa is obtained as δp_0 for the values of p_0^* ranging from 955.37 to 970.50 hPa.

Figure 3 shows the vertical profiles of the mean pressure biases expressed in δp and $\delta p/p$ estimated from four nighttime observations. The pressure biases are found to be positive below ~7 km but negative above it. They are statistically significant only above 15 km. The percentage pressure biases grow up in stratosphere as the air pressure decreases exponentially with altitude (Fig. 3b). The pressure biases, may possibly be attributable to the temperature dependency of the pressure sensor (Skrivankova 2004), agree qualitatively well with those from previous studies by Steinbrecht et al. (2008), who indicated no day-night difference in them. The biases thus estimated are used to correct the daytime as well as the nighttime pressure data under the assumption that there is no distinction between the two.

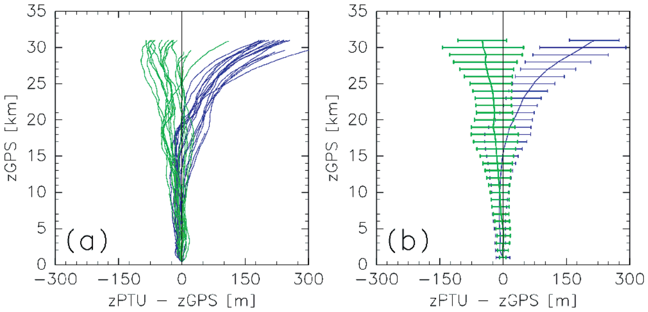

Fig. 4. Same as Fig. 2 but for seventeen daytime observations.

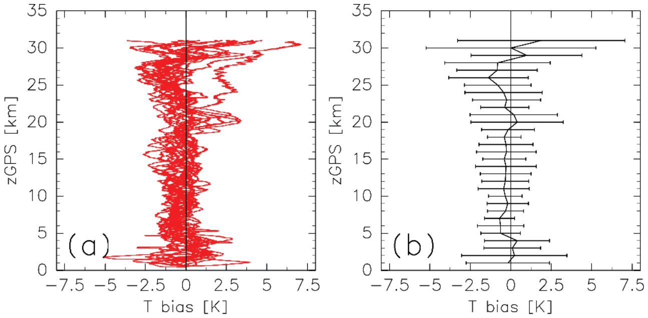

Fig. 5. Temperature bias for (a) individual observations and (b) the mean superposed by the 95% confidence intervals estimated from seventeen daytime observations.

3.2 Temperature data

When the observed pressure is adjusted by subtracting the pressure biases estimated in Section 3.1, the difference between z_{PTU} recalculated by using the adjusted pressure and z_{GPS} is largely eliminated in a statistical sense as seen from the green lines in Fig. 2. However, there may remain some residue in the daytime data when the same adjustment procedure is applied. The remaining systematic differences mainly result from systematic errors in daytime temperature observations arising from inaccurate radiation correction.

Figure 4 illustrates the vertical profiles similar to those in Fig. 2 but for those from daytime soundings. In order to assure the homogeneity of analyzed data, those profiles that exhibit large deviations exceeding the significance level of 0.01 from the population mean are rejected. The general features are not much different from those for the night. The mean profile based on adjusted pressures (green curve in Fig. 4b), however, indicates a slight negative shift with increasing altitude indicating that the daytime temperature is observed a little too low. Under the assumption that these differences are attributable only to the daytime temperature bias, the adjusted temperature T_i^* could be calculated from the observed p_w, z_{GPS} and adjusted pressure p^* by using the finite difference form of Eq. (4):

$$T_i^* = \frac{(z_{GPS\,i+1} - z_{GPS\,i-1})}{\frac{-R^*}{g_i M_d}\left\{1 - \frac{p_{wi}}{p_i^*}\left(\frac{M_w - M_d}{M_d}\right)\right\}\ln\left(\frac{p_{i+1}^*}{p_{i-1}^*}\right)}. \qquad (7)$$

Figure 5 shows the vertical profiles of the deviations of the observed temperature T from the adjusted temperature T^*, namely the daytime temperature bias in RS80, smoothed by applying ±60 s running mean. As seen from Fig. 5a, individual profiles of $\delta T \equiv T - T^*$ exhibit fluctuations too large to detect possible cold bias in the observed temperature (Fig. 5b). Previous studies have shown that the temperature bias in RS80 radiosonde system is negative and that it increases monotonously in the stratosphere (e.g., Steinbrecht et al. 2008). The temperature bias between the operational dataset and that adjusted by Luers and Eskridge (1998) reaches about −1.0 K at 10 hPa and about −0.25 K at 100 hPa. Unfortunately our method proposed here does not have enough sensitivity to confirm such biases, although gross features appear quite similar to those by previous studies.

4. Concluding remarks

The biases in the RS80 pressure and temperature measurements are estimated by using the simultaneous GPS height data during the SOWER campaigns 2004–2009. The humidity data by the RS80 Humicap are assumed to cause no noticeable error in the estimation of ellipsoidal height (z_{PTU}) estimated by integrating the hypsometric equation in which the latitude- and altitude-dependency of the gravity is taken into account. The temperature biases, dominated by inaccurate radiation correction, are considered only for the daytime data. The pressure biases are estimated by comparing z_{PTU} and GPS ellipsoidal height (z_{GPS}) in the nighttime data. The results are used to correct pressure data from daytime as well as nighttime soundings. The temperature biases during the day are estimated from the comparison between the pressure-corrected z_{PTU} and z_{GPS}. In summary, the pressure biases are found to be positive below ~7 km and negative above it with the values up to about −0.5 hPa above ~20 km. They are statistically significant above 15 km. Our method, however, does not have enough sensitivity to detect the daytime temperature bias.

In the SOWER campaigns, the humidity is observed by both the RS80 Humicap and the CFH. The value of z_{PTU} is virtually unaffected by the water vapor amount in the upper troposphere and above because these regions are extremely dry. While the Humicap cannot measure p_w in the stratosphere as the CFH does (Vömel et al. 2007a, 2007b), it provides reliable and accurate enough data in the water-rich lower troposphere. Thus almost the same results are obtained from the analysis when the CFH data are used in place of the Humicap.

As seen from Fig. 2, the nighttime data are quite stable to give good estimates for the biases $z_{\mathrm{PTU}} - z_{\mathrm{GPS}}$. However, the accumulation of the nighttime data is preferable to improve the reliability of the results. In addition, the pressure bias on the ground, if known by the ground checks, may have served to infer δp_0 on each sounding basis rather than a common value for all data.

It is interesting to estimate how the potential temperature is affected by the biases identified in this study as the isentropic coordinates are often used in the meteorological analyses. Our results may be converted to the biases of about 0.28, 0.38 and 0.49 K in the potential temperature at about 15, 16 and 17 km, respectively, in the tropics.

The current radiosonde systems are usually equipped with the GPS for wind and sometimes pressure observations. The method proposed in the present analysis may serve to correct the radiosonde data because it could be applicable to a set of radiosonde observations without relying on simultaneous reference observations. It is our hope that this technique could be used to improve the reliability of the radiosonde data for all purposes.

Acknowledgments

The authors are grateful to SOWER colleagues, M. Shiotani, H. Vömel, S.-Y. Ogino, S. Iwasaki, N. Nishi and T. Shibata in particular, for their collaborations. We are also thankful to the members of Lembaga Penerbangan dan Antariksa Nasional (LAPAN) of Indonesia, the Meteorological Offices of Tarawa, Kiribati and Ha Noi, Viet Nam. This work was supported by KAKENHI (15204043 and 18204041) and Global Environment Research Fund of the Ministry of the Environment (A-1 and A-071). The figures were produced by Dennou Library. Comments from two anonymous reviewers helped to improve the manuscript.

References

Fleagle, R. G., and J. A. Businger, 1980: *An Introduction to Atmospheric Physics*. Academic Press, 432 pp.

Goff, J. A., and S. Gratch, 1946: Low-pressure properties of water from −160° to 212°F. *Trans. Amer. Soc. Heat. Vent. Eng.*, **52**, 95–121.

Haimberger, L., C. Tavolato, and S. Sperka, 2008: Toward elimination of the warm bias in historic radiosonde temperature records–Some new results from a comprehensive intercomparison of upper-air data. *J. Climate*, **21**, 4587–4606.

Hasebe, F., M. Fujiwara, N. Nishi, M. Shiotani, H. Vömel, S. Oltmans, H. Takashima, S. Saraspriya, N. Komala, and Y. Inai, 2007: In situ observations of dehydrated air parcels advected horizontally in the Tropical Tropopause Layer of the western Pacific. *Atmos. Chem. Phys.*, **7**, 803–813.

Luers, J. K., and R. E. Eskridge, 1998: Use of radiosonde temperature data in climate studies. *J. Climate*, **11**, 1002–1019.

Nash, J., R. Smout, T. Oakley, B. Pathack, and S. Kurnosenko, 2006: WMO intercomparison of radiosonde systems, Vacoas, Mauritius, 2–25 February 2005. WMO/TD-No. 1303, 115 pp.

Skrivankova, P., 2004: Vaisala radiosonde RS92 validation trial at Prague-Libus. *Vaisala News*, **164**, 4–8.

Steinbrecht, W., H. Claude, F. Schönenborn, U. Leiterer, H. Dier, and E. Lanzinger, 2008: Pressure and temperature differences between Vaisala RS80 and RS92 radiosonde systems. *J. Atmos. Oceanic Technol.*, **25**, 909–927.

Vömel, H., D. David, and K. Smith, 2007a: Accuracy of tropospheric and stratospheric water vapor measurements by the Cryogenic Frost point Hygrometer (CFH): Instrumental details and observations. *J. Geophys. Res.*, **112**, D08305, doi: 10.1029/2006JD007224.

Vömel, H., V. Yushkov, S. Khaykin, L. Korshunov, E. Kyrö, and R. Kivi, 2007b: Intercomparisons of stratospheric water vapor sensors: FLASH-B and NOAA/CMDL frost-point hygrometer. *J. Atmos. Oceanic Technol.*, **24**, 941–952.

Yoneyama, K., M. Fujita, N. Sato, M, Fujiwara, Y. Inai, and F. Hasebe, 2008: Correction for radiation day bias found in RS92 radiosonde data during the MISMO field experiment. *SOLA*, **4**, 13–16.

Manuscript received 26 April 2009, accepted 5 July 2009
SOLA: http://www.jstage.jst.go.jp/browse/sola/