Preliminary Correction of Vaisala Radiosonde Humidity Measurements for Slow Sensor Time-Response at Cold Temperatures

L. M. Miloshevich and A. J. Heymsfield
National Center for Atmospheric Research
Boulder, Colorado

A. Paukkunen
Vaisala Oy
Helsinki, Finland

Introduction

The goal of this study is to improve the accuracy of relative humidity (RH) measurements from Vaisala radiosondes, especially in the upper troposphere (UT), by correcting measurement error that results from slow time-response of the RH sensor at cold temperatures. Accurate water vapor profiles are important for such applications as input to radiative transfer algorithms, calibration, or evaluation of remote-sensor water vapor retrievals, initializing numerical models, and improving parameterizations of cloud processes. Inaccurate measurement of water vapor profiles has been shown by Atmospheric Radiation Measurement (ARM) Program studies to be the primary limitation to improving clear-sky radiative transfer models (e.g., Clough et al. 1999). Although water vapor concentrations are much less in the UT than at lower levels, atmospheric cooling rates in the UT due to water vapor exceed those in the mid troposphere due to the very strong contribution by the wave number range 250 cm^{-1} to 350 cm^{-1} (Clough et al. 1992). RH measurements from Vaisala RS80-H radiosondes are heavily relied upon by ARM to characterize the water vapor profile in the UT, because other means such as Raman Lidar or Differential Absorption Lidar have accuracy and/or vertical resolution limitations in the UT (see Turner et al. 2000).

The accuracy of ARM radiosonde RH measurements has recently been improved by correcting for several sources of measurement error (Lesht 1999); however, the RH measurements in the UT may still be substantially inaccurate under certain conditions because the RH sensor responds very slowly to changes in the ambient RH at cold temperatures (Miloshevich et al. 2001). The time constant (63% response time) of the RS80-H humidity sensor exceeds 1 min below –50°C and 2 min below –60°C, leading to a “time-lag error” whose magnitude increases with decreasing temperature and with increasing ambient humidity (U_a) gradient. This study uses Vaisala laboratory measurements of the temperature-dependent time constant, $\tau(T)$, to develop a numerical model of the sensor’s response to a changing U_a field, which is the basis of a correction algorithm for time-lag error.

Mathematical Model of Humidity Sensor Response

Vaisala humidity sensors are shown below to respond to changes in the U_a according to the common "growth-law" equation, where the instantaneous rate of change of the measured humidity (U_m) is given by: $dU_m/dt \propto U_a(t) - U_m(t)$. If the timestep is short enough that U_a can be treated as a constant, then the solution of the growth-law equation gives the sensor response: $U_m(t)=U_a - [U_a - U_m(t_0)]\cdot\exp[-\Delta t/\tau(T)]$, where $\Delta t=t-t_0$ is the length of the timestep.

The Vaisala time-constant measurements consist of high-rate sampling of the U_m in response to a step-change in the U_a. Both τ and the 90% response time (τ_{90}) were determined over a wide temperature range, where the growth-law equation dictates that the ratio τ_{90}/τ should be 2.3. This ratio from the Vaisala data is indeed equal to 2.3 within the experimental uncertainty, indicating that RS80 humidity sensors respond exponentially as expected, and the growth-law equation is therefore a valid basis for the sensor response model. Example calculations of the RS80-H response to an increase in the U_a are shown in Figure 1, based on the Vaisala time-constant measurements. Time-lag error (measured RH minus ambient RH) increases substantially with decreasing temperature, especially below –40°C, and depends strongly on the U_a gradient.

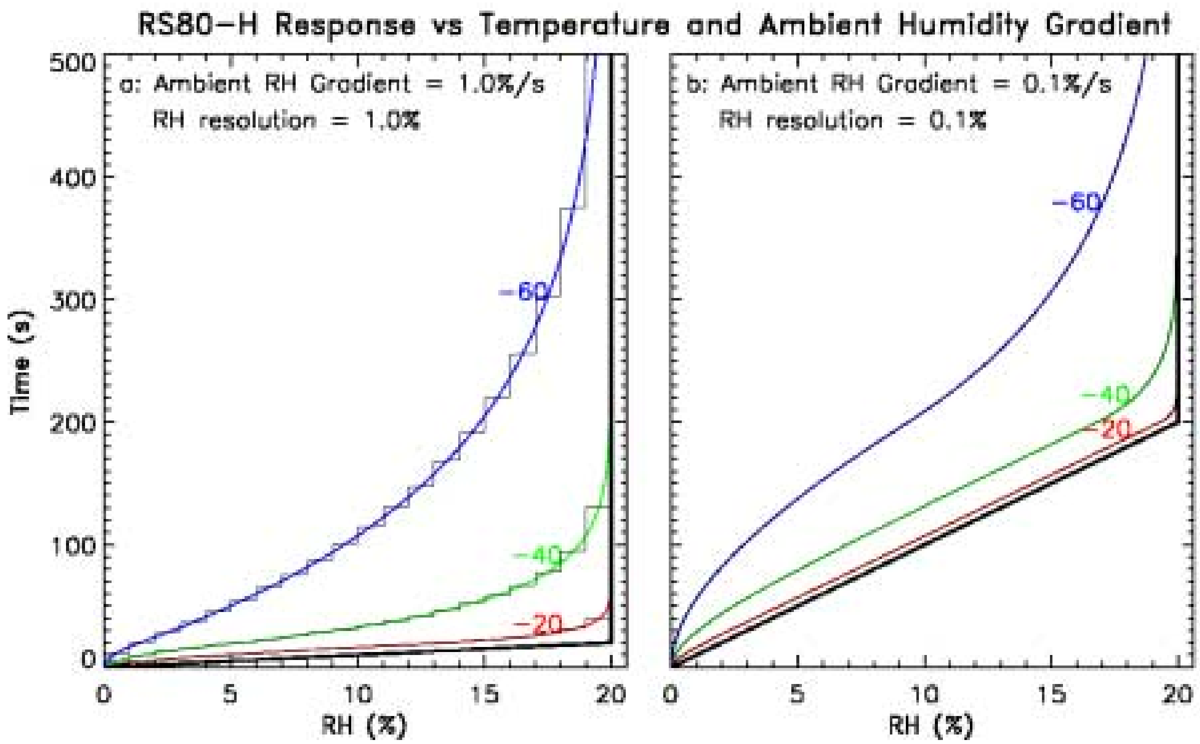

Figure 1. Simulated RS80-H response (colored curves) to a 20% RH linear increase in U_a (thick black curve), at three different temperatures (°C). Panel (a) shows a relatively steep U_a gradient, and Panel (b) a more moderate U_a gradient. The light black lines show the U_m if the resolution of the data was either 1% RH like the ARM data (Panel a), or 0.1% RH like certain other data systems (Panel b). The 500 s time period corresponds to 2.5 km of radiosonde ascent.

Preliminary Correction Algorithm

The essence of the time-lag correction involves solving the sensor response equation for U_a in terms of U_m and applying the inverse of the calculation used to construct Figure 1, where the U_a curve can be precisely recovered from any of the three U_m curves. Unfortunately it is not so simple when one considers real data, because real data contain noise, have finite resolution, and have usually been filtered or processed in some way. The jagged lines in Figure 1a simulate the 1% RH resolution and 2 s sample period of the ARM data, which is a highly non-physical set of measurements. Direct application of this physically based correction algorithm to the ARM data would yield large spikes whenever the humidity changes abruptly by 1% RH. It is therefore necessary to first modify the measurements to be physically reasonable (i.e., continuous and smoothly varying), while maintaining consistency with the original data to within the measurement resolution. In contrast, the 0.1% RH resolution shown in Figure 1b is barely distinguishable from the exact U_m curves, and experience shows that greater resolution simplifies the correction technique and allows recovery of a greater amount of detailed structure in the U_a profile.

The smoothing of data within specified limits is somewhat of a gray area in numerical analysis. The smoothing approach we have developed is to first select the data point in the center of each constant-RH period to represent that period, and assign it an "uncertainty" that is some fraction of the measurement resolution. Each of the selected data points is then allowed to move within its uncertainty limits such that the third derivative is minimized. Finally, new points are successively added between the smoothed points based on the same derivative-minimizing approach, until the original 2 s time series is recovered. The result is a relatively smooth set of measurements that is consistent with the original data within the specified limits.

Results from the preliminary correction algorithm are illustrated in Figure 2, applied to somewhat of a difficult case in that the algorithm must identify and handle both "missing data" (e.g., 10.2 km to 11.1 km) and "bad data" (15.1 km). The corrected profile (red) appears slightly rough in places because it is plotted in terms of a derived variable, altitude, instead of the fundamental independent variable, time. The following observations are based on Figure 2:

- Time-lag error is generally negligible in the lower troposphere, and is minimal in the mid troposphere unless the U_a gradient is steep (9.3 km). The time-lag error can be substantial in the UT even if the U_a gradient is moderate.

- The vertical scale over which time-lag error smoothes the profile increases with decreasing temperature, and can be several kilometers at the tropopause.

- The occurrence of a cirrus layer at the tropopause with dry air above and below is very common. Maximum time-lag errors exceeding 20% RH are typical in these situations. RH measurements are probably systematically overestimated for several kilometers above the tropopause.

- The overall implications of time-lag error for climate studies and radiative transfer calculations remains unclear until statistical analysis of a large dataset is performed. Time-lag error may be either positive or negative at a given temperature depending on the RH structure of a particular profile. In general, time-lag error is probably of greater importance to applications concerned with individual profiles than with statistical trends or climatologies. However, a statistical trend with temperature will exist if there are consistent trends in the atmospheric RH structure, such as the common occurrence of a cirrus layer just below the tropopause.

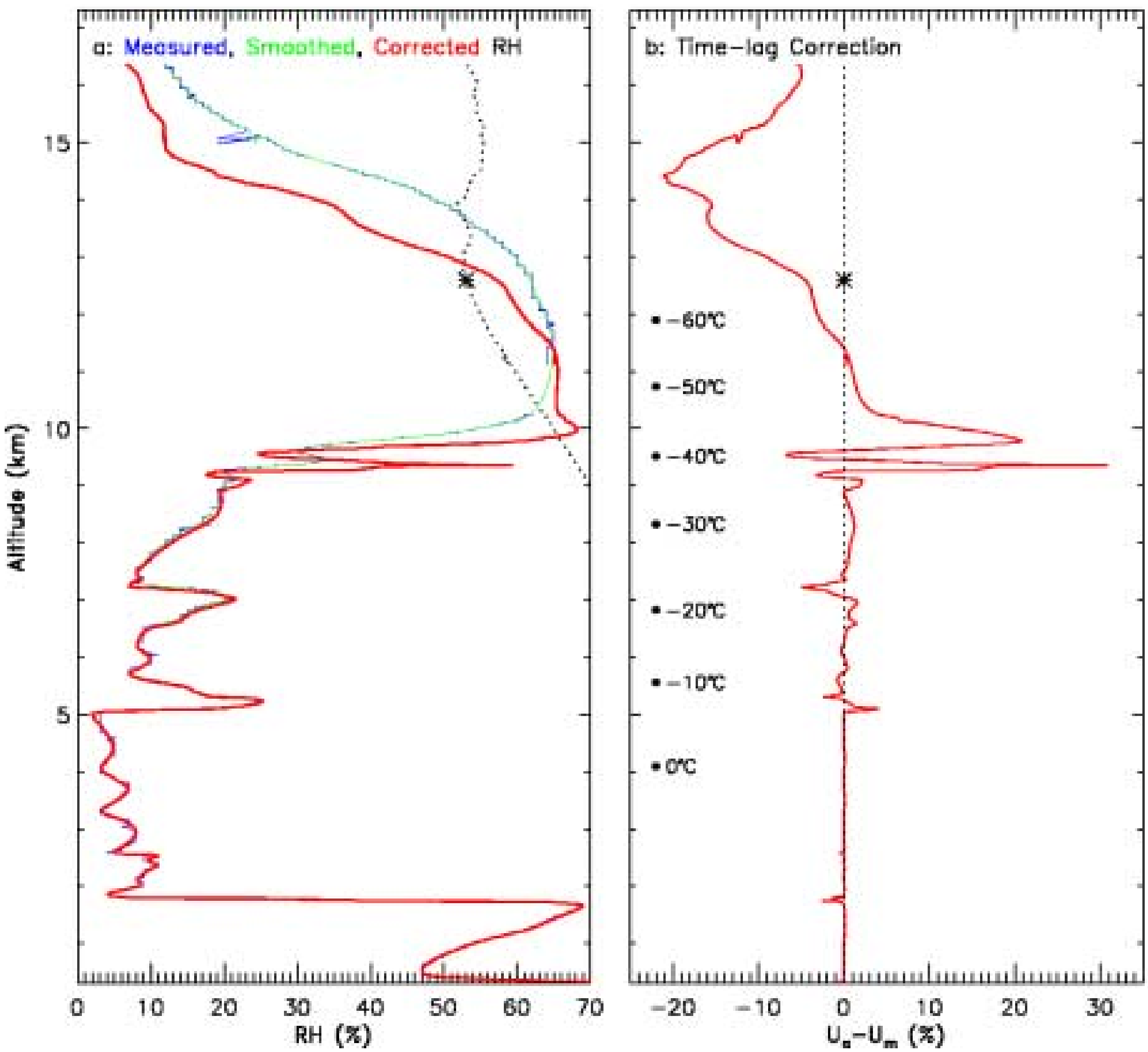

Figure 2. (Panel a) Correction of ARM RS80-H humidity data for time-lag error. Curves are: Original measurements (blue), smoothed measurements (green), corrected profile (red), and ice-saturation (dashed). (Panel b) The amount of time-lag correction, which is equal to the difference between the corrected measurements and the smoothed original measurements (U_a-U_m). The tropopause is indicated with an asterisk.

Corresponding Author

L. M. Miloshevich, milo@ncar.ucar.edu, (303) 497-8963.

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