Correction for Dry Bias in Vaisala Radiosonde RH Data

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Abstract

Extensive data analysis of sounding data from the Tropical Ocean Global Atmosphere-Coupled Ocean Atmosphere Response Experiment (TOGA-COARE) and other research projects coupled with supporting evidence from other sources have lead to the conclusion that there is a dry bias in Vaisala radiosonde relative humidity (RH) measurements. This dry bias occurs in both the A-type and H-type radiosonde RH sensors. Convinced of the problem, Vaisala engineers conducted extensive chamber tests on Vaisala sondes of varying age. Vaisala determined that the dry bias was due to contamination of the polymer used as the dielectric material in the capacitive RH sensor (humicap). They further demonstrated that the contamination comes from the packaging material and from plastic and Styrofoam material from which the sonde is made. They suspect that hydrocarbons out-gas from the plastic materials and compete with water vapor for bonding sites in the humicap polymer. This would then reduce the area of the polymer available for water vapor, resulting in a reduction in the measured RH (dry bias). This dry bias due to contamination was found to be a function of both sensor (sonde) age and measured RH. The dry bias in the H-type sensor was found to be greater (on the order of 8% at 80% RH after 1.5 years) than that in the A-type sensor (on the order of 5% at 80% RH after 4 to 5 years).

Introduction

Anomalous behavior in the dew point trace on many sounding skew-T plots from TOGA-COARE raised concern regarding the radiosonde relative humidity measurement. A large jump was seen in the dew point data (obtained from the radiosonde temperature and relative humidity measurement) from the surface to the near-surface boundary layer or mixed layer. (The surface point in the plots examined came from a surface sensor independent of the radiosonde.)

Sensor Arm Heating Induced Error

At first, this problem was thought to be entirely caused by the heating of the radiosonde sensor arm prior to launch, because an elevated temperature of that sensor arm would cause an erroneously low RH measurement. The measured vapor pressure would be referenced to a saturation vapor pressure that is too high (heated sensor arm) resulting in a lowered RH measurement.

The effect of this sensor arm heating on RH measurement persists through the first forty to sixty seconds (200 meters to 300 meters) of the sounding, diminishing with time (height) as the radiosonde ascends and the sensor arm comes to thermal equilibrium with the environment. The thermal time constant of the sensor arm is about 13 seconds. This sensor arm heating also affects the radiosonde temperature measurement, but that is short lived. The temperature sensor, mounted on a small diameter wire, comes into thermal equilibrium with the environment extremely quickly.

A correction for sensor arm heating (Cole and Miller 1995) was developed at the National Center for Atmospheric Research (NCAR) and applied to the daytime soundings at all NCAR sounding sites in TOGA-COARE. This correction assumed that the total difference in RH seen between the radiosonde RH prior to launch and the RH value measured at the surface meteorological station was due to sensor arm heating. This was an erroneous assumption. The difference seen at the surface before launch was actually the sum of the sensor arm heating induced error and a radiosonde dry bias error. As it turns out, the effect of sensor arm heating accounts for only a small part of the radiosonde RH measurement problem (dry bias) seen in TOGA-COARE and other sounding data, as it impacts only the lowest portion of the sounding.

Dry Bias Error

After implementation of the sensor arm heating correction, the sounding data still exhibited clear indications of a dry bias in the RH measurement as several investigators have pointed out (Zipser and Johnson 1998). A number of indicators of such a dry bias were indeed apparent in the TOGA-COARE sounding data set. Portions of skew-T plots where cloud penetrations were very likely did not show saturation (dew point temperature equal to ambient temperature). Analysis of all sounding RH data (individual ten-second data points) at several of the tropical sites showed no RH values greater than 96% (i.e., no saturation, no cloud penetrations). Overall the values of convective available potential energy (CAPE) calculated from the soundings were much lower than expected, low enough that little convection initiation would result if they were correct. In addition, high values of convective inhibition (CIN) were associated with these lowered CAPE values. Finally, the difference expected in the mixing ratio between the surface (determined from sensors independent of the radiosonde sensors) and the mixed layer was much greater than that indicated from theory and other observations (aircraft soundings using chilled-mirror dew point sensors).

Numerous skew-T plots showed an indication that the radiosonde penetrated a cloud. In those cases, no saturation was seen. Typically, where there is cloud penetration, the temperature trace on the skew-T plot is very nearly moist adiabatic and the dew point temperature trace parallels or overlays the temperature trace, with the dew point temperatures very near or equal to the ambient temperature values. In the cases indicating a radiosonde RH measurement dry bias, the dew point temperature trace parallels the temperature trace but the dew point temperature values are lower by two or more degrees. The associated RH values are on the order of 90% to 95%.

Examination of point-by-point sounding RH values also reveals an indication of a radiosonde RH measurement dry bias. At most of the NCAR sites, RH data showed no values greater than roughly 96% over the entire intensive observation period (IOP). One would expect to see a significant number of occurrences of RH measurement near or equal to 100% in soundings taken at a site in the equatorial western Pacific. It is highly unlikely that not a single radiosonde penetrated a wet cloud (temperature greater than 0 °C) through the four-month IOP.

CAPE values calculated for each of the soundings (whether corrected for sensor arm heating or not) also indicate a possible dry bias in the radiosonde RH measurement. The CAPE values are calculated using the lowest (near-surface) 50 mb of temperature and dew point data. A large percentage (on the order of 50% or more) of the CAPE values fall below a value of 800 J/kg. (Figure 1a shows a histogram of uncorrected sounding CAPE values obtained from the three cruises of the Moana Wave.) These values are significantly lower than expected and would preclude the likelihood of convection initiation if they were correct. The CAPE values from these soundings would lead one to speculate that it would be difficult to initiate convection over the TOGA-COARE region. Results from studies of mesoscale convective systems during TOGA-COARE (LeMone et al. 1998) indicate that higher CAPE values would be expected. In that study, an aircraft study in the vicinity of 20 convective systems, CAPE values were observed between 812 J/kg and 1925 J/kg.

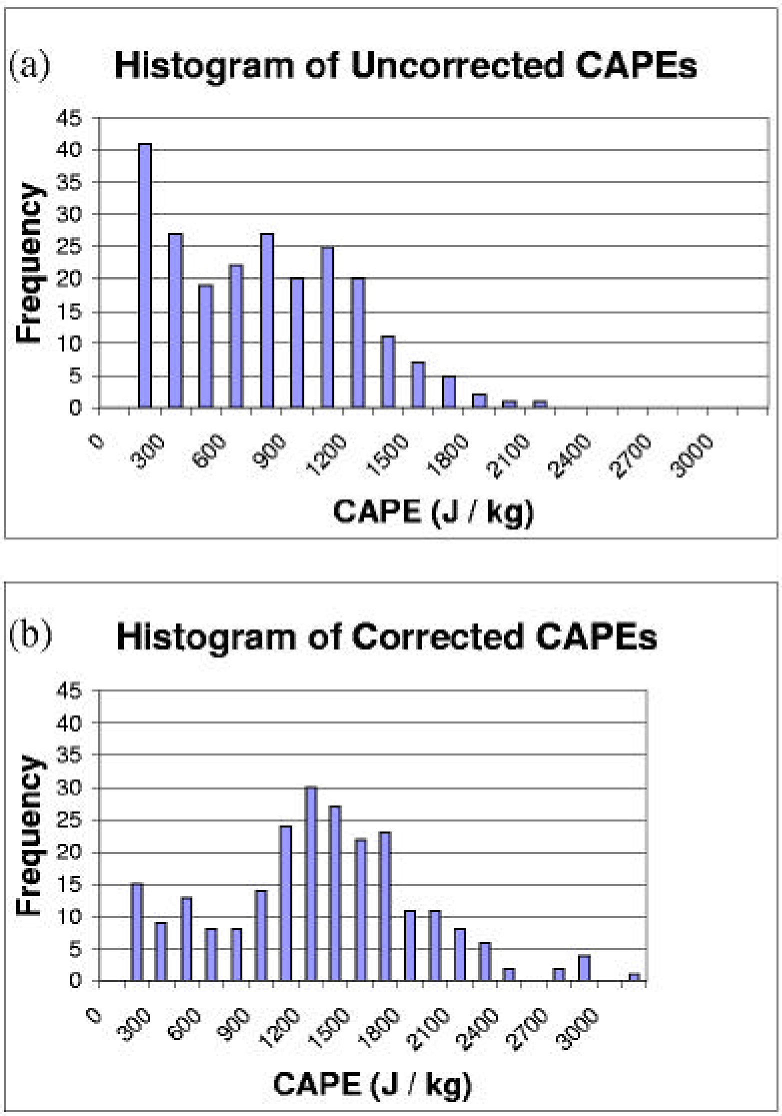

Figure 1. Histogram of (a) uncorrected and (b) corrected CAPE values.

The likelihood of convection would also be low if the large values of CIN seen in these soundings were correct. Analysis of corrected and uncorrected Moana Wave sounding data (Guichard et al. 1999) shows that a large percentage of the uncorrected soundings had CIN values of a magnitude such that if all the kinetic energy required to overcome the convective inhibition were to be supplied by vertical motion, unrealistically large vertical velocities would be required to initiate or maintain convection. (Figure 2a shows a histogram of uncorrected sounding CIN values obtained from the three cruises of the Moana Wave.)

Another indicator of the dry bias in the RH measurement is the difference between the surface mixing ratio value and that of the mixed layer above the surface, the surface mixing ratio being determined from sensors independent of the radiosonde. Typically, differences of 2.0 g/kg to 3.0 g/kg were observed in the uncorrected soundings. The Monin-Obukhov similarity theory would predict those differences to be more on the order of 1.0 g/kg to 1.25 g/kg for the prevalent conditions in a well-mixed tropical maritime boundary layer.

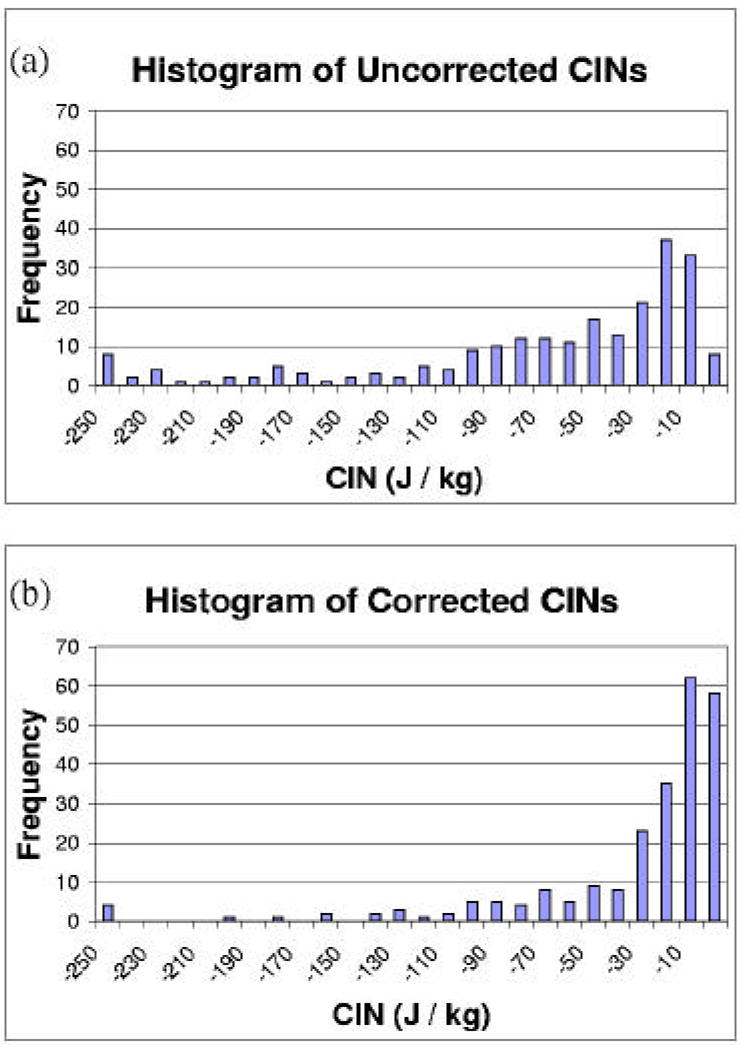

Figure 2. Histogram of (a) uncorrected and (b) corrected CIN values.

In addition, data from aircraft soundings support the possible dry bias in the radiosonde RH data. When there were reasonable comparisons available between the radiosonde data and an aircraft sounding into the mixed layer, the aircraft RH values were systematically higher than the radiosonde RH values. The aircraft mixing ratio values in the mixed layer were also more in line with the expectations from theory. The aircraft uses a chilled mirror dew point sensor that was calibrated before and after the project.

Direct comparison of surface station RH values to radiosonde RH values before launch also indicates a possible dry bias in the radiosonde RH measurement, particularly when examining nighttime data (no sensor arm heating). Such comparisons of daytime data involve both the possible or suspected dry bias component and the sensor arm heating component.

Indeed those direct comparisons of RH data from each radiosonde prior to launch to that from the surface meteorological station RH sensor were used in the subsequent dry bias error correction scheme. Such comparisons revealed considerable variability in the dry bias from one radiosonde to another.

In the daytime soundings where the measured RH difference at the surface was the combination of both dry bias error and sensor arm heating error, estimates of the error due to sensor arm heating were made using the radiosonde temperature measurement before launch. The dry bias error was then determined from the difference of the overall surface RH difference minus the estimated sensor arm heating error component.

Dry Bias Determination

Vaisala engineers conducted an extensive testing program on numerous radiosondes of varying age to determine the nature and extent of the perceived dry bias. Both A-type polymer and H-type polymer RH sensor radiosondes were evaluated. The testing program verified that a dry bias did indeed exist in the RH measurement. The cause and magnitude of the dry bias were also determined.

The tests revealed that the dry bias was caused by contamination of the polymer used as the dielectric in the capacitive RH sensor (humicap). The testing indicated that the contamination came from the radiosonde packaging material as well as the plastic and Styrofoam materials used in the construction of the radiosonde itself. The effect of the contamination was also seen to increase with radiosonde age. It is thought that hydrocarbons off-gas from the plastic and Styrofoam materials and tie up bonding sites on the polymer, reducing the area or number of sites available to water vapor.

The Vaisala radiosonde RH sensor is a “humicap” sensor that contains either an A-type polymer or an H-type polymer dielectric material. The H-type polymer is more sensitive to water vapor and, as might be expected, more sensitive to contamination as well. The magnitude of the dry bias error due to contamination is significantly greater in the H-type polymer RH sensor than in the A-type polymer sensor.

The dry bias error is a function of both radiosonde age and measured RH. In both the A-type and H-type RH sensor radiosondes, the dry bias due to contamination is seen to increase with sensor age to a more or less maximum limit. In the case of the H-type RH sensor, that limit is reached in a period of two years or less. In the A-type RH sensor, it takes up to five years or more for the effect of contamination to reach its maximum limit. A maximum dry bias error due to contamination for the H-type RH sensor is roughly 8% to 10% RH at measured RH values of 80% and above. For the A-type RH sensor that maximum dry bias error is slightly greater than 5% at measured RH values between 70% and 80%.

Correction Algorithm

The testing program provided ample data to generate a correction scheme. A correction algorithm that is a function of both radiosonde age and measured RH was generated. That algorithm, along with a known radiosonde age, will give the dry bias correction. Alternatively, if the age is unknown, the algorithm can be modified to use an independent reference RH measurement to determine the dry bias error. The age for a Vaisala radiosonde can be obtained from the date of manufacture encoded in the serial number of that radiosonde.

Soundings taken with H-type RH sensor radiosondes at NCAR Atmospheric Technology Division (ATD) sites during TOGA-COARE have been corrected using the algorithm generated by Vaisala. Age information was not available for those soundings so an independent reference RH measurement at the surface before launch was used instead. That reference RH was compared to the radiosonde RH before launch and used in the modified algorithm. This procedure has an advantage in that it takes into account any sonde-to-sonde contamination variation. Indeed the use of an independent surface RH reference (TOGA-COARE H sonde corrections) in the correction has revealed dry bias values greater than those indicated by the Vaisala testing program.

In the effort to characterize the dry bias error, the Vaisala testing program provided additional information that improves the radiosonde RH data. As a spin off of the testing effort, improved temperature dependence information associated with the RH measurement calibration was obtained. This resulted in improved RH values at colder temperatures (less than –20 °C) for both the A-type and H-type RH sensors. Vaisala also included a recent calibration improvement that eliminates a small moist bias that was present at very high humidity.

Results of the Correction

A modified correction algorithm, using an independent surface RH measurement as a reference, has been successfully applied to the NCAR H-type RH sensor sounding data set from TOGA-COARE. Preliminary investigations indicate that the correction results are promising. Analysis of uncorrected and corrected Moana Wave soundings during the TOGA-COARE intensive operating period by Guichard et al. (1999) quantifies the effects of the dry bias correction and provides some confidence that the correction is reasonable. Analysis of corrected NCAR sounding data shows improvement in all the areas of concern detailed in the previous section.

Evaluation of skew-T plots and individual data points from corrected soundings shows that the correction is exhibiting positive results. In portions of various soundings where cloud penetration is likely, the skew-T plots and data values show reasonable results, i.e., saturation at temperatures greater than 0 °C. An example of a corrected H-type RH sensor sounding is shown in Figure 3. This skew-T plot shows both uncorrected and corrected dew point traces. Note that there is a probable cloud penetration between 750 mb and 800 mb. The corrected dew point trace shows saturation through this portion of the sounding with individual RH values reaching 100% RH. A second cloud penetration is likely near 550 mb. The corrected dew point trace shows near saturation with respect to ice between -2 °C and -5 °C. (Saturation with respect to ice at -3.2 °C equates to 97% RH with respect to water. The corrected sounding RH, calibrated with respect to water, is 96.1% at -3.2 °C.)

The calculated CAPE and CIN values for the uncorrected soundings would lead one to conclude that the TOGA-COARE region was generally stable and that initiation of convection would be unlikely. This is not what is expected in this region. After correction, the calculated CAPE and CIN values are more in line with expectations based on other efforts and studies. The majority (70% or more) of the corrected sounding CAPE values range from 800 J/kg to 2500 J/kg. (Figure 1b shows CAPE values calculated from corrected soundings from the Moana Wave.) These results are much more in line with the results of LeMone et al. (1998) in aircraft studies of mesoscale tropical convection. In the example skew-T plot presented in Figure 3, the CAPE value calculated from the uncorrected dew point trace is 692 J/kg, while the CAPE value calculated from the corrected dew point trace is 1695 J/kg.

After correction, the majority of the sounding CIN values are of such a magnitude that the energy (related to vertical velocity) required to initiate and maintain convection is not an unrealistically large quantity. A histogram of corrected CIN values from the three cruises of the Moana Wave is presented in Figure 2b. Given the values of both CAPE and CIN from the corrected soundings, one would correctly conclude that the region was generally unstable to convection.

The corrected TOGA-COARE soundings also show a more reasonable moisture profile near the surface and up through the mixed layer. There is no longer a noticeable jump in moisture from the surface (independent RH sensor) to the low level sounding data. The differences in mixing ratio observed between the surface and the mixed layer for these corrected soundings are more consistent with what might be expected from theory for a maritime tropical environment. These differences range from 0.0 g/kg to 2.0 g/kg with the mean value of that difference very close to 1.0 g/kg in the corrected sounding data set.

Conclusions

The testing program conducted by Vaisala has conclusively verified the suspected Vaisala radiosonde RH measurement dry bias. That dry bias is present in both the A-type and the H-type RH sensor radiosonde. The dry bias is significantly greater in the H-type RH sensor radiosonde. This is not unexpected because the H-type polymer is more sensitive to water vapor and hence probably more susceptible to contamination.

The magnitude of the contamination-induced dry bias is not only greater in the H-type RH sensor, it also increases at a significantly faster rate. A dry bias as high as 6% RH may be seen from the H-type sensor at high RH values (greater than 80%) after only six months. Laboratory testing by Vaisala indicates that the dry bias has reached its maximum (8% to 10% RH) in the H-type sensor after only eighteen months. At eighteen months, the dry bias in the A-type sensors tested reached 3.5% RH.

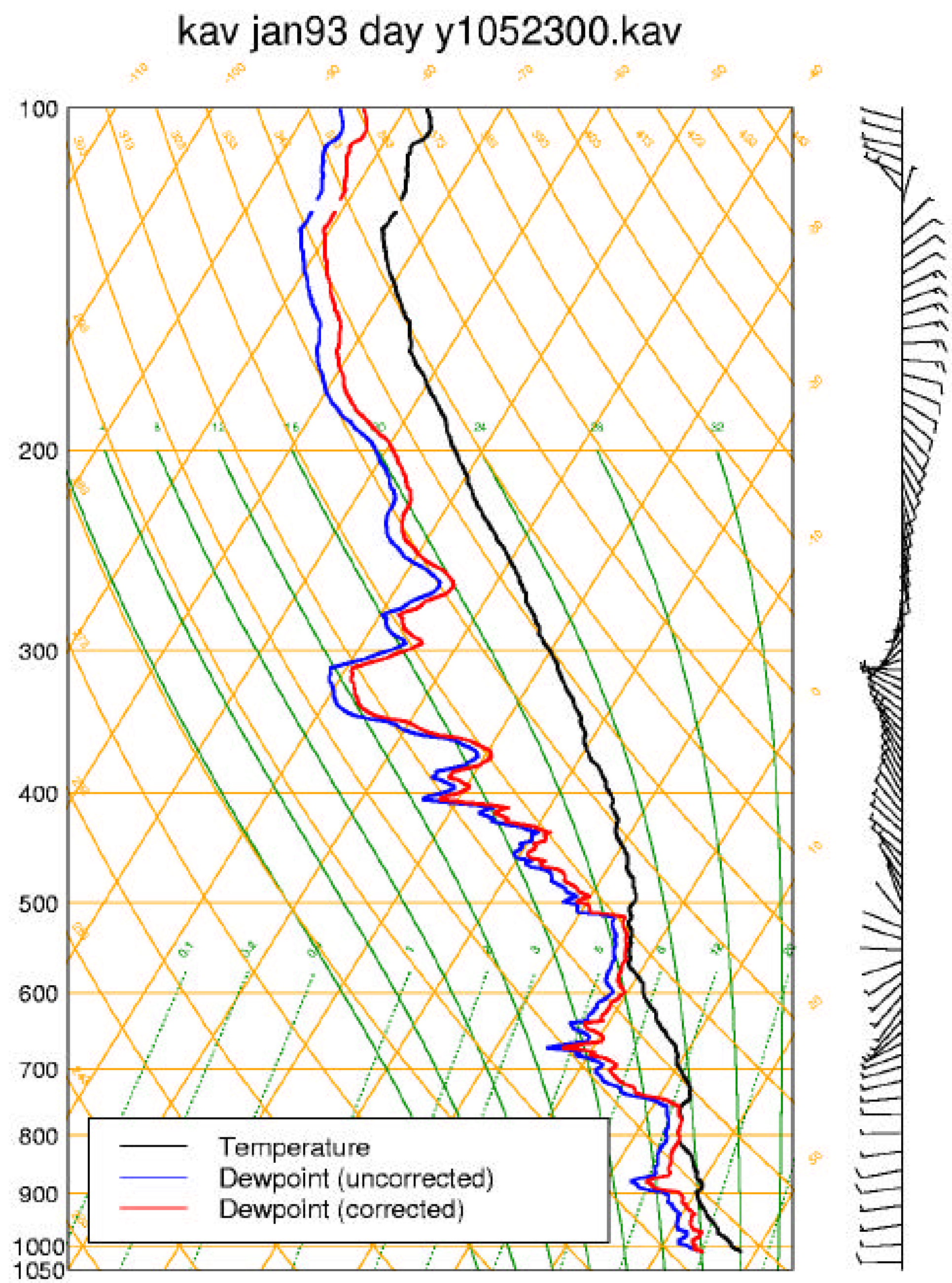

Figure 3. Skew-T plot showing both uncorrected and corrected dew point trace.

Vaisala and NCAR ATD have generated and perfected a correction algorithm that has given very satisfactory results when applied to H-type RH sensor radiosonde data from the NCAR TOGA-COARE sounding data set. Analysis of the corrected H-type sonde sounding data set provides confidence in the correction applied and underscores the significance of the dry bias.

The H-type RH sensor radiosonde was introduced in the early 1990s. For the most part, its distribution has been limited to North America. Vaisala is acutely aware of this problem and is currently working to mitigate it. One step already introduced has been a change in the packaging desiccant that reduces the contamination effect during storage. That change went into effect in August 1998.

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