Evaluation of the Performance of the Dropsonde Humidity Sensor in Clouds

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ABSTRACT

The Dynamics and Chemistry of Marine Stratocumulus, Phase II (DYCOMS-II) experiment provided us a unique opportunity for in-depth study of the dropsonde humidity sensor’s performance within well-layered stratocumulus clouds. We analyzed plots of the dropsonde’s relative humidity (RH) profiles from DYCOMS-II and characterized them as either expected or unexpected, using liquid-water content (LWC) measurements to define cloud regions. Expected profiles (Type-1) displayed 100% RH within clouds and <100% RH outside clouds. Classified as unexpected profiles were those that never reached 100% RH (Type-2), and those that read 100% RH at cloud-base (Type-3) or from cloud-base to surface (Type-4). We compared unexpected profiles to RH and LWC profiles collected by sensors on NCAR’s EC-C130Q aircraft.

Our comparisons revealed three features of the dropsonde humidity sensor within clouds. First, due to the sensor’s error, there is a ~13 second time lag in measuring near-saturation RH values when the dropsonde enters clouds. Second, dropsonde-measured RHs resemble those measured by a dew-point hygrometer (DPH) on the C130 near the cloud-base. Finally, dropsonde-measured RHs remain near-saturation from cloud-base to 100-400 m below clouds, sometimes never returning to ambient conditions. This may be caused by liquid-water deposition on the humidity sensor. We believe alternate heating of the two humidity sensors will accelerate evaporation of water on the sensor. Exploration of these results can foster improvement of the world’s only operational dropsonde model and generate better RH data sets for hurricane and climate forecasting.

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INTRODUCTION

Dropsonde

The NCAR GPS dropsonde system, also known as the Airborne Vertical Atmospheric Profiling System (AVAPS), is a cylindrical instrument released from an aircraft to obtain measurements of atmospheric temperature, pressure, wind, and relative humidity (RH) (Figure 1). The dropsonde’s manufacturer, Vaisala Inc., makes over 5000 dropsondes per year. The instrument uses the H-Humicap thin film capacitor to measure RH. Once the instrument’s parachute is deployed, it falls at a rate of about 15 m/s (Vaisala, 2003). Measurements are made every half second until the dropsonde reaches the surface.

![Dropsonde instrument diagram](image)

Figure 1. Dropsonde instrumentation. Picture courtesy of NCAR/ATD.

The H-Humicap Sensor actually consists of two separate sensors, an upper one and a lower one (Figure 2, circled). Both sensors make measurements, but RH values in the final dataset are measured by the lower sensor because its position allows more interaction with the surrounding environment. The dropsonde and Vaisala’s RS90 radiosonde use the same humidity sensor, but the radiosonde is programmed to use alternative heating of dual sensors. While one sensor measures, the other sensor is heated to rid any liquid water or ice that may be present. Once the sensor cools, it measures while the other is then heated and cooled. The alternative heating did not work well for the dropsonde during lab testing. The sensor that was heated and cooled did not cool fast enough to return to ambient conditions to re-measure RH. Scientists and engineers at ATD therefore removed the dual-sensor approach for dropsonde measurements.

Scientists use dropsondes where a radiosonde (an instrument carried by a weather balloon that travels up through the atmosphere) would be difficult to release, e.g., in mountainous, polar, and water-covered regions (radiosondes are preferred because their release does not require an aircraft). Six different nations use dropsondes for worldwide research projects. Meteorologists utilize them extensively by dropping them into a
hurricane’s eye to gather pressure, temperature, humidity, and wind data to predict its future intensity and direction.

Figure 2. The H-Humicap dropsonde humidity sensor. Picture courtesy of NCAR/ATD.

DYCOMS-II experiment

The DYCOMS-II experiment was implemented in July 2001 to characterize the dynamics and environment of nocturnal marine stratocumulus clouds (Stevens et al., 2002). The project took place west-southwest of San Diego, California (Figure 3) and included seven different research flights (RF). NCAR’s EC-C130Q (C-130) aircraft released the dropsondes. The plane also made other measurements (such as RH and liquid-water content (LWC)) with instruments located on the aircraft. During DYCOMS-II 63 dropsondes were dropped into well-layered stratocumulus clouds, most of which are shown in Figures 8 and 9. Upon completion of DYCOMS-II, NCAR’s Atmospheric Technology Division (ATD) analyzed and plotted RH data to see how well the humidity sensor performed. The sharp increase in RH denoting the cloud-top was consistent in altitude with the small temperature inversion present. This was expected because stratocumulus cloud-tops are characterized by a temperature inversion. What was unexpected was the lack of profiles resembling the ideal profile (Type-1, Figure 7-A). In some instances, RH never reached 100% (Type-2, Figure 7-B); in others 100% RH was not reached until the cloud-top had been passed (Type-3, Figure 7-C); still others read 100% RH from the cloud-top all the way to the surface (Type-4, Figure 7-D).

Problem

When looking at RH profiles obtained by the dropsonde in and around clouds on several DYCOMS-II research flights, one notices that the dropsonde humidity sensor sometimes reports ambient RH imprecisely. Within warm clouds, RH should theoretically be 100% because the air is completely saturated. Immediately above and below a cloud, RH should decrease rapidly because the air is drier (Figure 7-A). However, these results were not always obtained during DYCOMS-II. Although
DYCOMS-II humidity measurements plotted on a color scale of 0% to 100% RH show high humidity layers indicating the presence of clouds (Figure 4). RHs are highly variable in and around clouds when plotted on a color scale of 90% to 100% RH (Figure 5). This indicates potential problems with the dropsonde humidity sensor.

**Figure 3.** DYCOMS-II Target Area, located west-southwest of San Diego, CA. Picture courtesy of www.atmos.ucla.edu.

**Figure 4.** 0% to 100% scale of relative humidities for each research flight in stratocumulus cloud regions during DYCOMS-II. Picture courtesy of ATD.
Goal and impacts of research

The goal of this research was to determine (i) how well the humidity sensor measured RH, (ii) what may be causing the subpar performance of the sensor, and (iii) how we might improve the sensor (and, indirectly, future humidity data) with a better understanding of the sensor’s operation.

Due to insufficient knowledge of the quality of humidity data, hurricane forecasters presently ignore it. Were it more reliable, they could couple it with other data and better forecast a hurricane’s strength and path, possibly saving many lives.

Enhanced measurements of water vapor could also improve estimation of the planetary energy budget. Climatologists studying global warming seek accurate water-vapor concentration measurements because it is such an important greenhouse gas. Two intriguing questions facing climate modelers are how clouds and water vapor affect the radiation budget and how the radiation budget affects clouds and water vapor (NASA, 1996). Both influence the flux of incoming solar radiation and outgoing longwave radiation, thereby affecting the Earth’s climate. To better understand these energy partitions and enhance predictions of changes in our climate, scientists need accurate measurements of water-vapor concentrations.

Finally, improved understanding of the dropsonde humidity sensor leads to the manufacture of superior dropsondes. Because Vaisala is the sole manufacturer of operational dropsondes worldwide and uses the same humidity sensor in its radiosonde, improvements suggested by ATD’s findings could benefit the entire research community.

In the following sections, this paper documents experimental methods, discusses results, and considers conclusions and future scientific implications.

METHODS

Problem analysis

We characterized our research problem and objective by first observing plots of RH measured during DYCOMS-II (Figures 4 and 5). The plots document the positive and negative aspects of the dropsonde. The positive aspect is that the dropsonde measured high-humidity layers in all soundings, corresponding to occurrences of marine...
stratocumulus clouds. The negative aspect is that it showed many sub-saturation RH values, i.e., RH < 100%, within clouds; one would expect 100% RH measurements inside warm clouds.

We also studied the dropsonde RH data of each RF to determine maximum humidities registered during each dropsonde drop. We plotted a histogram of the frequency of each maximum RH value (Figure 6). It shows that 29% of dropsonde soundings reach 100% RH, while the rest have maximum RHs from 94% to 99%.

**Figure 6. Frequency of maximum RH registered by the dropsonde during each drop.**

**Dropsonde data analysis**

DYCOMS-II dropsonde humidity profiles were plotted using the statistics package S-plus. All plots included temperature and humidity profiles from the surface up to 3 km. We focused our attention on the cloud region, which occurs at a height of about 1 km. The temperature inversion and dramatic increase in RH gave us a qualitative picture of the cloud top for each RF. Table 1 shows the number of good soundings available from each research flight.
Table 1. Date and number of good dropsonde soundings during DYCOMS-II Research Flights. No dropsondes were released during RF 06. Number of each type of RH profile is also shown. Type-1 profiles are ideal, Type-2 profiles never reach 100% RH, Type-3 profiles read 100% RH near the cloud-base, and Type-4 profiles display 100% RH down to the surface. Some profiles were classified as more than one type.

<table>
<thead>
<tr>
<th>Research Flight</th>
<th>Date (UTC)</th>
<th># good soundings</th>
<th># soundings</th>
<th># Type-1</th>
<th># Type-2</th>
<th># Type-3</th>
<th># Type-4</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF 01</td>
<td>10 July</td>
<td>5</td>
<td>7</td>
<td>0</td>
<td>5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>RF 02</td>
<td>11 July</td>
<td>6</td>
<td>7</td>
<td>0</td>
<td>4</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>RF 03</td>
<td>13 July</td>
<td>7</td>
<td>8</td>
<td>0</td>
<td>4</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>RF 04</td>
<td>17 July</td>
<td>6</td>
<td>8</td>
<td>0</td>
<td>4</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>RF 05</td>
<td>18 July</td>
<td>7</td>
<td>8</td>
<td>3</td>
<td>5</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>RF 07</td>
<td>24 July</td>
<td>9</td>
<td>10</td>
<td>0</td>
<td>2</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>RF 08</td>
<td>25-26 July</td>
<td>8</td>
<td>10</td>
<td>0</td>
<td>4</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>48</td>
<td>58</td>
<td>3</td>
<td>28</td>
<td>18</td>
<td>6</td>
</tr>
</tbody>
</table>

Once we knew which soundings were useful for data analysis, we focused on their corresponding RH profiles to separate the profiles into four groups (Figures 7-A through 7-D):

1. Ideal profiles
2. Profiles that never reached 100% RH
3. Profiles reading 100% RH closer to cloud-base than cloud-top
4. Profiles showing 100% RH from cloud-top down to surface

Characterization of the profiles focused our attention on these four specific, unexpected profile types that could be occurring due to the dropsonde sensor’s substandard performance. Table 1 displays the number of each type of humidity profile obtained from each research flight.

We then plotted the location of each dropsonde release and the latitude and longitude for each drop of each RF (Figures 8 and 9) to get a picture of the spatial distribution of the dropsonde drops.
Figure 7. Type-1, Type-2, Type-3, and Type-4 RH profiles.
Figure 8. Locations of dropsonde drops for RF01, RF02, and RF03.

Figure 9. Locations of dropsonde drops for RF04, RF05, RF07, and RF08.
Time-series plot analysis and data matching

We used S-plus to make time-series plots of several variables measured by instruments located on the C-130 aircraft for each RF. We included flight altitude (all RF flight paths followed a similar pattern as that shown in Figures 10 and 11); RH measured by the General Eastern, Model 1011B Dew Point Hygrometer (DPH); LWC measured by the PMS Liquid Water Sensor (LWS); and dropsonde release times (Figure 10).

![Time-series plot of C-130 aircraft measurements](image)

Figure 10. Plot of the C130’s altitude, the C130’s measurements of RH and LWC, and times of dropsonde drops.

After studying the previous plot a similar, we produced a simpler plot to match dropsonde release times with ascending and descending flight legs (Figure 11). We first located the time period of each RF when the airplane ascended or descended continuously through clouds. Anytime the plane traveled up and down through clouds, RH and LWC data measured at different heights by stationary instruments located on the aircraft—the DPH and LWS—could be made into profiles. The DPH measures the current dew point and infers RH based on the following equation:

$$\text{RH} = \frac{e_{s}(T_{d})}{e(T)} \times 100\%$$

where $e_{s}(T_{d})$ is the saturation vapor pressure at the dew point temperature and $e(T)$ is the current environmental vapor pressure. The DPH was used as a RH reference because the physics behind its measurements are sounder than that of the dropsonde (Wang et al. 2003).
We then used those times of day to temporally locate humidity data from the DPH to compare with dropsonde humidity data. Next, we chose dropsonde drops that occurred in time near the aircraft ascensions and descensions. Ultimately, these steps allowed us to match dropsonde humidity profiles with DPH humidity profiles in time and space as closely as possible to see how well the dropsonde reported RH.

Figure 11. Plot of C130 altitude and times of dropsonde drops.

Research on instruments providing data

We gathered information from publications and ATD staff to understand the specifications and performance error of all instruments producing data that we analyzed in this study (Table 2). We kept these specifications in mind to ensure making valid comparisons while analyzing data.
Table 2. Specifications and accuracy for different instruments used in this study.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Variables</th>
<th>Precision</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dropsonde</td>
<td>humidity pressure</td>
<td>1%</td>
<td>5%</td>
</tr>
<tr>
<td></td>
<td>temperature wind</td>
<td>0.1 hPa</td>
<td>1.5 hPa</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.1 °C</td>
<td>0.5 °C</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.1 m/s</td>
<td>±0.5 m/s</td>
</tr>
<tr>
<td>General Eastern 1011B Dew Point</td>
<td>dew point temperature</td>
<td>0.006°C</td>
<td>±0.5 °C (&gt;0 °C)</td>
</tr>
<tr>
<td>Hygrometer</td>
<td></td>
<td></td>
<td>±1.0 °C (&lt;0 °C)</td>
</tr>
<tr>
<td>PMS Liquid Water Sensor</td>
<td>liquid water content</td>
<td>0.001 g/m³</td>
<td>0.02 g/m³</td>
</tr>
</tbody>
</table>

Comparison of dropsonde humidity data with C130 DPH humidity data

Once all of the RH and LWC data were gathered, we plotted the data to get an idea of what may be causing the four unexpected types of dropsonde humidity profiles obtained during DYCOMS-II. We plotted the dropsonde’s measurements of temperature and RH with the C130’s measurements of temperature, RH, and LWC (Figure 12). We then defined the cloud-top and cloud-base using a threshold of minimum LWC of 0.08 g/m³ inside clouds. This definition worked well because our cloud-top layer did in fact occur at the C130 temperature inversion and large increase in C130 RH. The definition worked well for our cloud-base because it occurred at the altitude where C130 RH began to decrease. All results were analyzed and documented.

RESULTS AND DISCUSSION

Dropsonde maximum RH measurement frequency

Histograms of the frequency and number of drops of the dropsonde’s maximum RH measurement during each dropsonde drop revealed a range of 94% to 100% maximum humidity (Figure 6). These graphs provide a quick summary of the dropsonde’s performance in measuring 100% RH in and around clouds (assuming that the highest RH for each drop occurs near clouds). 100% maximum RH was the most common at 14 drops (occurring about 29% of the time). 94% maximum RH was the least common at 2 drops (occurring about 5% of the time). These results indicate that the dropsonde measures a maximum RH of 100% most often, but not always. Maximum RH values of 94%, 95%, and 96% lay on the threshold of the dropsonde’s ±5% accuracy range. These values occurred during 14 drops or 29% of the time. Many drops were therefore very close to falling outside of the accuracy range, indicating that there may be room for improvement for the dropsonde humidity sensor.

Preliminary observations

When temporally matching dropsonde RH drops with C130 ascensions and descensions for each RF, we included all instances when the plane traveled completely through the cloud region. Our plot results of the final flight descension showed little
agreement between the dropsonde and DPH RH readings. The approximate hour-long
time lag between the last dropsonde drop and the final C130 descension proved to be too
large; the dropsonde and DPH were sampling different clouds. We therefore omitted
the final C130 descension’s measurements of RH and LWC for all RFs in our analysis.
Figure 12 shows this problem; the descending profile on the right displays a large
discrepancy between dropsonde and C130 RH profiles at an altitude of 700 m near the
cloud-top region.

We also noticed that the descending C130 DPH humidity profiles as a whole were
not as accurate as ascending ones. Descending DPH profiles often reported super-
saturated RHs and time-delayed increases of RH near the cloud-top. We believe this was
due to the C130 DPH moving from an extremely dry, above-cloud region to a much more
moist cloud and below-cloud region. We consequently did not include descending C130
RH data in our analysis. The LWC profile was still considered in our study because the
LWS is not affected by large changes in atmospheric moisture like the DPH. The left
profile in Figure 12 shows this problem; the flight shows super-saturated, irregular C130
RH measurements in the cloud region.

Finally, we wish to make clear that there was no evidence that the cloud region
sampled by the dropsonde was identical to the region sampled by the C130’s DPH. However, we did attempt to keep dropsonde drops and flight ascensions no more than
five to ten minutes apart.

![Figure 12](image)

Figure 12. Dropsonde RH profiles plotted with C130 descending and ascending RH
profiles for RF01. Gray lines represent cloud-tops and –bottoms.

Summary of Type-2, Type-3, and Type-4 profiles

Unexpected dropsonde RH profiles relate to the C130 RH profiles in a similar
fashion (Figure 13), regardless of profile type. At the cloud-top the dropsonde usually
underestimated the C130 RH measurements. This is due to the time lag the dropsonde
humidity sensor incurs when it experiences drastic changes in humidity. Within the cloud, the dropsonde measured a relatively constant maximum RH, but its measurements remained less than the 100% RH. At the cloud-base, the dropsonde and DPH RH profiles were similar. This may be due to an error in the DPH causing it to read less than 100% RH, or, more likely, due to the cloud being quite diffuse in the region we defined as the cloud-base. From the cloud-base to the surface, the dropsonde overestimated the RH measurements of the DPH. This is probably due to the presence of liquid water on the dropsonde humidity sensor. Liquid water can come from the cloud itself as well as any low-lying drizzle. Drizzle was prevalent on several dropsonde drops, as indicated by LWC profiles. To combat liquid water’s presence on the sensor, we suggest re-implementing the dual-sensor heating-cooling cycle explained earlier. ATD is studying the procedure again to see if they can reduce the sensor’s required time to return to ambient conditions.

Figure 13. Dropsonde RH profile Types plotted with C130 RH and LWC profiles.

Explanation of Type-2 and Type-3 profiles

Type-2 and Type-3 dropsonde RH profiles seem due to technical inaccuracies of the sensor (Figure 13). The Type-2 dropsonde’s RH measurements never reached 100% RH during its descent. However, this was usually within the ±5% accuracy of the humidity sensor.

Several Type-3 RH profiles displayed a delay in reading a saturated, cloud-top RH value. We found that this was due to the time-lag properties of the humidity sensor. The time lag is most pronounced when the time response is large due to low temperatures, as well as when the sensor experiences a dramatic change in RH. The latter is a factor near the stratocumulus cloud-top.

Explanation of Type-4 profiles

We hypothesize that humidity sensor measurements of 100% RH from the cloud-base to the surface are due to the presence of liquid water on the humidity sensor. We believe that the sensor becomes contaminated with liquid water while it is in the cloud. When the dropsonde exits the cloud, there is still water present on the sensor. This leads
to a prolonged dropsonde humidity sensor reading of saturated conditions. There was also often a display of 100% RH from the cloud to the surface during days with occurrences of high LWC near the surface (Figure 13). DYCOMS-II weather reports also occasionally reported drizzle conditions. This would also cause the humidity sensor to read 100% RH at the surface.

CONCLUSION AND FUTURE RESEARCH

Conclusion

The ascending C130 DPH RH profiles proved to be a good reference for evaluating the dropsonde humidity sensor’s ability to measure RH accurately. Type-2 and Type-3 profiles seem due to the dropsonde sensor’s accuracy and time-lag limitations. The dropsonde does not measure RH well in and around clouds because of the large moisture variations in these regions. We believe Type-4 profiles occurred because of the presence of liquid water on the humidity sensor. Cloud exits and near-surface drizzle conditions are thought responsible. With this information, scientists will know to question dropsonde humidity measurements that are obtained near clouds.

We learned that ascending C130 DPH RH measurements are much better than descending measurements. A descending flight path causes the DPH to experience drastic RH changes as it travels from extremely dry air down through clouds. This causes erratic DPH RH measurements. It was also noted that there is much more agreement between dropsonde and C130 RH profiles near the cloud-base region than the cloud-top, in-cloud, and below-cloud regions. Further research is necessary to explain the dropsonde humidity sensor’s performance within the cloud, at the cloud-base, and below the cloud-base.

Future research

Any research project requiring airplane measurements and sampling near a layered cloud with a well defined cloud-top and cloud-base would provide an opportunity to test the dropsonde humidity sensor further. Another study should include several modifications. First, more aircraft ascensions through clouds should be planned since ascensions provide the best DPH RH measurements. Second, the humidity sensor’s moisture protection should be reconsidered. Much care is needed to ensure that liquid water does not contaminate the sensor. The manufacturer’s re-implementation of the dual-sensor technique in the future could be useful in evaporating liquid water present on the humidity sensor in and around clouds. Finally, researchers should attempt to release dropsondes near C130 ascensions both spatially and temporally. This would mean less horizontal variation between the two sampled air columns.
REFERENCES


