Cloud Liquid Water Measurements

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Why Measure Cloud Liquid Water Content?

• Determines the Potential of Enhancing Precipitation using Cloud Seed Techniques (Mali, Saudi Arabia)

• Basic Cloud Parameter (MPACE)

• Icing Studies (WISP04, Sikorsky)

• Comparison with Remote Sensing Measurements (THORpex, IOP1)
Forward Scattering Spectrometer Probe (FSSP) On the Left Wing of the King Air 200 Research Aircraft
The amount of liquid water for a given volume of air may be determined through mass integration of the cloud droplet distribution.

\[
LWC = \left( \frac{\pi}{6} \right) \rho_w \sum_{i=1}^{m} N_i d_i^3
\]

LWC – Cloud Liquid Water Content
\(\rho_w\) – Density of Water
\(N_i\) – Concentration of Droplets in Size Channel i
\(d_i\) – Droplet Diameter in Size Channel i
\(m\) – Total Number of Size Channels
March 13, 2008 Flight

FSSP cloud liquid water content measurements near Hail, Saudi Arabia at -16 C and 19,000 ft.
Liquid Water Content Probe on the King Air 200 Research Aircraft
Liquid Water Content Probe

- Coil is heated to given temperature \( \sim 185 \) °C.
- Coil supplies energy in the form of heat to vaporize drops.
- Power is supplied to coil to maintain a constant temperature.

\[
P = P_{\text{dry}} + P_{\text{wet}}
\]

- \( P \) – Total Power
- \( P_{\text{dry}} \) – Dry Power Term
- \( P_{\text{wet}} \) – Wet Power Term
Dry Power Term

- Energy is transferred to passing air molecules due to thermal conduction.
- Energy transferred is a function of air speed, pressure, and temperature

\[ P_{dry} \approx C (T_s - T_a) \times (pv)^x \]

- \(C\) – Calibration Constant
- \(x\) - Calibration Constant
- \(T_s\) - Wire Temperature
- \(T_a\) - Ambient Air Temperature
- \(p\) - Ambient Atmospheric Pressure
- \(v\) - True Air Speed

King et. al, 1981
Wet Power Term

- Energy is transferred to heat droplets to the boiling point and vaporize the droplet.
- Function of the mass of droplets.

\[
P_{\text{wet}} \approx Mlvdv \left[ L_v + c_w (T_v - T_a) \right] \quad \text{King et. al, 1981}
\]

- M - Liquid Water Content
- l - Length of Wire
- d - Diameter of Wire
- v – True Air Speed
- \(L_v\) - Latent Heat of Vaporization
- \(c_w\) - Specific Heat of Water
- \(T_v\) - Boiling Temperature of Water
- \(T_a\) – Ambient Temperature
Liquid Water Content Formula

Combine the Wet and Dry Power Terms

\[ P \approx C (T_s - T_a) \ast (Pv)^x + Mldv \left[ L_v + c_w (T_v - T_a) \right] \]

Solve for Liquid Water Content

\[ M \approx \frac{P - C (T_s - T_a) \ast (pv)^x}{ldv \left[ L_v + c_w (T_v - T_a) \right]} \]

- \( P \) – Total Power
- \( C \) – Calibration Constant
- \( x \) - Calibration Constant
- \( T_s \) - Wire Temperature
- \( T_a \) - Ambient Air Temperature
- \( p \) - Ambient Atmospheric Pressure
- \( v \) - True Air Speed
- \( M \) - Liquid Water Content
- \( l \) - Length of Wire
- \( d \) - Diameter of Wire
- \( L_v \) - Latent Heat of Vaporization
- \( c_w \) - Specific Heat of Water
- \( T_v \) – Water Boiling Temperature
Objectives

- Create calibration routine to determine calibration coefficients for the Liquid Water Content Probe.
- Create data processing routine to apply offset correction to liquid water measurements.
- Compare measurements of liquid water content from Hot Wire probe and FSSP to validate the offset correction data processing routine.
**Calibration Data**

- Developed a “king_calib” software routine that calculates coefficients C, x, and the correction factor A.

- Calibration software requires flight measurements of the hot wire voltage and the true air speed.
  - Sample out of cloud in dry air.
  - Vary air speed from maximum to minimum and then back to maximum while maintaining constant altitude.
  - Conduct measurement at altitude typical for liquid water content measurements.
Calibration Algorithm

• Fit a curve to voltage versus airspeed data points with a function of the form:

\[ v_a = kv^x + a \]

• Va is hot wire voltage.
• v is true air speed.
• Model coefficients are k, x, and a.
• Calibration coefficients are C, x, and A.
• “A” results from the fact that this model does not pass through (0,0).
Calibration Equation

Dry Term is: \[ P_{dry} = C(T_s - \bar{T}_a) \star (\bar{p} \, v)^x + A \]

Group Constants: \[ P_{dry} = [C(T_s - \bar{T}_a) \star \bar{p}^x] \, v^x + A \]

Substitute for P: \[ 10V_a = [C(T_s - \bar{T}_a) \star \bar{p}^x] \, v^x + A \]

Define Constants: \[ k = \frac{C(T_s - \bar{T}_a) \star \bar{p}^x}{10} \quad a = \frac{A}{10} \]

Solving: \[ C = \frac{10 \star k}{(T_s - \bar{T}_a) \star \bar{p}^x} \quad A = 10 \star a \]

C, A, and x are the calibration constants needed.
Calibration Results: June 21, 2004

Time Interval = 62,900 - 63070 sfm
Average Pressure = 693 mb
Average Temperature = -6.3 °C

\[ v_a = 0.21486v^{0.4408} - 0.2546 \]

\[ C = 6.30 \times 10^{-4} \]
\[ x = 0.4408 \]
\[ A = -2.545 \]
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Graph:

- Linear regression equation: \( y = -0.0001x + 0.1107 \)
- \( R^2 = 0.803 \)
Hot Wire Probe cloud liquid water content (unadjusted offset) measurements near Hail, Saudi Arabia at -16 C and 19,000 ft.
Offset Correction

• In theory, the liquid water content measurement should be zero when out of cloud.

• Calibration error affects the liquid water content measurements and cause the baseline to be offset from zero.

• The “king2lwc” data processing subroutine attempts to adjust the liquid water content data so that the baseline is near zero.

• The offset correction requires FSSP concentration measurements.
Offset Correction Algorithm

• An in cloud parameter based on the FSSP concentration measurement is used to define when sampling in or out of cloud.

• The offset correction is determined right before and right after a cloud measurement.

• An average liquid water content of 20 second interval is for the offset.

• The calculated offset value is subtracted from the in cloud liquid water data.
Offset Correction Conclusions

• Most of the time the offset correction algorithm is successful.

• However, the offset correction algorithm can give poor results if:
  • The aircraft takes off in clouds.
  • The aircraft lands in clouds.
  • The aircraft's altitude changes greatly while in cloud.
March 13, 2008 Flight

Hot Wire Probe cloud liquid water content (adjusted offset) measurements near Hail, Saudi Arabia at -16 C and 19,000 ft.
Hot Wire Probe (Black) and FSSP (red) cloud liquid water content measurements near Hail, Saudi Arabia at -16 C and 19,000 ft.
March 13, 2008 Flight

FSSP cloud liquid water content versus the Hot Wire Probe cloud liquid water content measurements between 9:20 and 10:00.
Conclusions

- Hot Wire Liquid Water Content Probe can be calibrated during a field project.
- Typical unadjusted Liquid Water Content error is $\sim 0.04 \text{ g/m}^3$.
- Hot Wire Liquid Water Content error has some dependence on altitude and over extreme altitude ranges is approximately $0.07 \text{ g/m}^3$.
- The baseline offset corrections in the Hot Wire Liquid Water Probe can be adjusted during post-processing; however, does not work properly under all circumstances.
- Hot Wire and FSSP Liquid Water Content do agree under some measurement conditions if each instrument is correctly calibrated and processed.
Future Work

• Collect some Hot Probe calibration data during a Research King Air flight.

• Determine calibration coefficients and reprocess the Saudi 2007/2008 data set.

• Lot of work still to do (e.g. AIMMS Probe).
Any Questions?