A Solution for the Tower Effect on Upwelling Longwave Radiation at COVE

Bryan Fabbri\textsuperscript{1}, Greg Schuster\textsuperscript{2}, Fred Denn\textsuperscript{1}, Jay Madigan\textsuperscript{1}

\textsuperscript{1} – Science Systems and Applications, Inc. (SSAI), Hampton, Virginia

\textsuperscript{2} – NASA Langley Research Center, Hampton, Virginia

CERES Science Team Meeting, April 28-30, 2020, Virtual Meeting
Tower Effect at CLH

- Downwelling LW
  - ~37 meters above sea level
- Narrowband Upwelling IRT (9.6-11.5 μm)
  - [Field of View: 2.8° and 8.9°]

Broadband Upwelling LW (4-50 μm)
- [Field of View: 180° 2π sr]

~8 meters

~21 meters

Fish eye lens view from upLW location shows tower obstruction, estimated at 15%
**Tower Effect Equations**

**What we had:**

\[
\text{Measured } LW_{up} = (1 - f) (\varepsilon_w \sigma T_w^4 + (1 - \varepsilon_w) \cdot LW_{dn}) + f \varepsilon_T \sigma T_T^4
\]

- Water surface thermal emission
- Reflected flux of downward atmospheric emission
- Tower Emission

**What we want:**

* Derived \( LW_{up} = \varepsilon_w \sigma T_w^4 + (1 - \varepsilon_w) \cdot LW_{dn} \)

Where,

- \( f \) = The estimated fractional obstruction the tower is in the field of view of \( LW_{up} \). At COVE, 0.15 was the estimate.
- \( \varepsilon_w \) = Emissivity of water (\( \varepsilon_w = 0.990 \)).
- \( \sigma \) = Stefan-Boltzmann constant (\( \sigma = 5.6697 \times 10^{-8} \)).
- \( T_w \) = Water temperature in degrees K. Measured with an IRT (9.6 – 11.5 \( \mu m \)).
- \( LW_{dn} \) = Downwelling longwave radiation. Measured with an Eppley PIR (4 – 50 \( \mu m \)).
- \( \varepsilon_t \) = Emissivity of tower. Unknown, but reduced \( \chi^2 \) equation indicates \( \varepsilon_t = 0.90 \) (shown later).
- \( T_t \) = Temperature of tower in degrees K.

* From NOAA NESDIS Center for Satellite Applications and Research, Algorithm Theoretical Basis Document "ABI Earth Radiation Budget, Upward Longwave Radiation: Surface (ULR)" by H.T. Lee, I. Laszlo and A. Gruber (September 2010)
Single Year (upper) and Total Time Period (lower) Comparisons

- Data above the solid black lines is nighttime.
- The darker red lines indicate the tower heats up in the afternoons, particularly summer, as captured by the wide field of view Measured \( \text{LW}_{up} \) measurement.
- But there is a lot of blue, at night and in the morning, displaying explicit differences between the two measurements.
Single Day Results

Scenarios:

• Summer clear
• Summer overcast
• Winter clear
• Winter overcast
Evidence suggests that the tower is altering the Measured LW, noticeable on this clear, summer day.

But on overcast days, LW measurements and water emission measurements are closer to the 1:1 line.

At night, an increase in air temperature alters the Measured LW.
• On a clear, winter day, evidence suggests the tower is again altering the Measured LW, but not as much as the summer, clear day.
• Another significant difference is the spread from the 1:1 line. There is a large bias in the Water Emission.

• The winter overcast day, like summer overcast, are closer to the 1:1 line, but like clear winter, there is still a bias in the Water Emission.
• Another way to show single day plots.
• The same variables as the previous slide are shown, but the Derived LW_{up} is added
Single day plots continued…..The other single day scenarios included

- Vertical black lines represent the sunrise and sunset times for the 4 single day scenarios
- Measured LW has lower values in the winter and has more variability due to the tower obstruction
- The Derived LW is not affected by the tower emissions (e.g. the temperature and solar insolation during the day)
Results/Statistics Months

Time period for monthly data is 2004-2013
Relative Bias = \(\frac{(\text{Measured LW}_{\text{up}} - \text{Derived LW}_{\text{up}})}{\text{Derived LW}_{\text{up}}} \times 100\)

- As of 2004, BSRN target uncertainties for upwelling longwave radiation is 2% or 3 W/m², whichever is greatest (The shaded regions will represent the 2%).

Individual monthly plots show biases in the Derived LW_{up} with all months, mean, and medians below 0

Warmer months have better agreement, less data outside the BSRN target uncertainty
Results/Statistics for Annual

The 10 year period is from 2004-2013
Individual year plots continue to show biases in the Derived LW\(_{up}\) with all years mean and medians below 0 (upper plots)

- All years are outside the the target uncertainty with some as high as 50% (lower left)
- The lower right plot is the entire 10 year time period displaying 1/3 of the data outside BSRN target uncertainty
Attempt to Quantify the Impact of F on obstructed Measured $LW_{\text{up}}^\uparrow$ measurements

Quantifying the Tower Emissivity

If our measurements are accurate and our approach is sound, we can compute the emissivity of the tower. For N measurement times, our radiation balance results in N equations and N + 1 unknowns:

$$LW_{m,i}^\uparrow = (1 - f)[\varepsilon_w \sigma T_{w,i}^A + (1 - \varepsilon_w)LW_{m,i}^\downarrow] + f \varepsilon_{twr} \sigma T_{twr,i}^A \text{ for } i = 1, \ldots, N$$

We can reduce this to N equations and 1 unknown if we solve for $T_{twr}$ and assume that the tower is in equilibrium with the measured air temperature at night:

$$T_{twr,i}(\varepsilon_{twr}) \simeq T_{air,i}.$$  

The problem is now overconstrained (N equations, 1 unknown), so we use $\chi^2$ minimization to find optimum $\varepsilon_{twr}$:

$$\chi^2(\varepsilon_{twr}) = \sum_i \frac{T_{air,i} - T_{twr,i}(\varepsilon_{twr})}{T_{twr,i}(\varepsilon_{twr})} \to 0.$$  

$$\Rightarrow \varepsilon_{twr} = 0.90$$
• Measured $LW_{up} - Derived \ LW_{up} = f(\epsilon_T \sigma_T^4 - \epsilon_w \sigma_w^4 + (1 - \epsilon_w) L\ W_{dn})$

• The values of Measured $LW_{up}$ ($f \neq 0$) and Derived $LW_{up}$ ($f = 0$) diverge when $F > 0$

• COVE's obstruction is 15%. If one could move the instrument closer to the tower (as $F$ increases), the relative bias between Measured $LW_{up}$ and Derived $LW_{up}$ expand. As $F$ gets smaller and eventually to 0, the results match. One could use this method on any obstruction.

![Graph showing the relationship between F (% Tower Obstruction) and Relative Bias (%). The graph illustrates the trend of increasing bias with increased obstruction, and a note indicating the need to move the instrument 14m further away from the tower to be within target uncertainty.]
Summary

- COVE's tower obstruction, estimated at 15%, caused anomalous readings on the Measured $L_{\text{w}_\text{up}}$ instrument.

- We used SST measurements at COVE and the reflected flux of the downward LW atmospheric emission to derive an upwelling LW emission (Derived $L_{\text{w}_\text{up}}$).

- The Derived $L_{\text{w}_\text{up}}$ emission is not susceptible to changes in air temperature and direct solar heating on sunny days, unlike Measured $L_{\text{w}_\text{up}}$.

- The relative bias is largest in the colder months when the air temperature and water temperature are greatest. The relative bias is smaller in the warmest months.

- We have not submitted $L_{\text{w}_\text{up}}$ to the BSRN archives due to the tower effect. Using Derived $L_{\text{w}_\text{up}}$ will provide over 10+ years to the BSRN archive.

- Using instruments that derive $L_{\text{w}_\text{up}}$ could be used at sites such as Granite Island where constraints limit using a wide field of view instrument.

- This solution could be used on any tower or obstruction.