NOAA Pacific Marine Environmental Laboratory
Ocean Climate Stations Project

TECHNICAL NOTE 11

Systematic Outlier Longwave Radiation Measurements at the Kuroshio Extension Observatory Mooring

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Introduction

Shortwave (SWR) and longwave (LWR) radiation constitute the largest terms in Earth's overall energy budget. SWR originating from the sun enters the top of Earth's atmosphere (TOA) at a relatively constant rate, often cited as the "solar constant" around 1370 W/m^2. The surface and atmospheric column reflect a percentage of SWR back to space, contributing to the global average albedo of ~0.3 (TOA). Non-reflected SWR is absorbed by the surface or atmosphere and reemitted in all directions as LWR. Greenhouse gas concentrations dictate the degree to which LWR absorption/reemission occurs, but ultimately, Earth radiates net LWR to space, establishing an equilibrium with incoming SWR. Upwelling and downwelling LWR components occur throughout the atmosphere, damping outbound heat transfer, and giving Earth an equilibrium temperature (~288K) above that of it's radiative equilibrium temperature (~255K).

As LWR is dependent upon the temperature and humidity of the overlying atmosphere, LWR signals are often correlated with surface ATRH measurements. Downwelling LWR exhibits a semi-predictable seasonal variability, and climatological norms have been established at Papa (225 – 400 W/m^2) and KEO (250 – 450 W/m^2). The following figure is an example showing that ATRH and LWR time-series often share prominent features. A similar figure will be presented later, to show these similarities break down where LWR spikes occur.

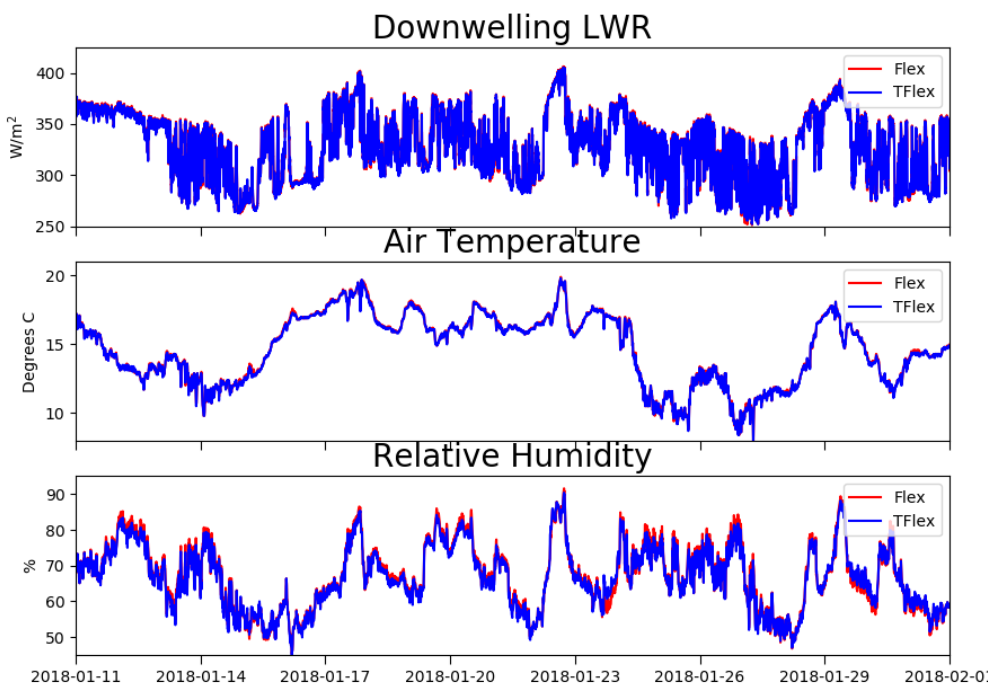

Figure 1: A 20-day example of LWR, AT, and RH time-series from the KEO mooring, showing the association between longwave and ATRH.

Downwelling LWR is calculated by custom circuitry designed by PMEL and interfaced with an Eppley PIR sensor. Net LWR is measured as a voltage (V_{ac}) from the PIR thermopile. An instrumentation amplifier provides a gain stage before being read by an embedded microcontroller. Additionally, case and dome temperatures (T_c and T_d, respectively) are monitored by thermistors embedded within the sensor. A non-inverting amplifier is used with a precision voltage source to generate a voltage based on the resistance of the thermistors, also measured by the microcontroller. The Net LWR of the sensor is calculated by dividing the measured voltage of the thermopile by the calibration sensitivity determined by Eppley for each unit. Finally, a correction factor utilizing case and dome temperatures is applied to account for dome heat radiating back onto the thermopile. The manufacturer provides the following equation first established by Albrecht and Cox, 1977:

$$\underbrace{R_{in}} = \underbrace{V_{ac} / S} + \underbrace{\sigma T_c^{\,4} - k\sigma(T_d^{\,4} - T_c^{\,4})}$$

Categorization:	DOWN	NET	UPWELLING (2 terms)	
Eppley designation:	(DOWN)	(A)	(B)	(C)

This equation can be split apart into 4 components (left-to-right) – Downwelling LWR, sensor Net LWR (a factor of voltage), and two terms based on the Stefan-Boltzmann equation that combine to form the sensor's Upwelling LWR. The first sigma term is upwelling based on the case temperature, while the second sigma term is a corrective factor that accounts for case/dome temperature differences, where k is a constant 3.5. Under typical conditions with no atmospheric inversion, LWR "up" is strongly positive, "down" is moderately positive, and "net" is slightly negative.

The Eppley designation terms (A, B, and C) will be used throughout this document.

Noise in Realtime Data

In recent years, a high mid-summer LWR anomaly is observed at the Kuroshio Extension Observatory (KEO). One or both sensors witness a ~50 W/m^2 jump above climatology, and the data become noisy. Even when this anomaly occurs in both instruments, the measurements do not agree. As time passes and the environment cools, the measurements eventually return to normal ranges, often agreeing again to within instrument accuracy specifications. The data presented here are hourly, so spike severity may be obscured compared to the high-resolution (10-minute) data presented later.

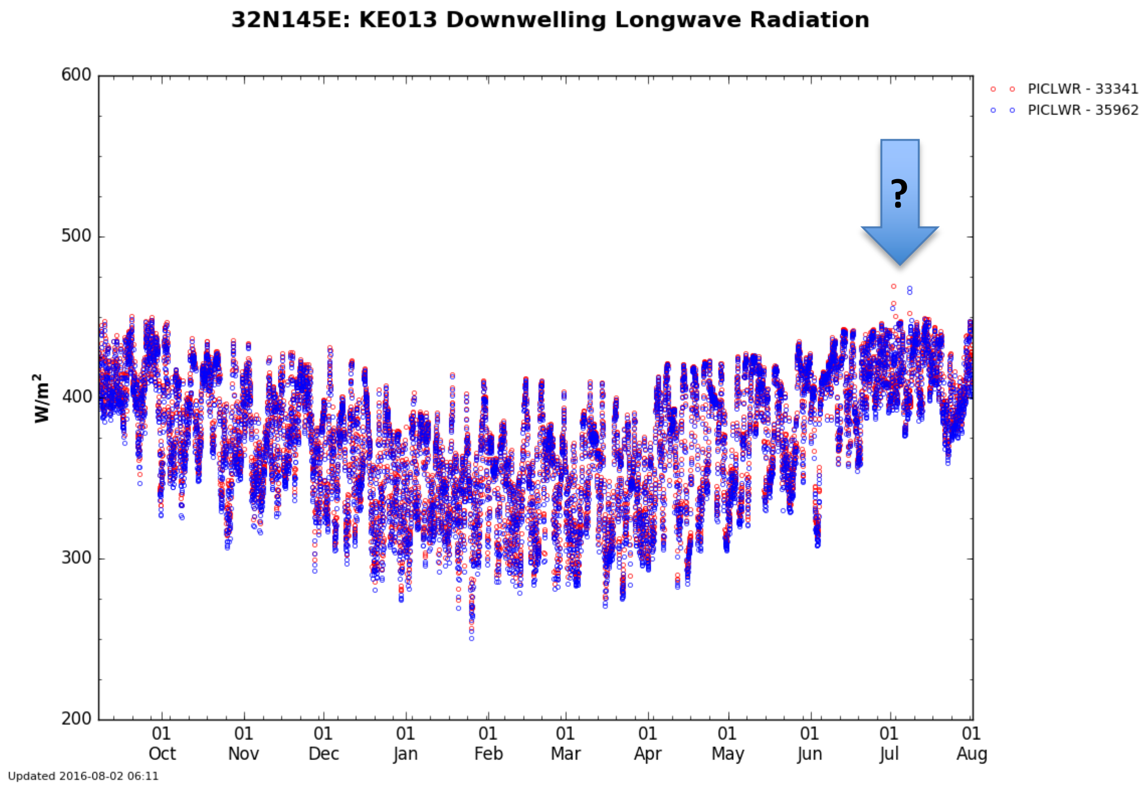

Figure 2: KE013 (2015 – 2016) shows the first hint of an anomaly in July 2016.

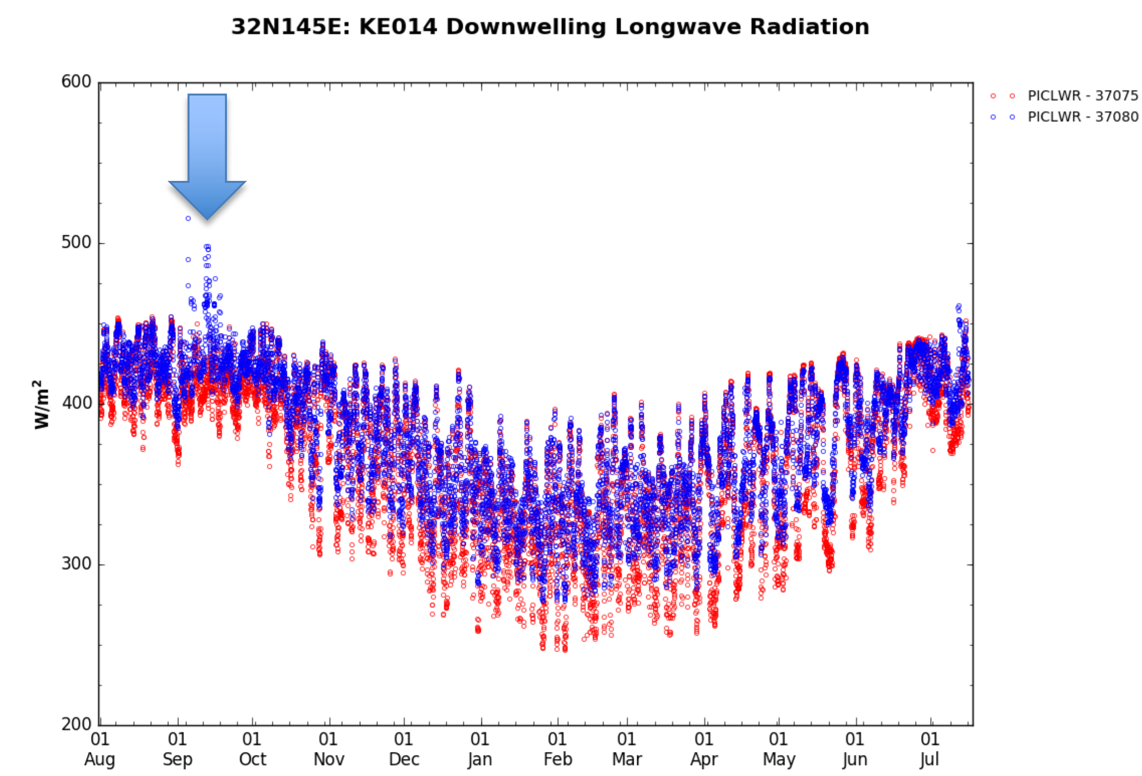

Figure 3: KE014 (2016-2017) shows the LWR anomaly in one instrument in September 2016.

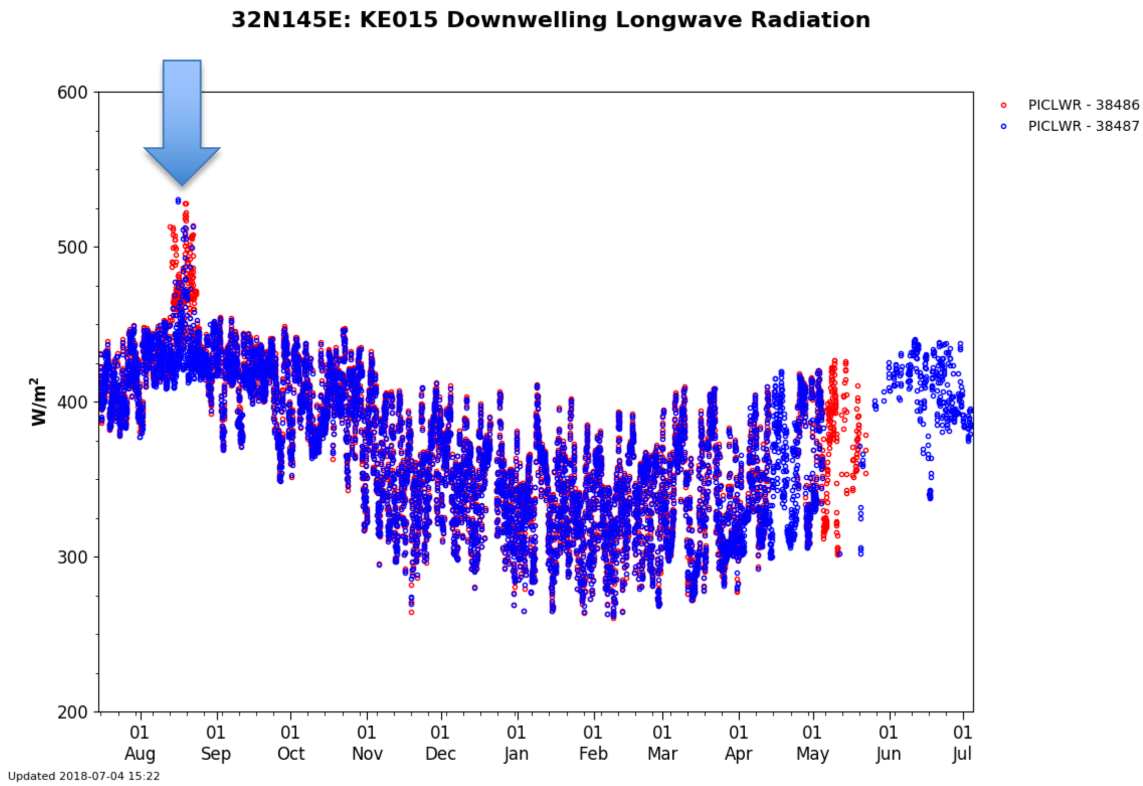

Figure 4: KE015 (2017 – 2018) exhibits a dual LWR anomaly in August 2017, with differences >50W/m^2.

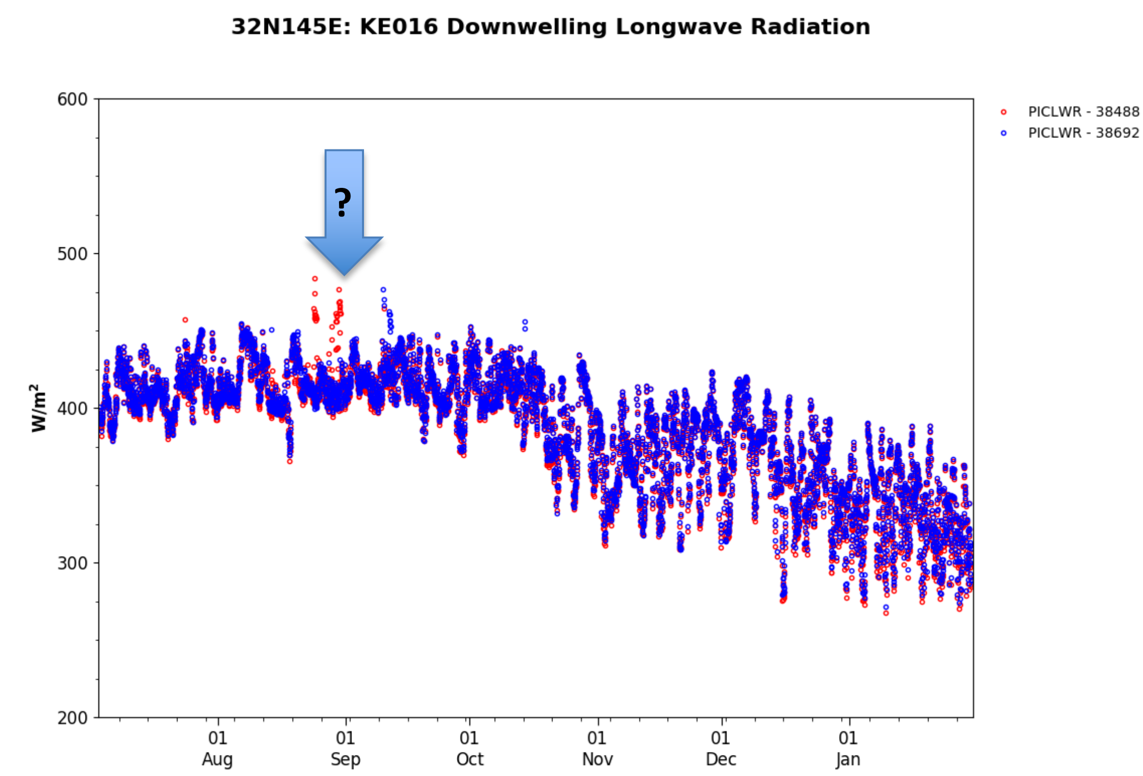

Figure 5: KE016 (2018 – 2019) is currently deployed, and shows hints of the summertime anomaly.

Noise in Delayed-Mode Data

Several years of delayed-mode data are now available showing the KEO LWR anomaly. In this section, lessons learned from each figure will be presented in the captions that follow. The overall conclusion is that a poor net LWR measurement (whether real or artificial), is propagating into the calculation of downwelling LWR. Hypotheses are presented below.

	Evidence For	**Evidence Against**
Moisture	Sensor recovers; drying plausible	High RH throughout; if glass reseals, it would trap moisture
Dome Seal	High temp expansion might unseat glass dome; cold reverses/reseals	Many buoys see ↑T. Why KEO?
Lightning	LWR from lightning's heat or a secondary electronic effect	Spikes not always seen in both sensors; isolated to LWR; no rain evident at onset
Bird Guano	Explains sensor offset and makes rain/wash-off recovery plausible	Doesn't explain spikes; no rainfall/wash-off @ anomaly end
Electronics Issue	Might explain the noisy oscillation about net LWR = 0	Noise is acquisition system and sensor independent; expect sensor consistency

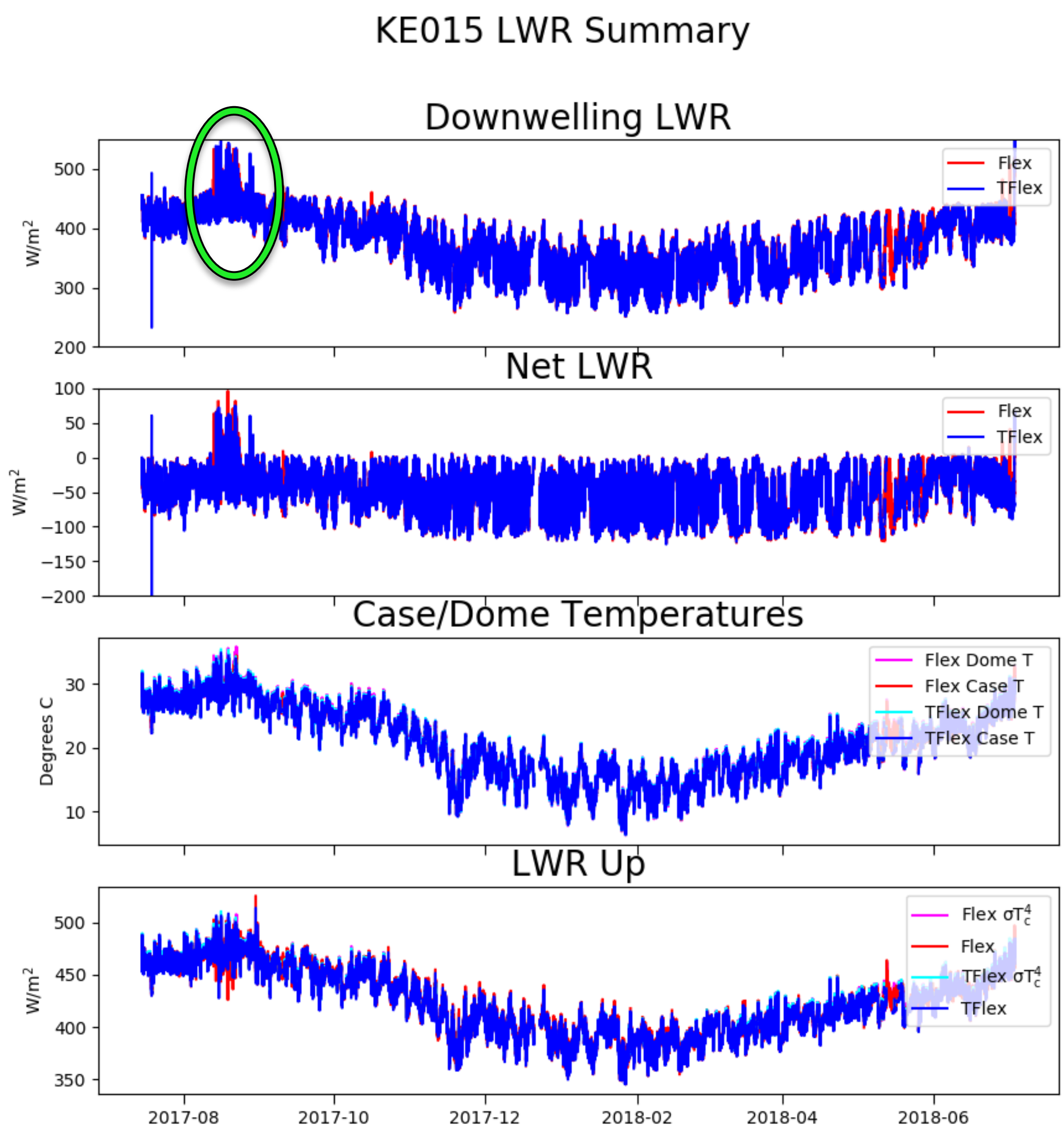

Figure 6: Full time series of KE015 delayed-mode LWR data, split by components. The anomaly most clearly originates in the Net LWR (thermopile) measurement. Some temperature effects are possible, but Eppley showed that corrective term "C" is typically close to 0 W/m^2 – especially at night, when temperatures homogenize – and is unlikely responsible for the >50 W/m^2 downwelling LWR differences (circled).

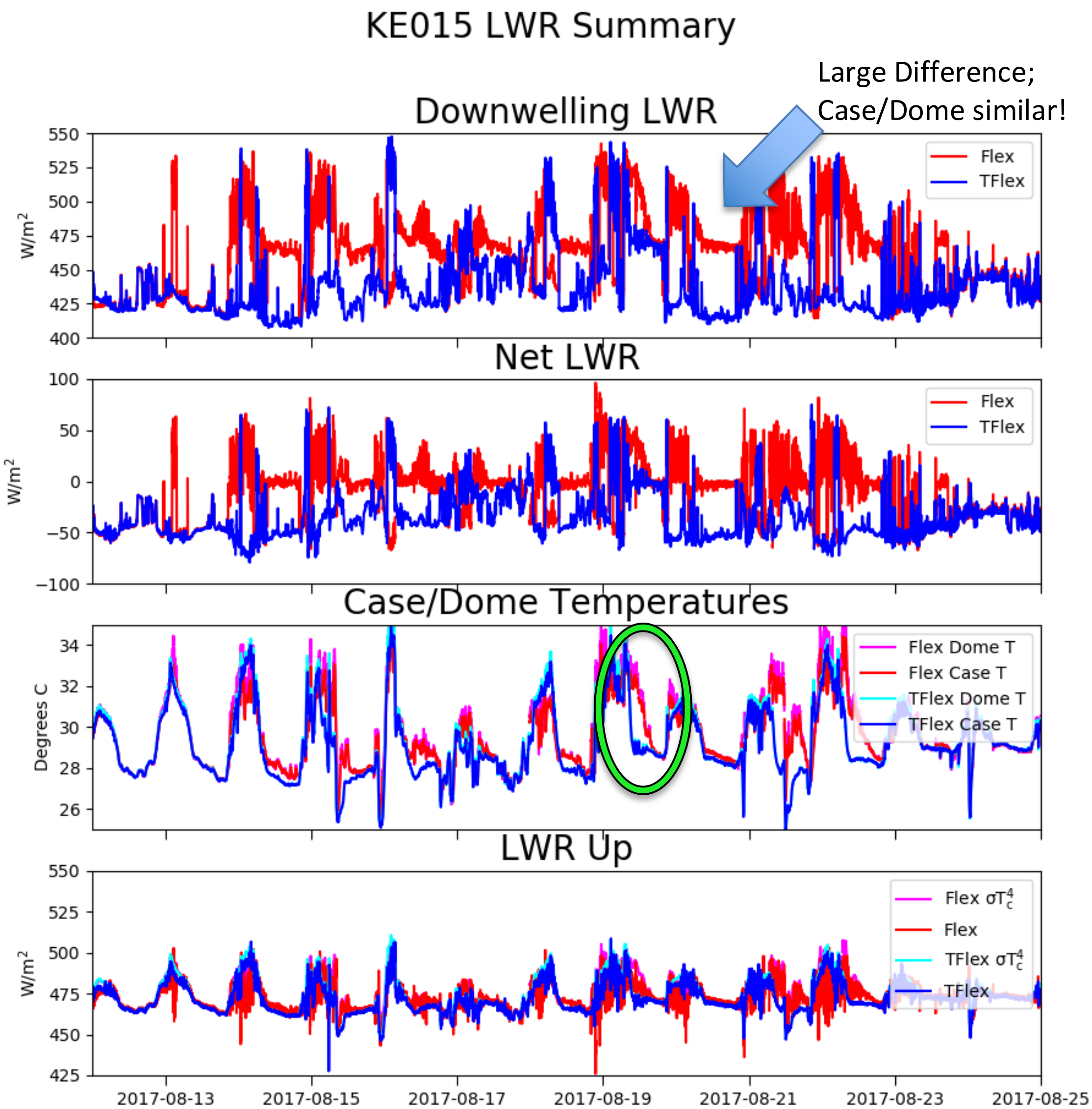

Figure 7: Zoom-in on the two-week anomaly in Figure 6. Persistent positive Net LWR (term A) is unrealistic during the summer months with high SWR (Figure 10). There is evidence the Flex/TFlex LWR sensors cooled differently (third plot, circled), but this does not appear to cause the downwelling offset. The offset is present even during periods of Flex/TFlex case/dome temperature agreement (see arrow).

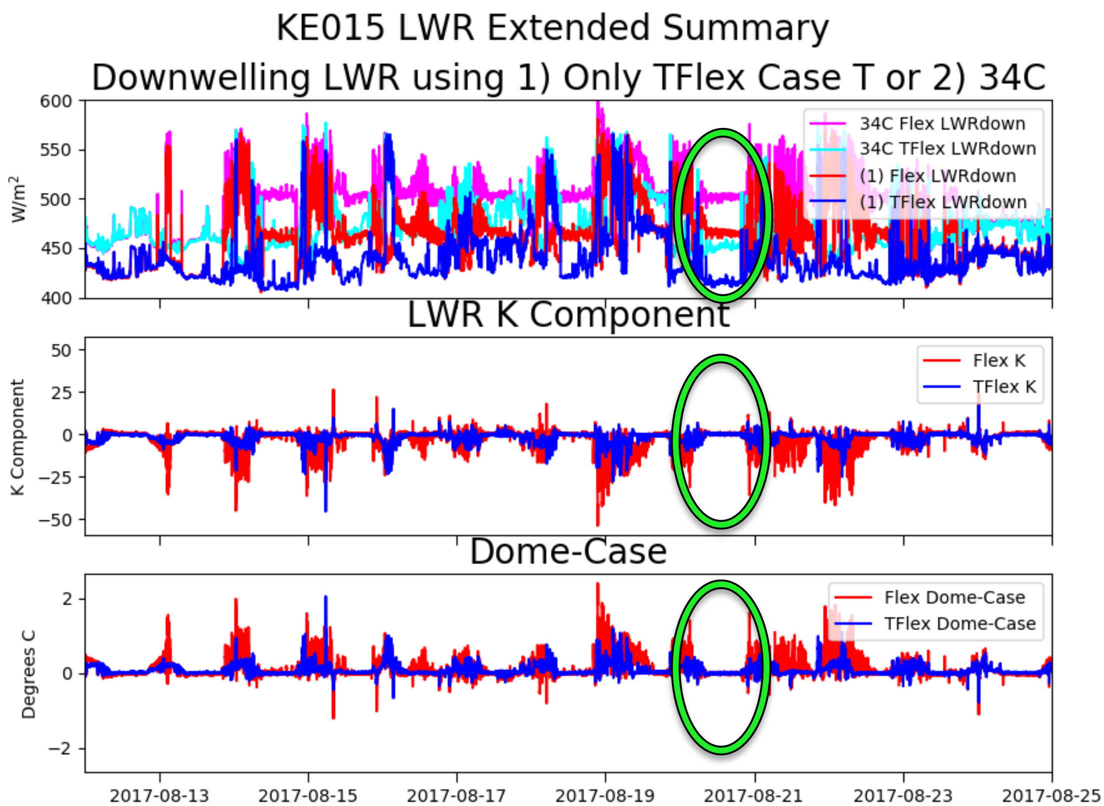

Figure 8: Same timeframe as Figure 7, but splitting apart LWR equation components. The top plot adds respective Flex/TFlex net LWR (term A) to either of 2 methods of calculating term B: 1) using the TFlex case temperature time-series or 2) using a constant of 34˚C, the highest temperature witnessed. Both approaches attempt to eliminate temperature effects. The middle plot shows term C, whose magnitude goes to 0 at night. Case/dome temperature differences, critical to the calculation of term C, are shown in the lower plot.

From the top panel of Figure 8, an offset between the Flex and TFlex downwelling LWR is apparent. Regardless of the temperatures input into the Eppley equation, the circled period shows that Flex and TFlex downwelling LWR disagree by ~50 W/m^2 (red minus blue or magenta minus cyan). Since case and dome temperature differences go to 0 at night, so does term C. No additive combination of term C with terms A+B explains the ~50 W/m^2 offset between Flex/TFlex downwelling LWR. Thus, the anomaly is attributed to differences in the base measurement, net LWR. Temperature could still play a role in LWR spikes, but the offset between systems is not due to temperature.

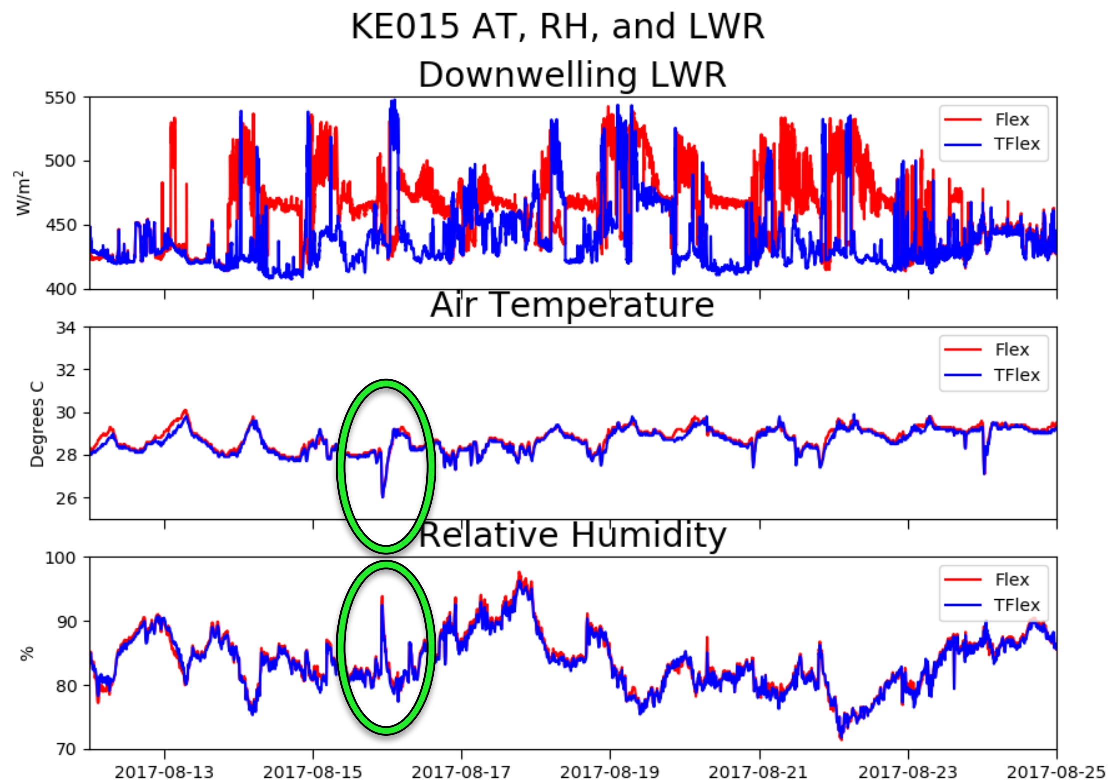

Figure 9: Timeframe as in Figure 7, showing ATRH. No prominent spikes in ATRH suggest that LWR spikes are not real. A persistent inversion is unlikely, given the duration (2 wks) and mid-summer atmospheric mixing. Minor ATRH spikes associated with rain (circled) are real, yet disparate LWR records persist.

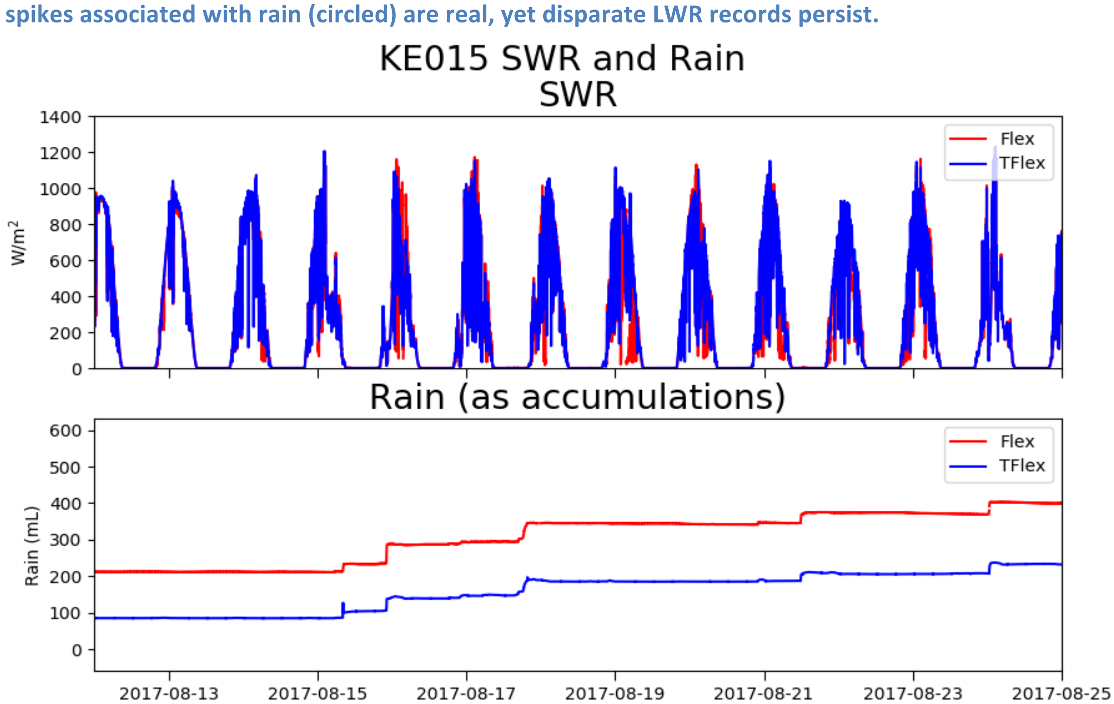

Figure 10: Raw KE015 SWR and Rain data during the 2 week anomaly. The rain (esp. 8/15) appears in the ARTH time-series as the cool/moist event in Figure 9, but the LWR anomaly extended days before and after any rain event. SWR indicates transient clouds in an overall sunny regime (near 1000 W/m^2 maximum each day).

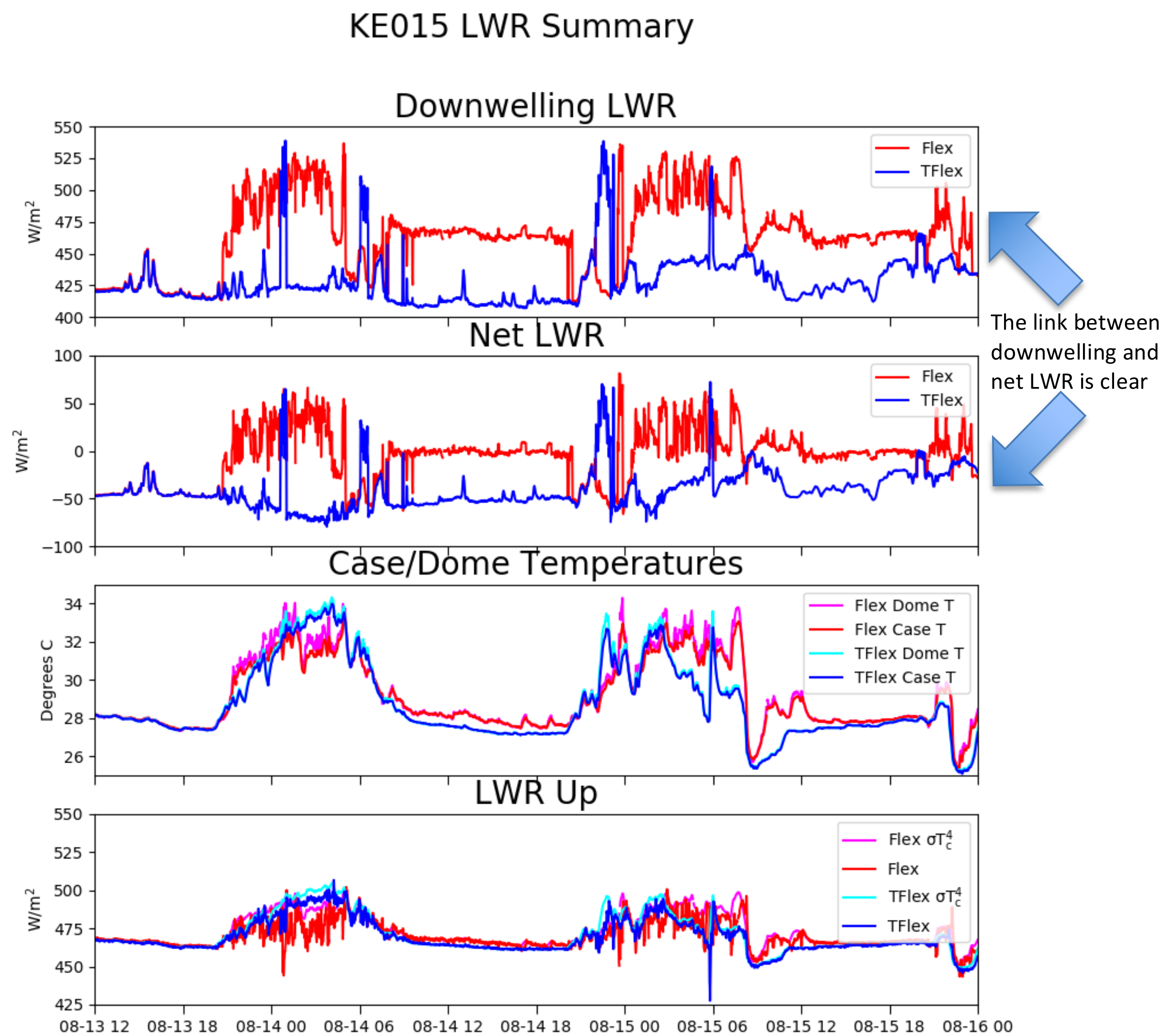

Figure 11: As in Figure 7, but zoomed to 2 days.

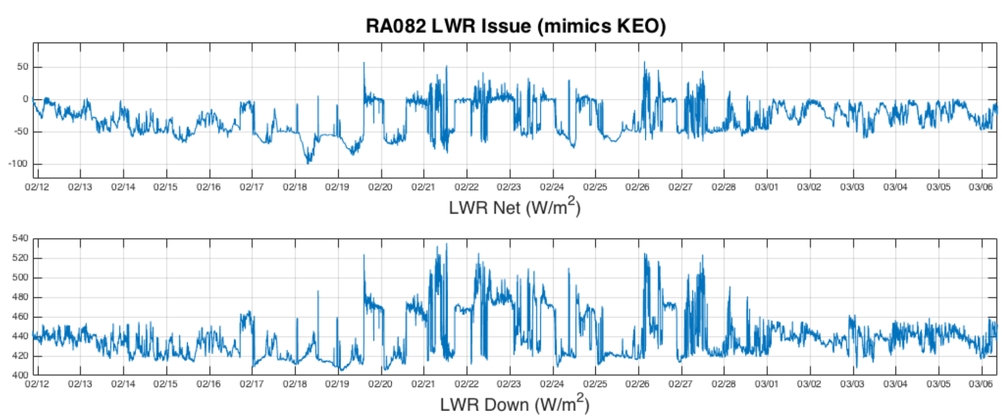

Figure 12: An ATLAS-based GTMBA mooring (8S67E) seems to mimic the KEO anomaly. Downwelling radiation is quite high, and positive net LWR excursions occur mid-summer (February in S. Hemisphere). The acquisition system independence suggests a sensor/electronics issue, but many sensors exhibit the LWR anomaly.

Conclusion

KEO LWR frequently becomes noisy during the hottest weeks of summer. Hypotheses explaining the sensor noise and offsets include electronic noise, nearby electrical storm effects, biological interference, intruded moisture, or an inadequate glass dome seal. Evidence against each case suggests that further testing or a new hypothesis is needed. It is strongly suspected that the LWR anomaly is false, due to:

1) Lack of corroboration between LWR sensors (disagreement can exceed 50 W/m^2)
2) Poor supporting evidence from other sensors (ATRH, SWR, and RAIN)
3) Instrument directionality – Flex/TFlex sensors point to the same hemisphere.
    - Instrument mounts point the same direction, are <1m apart, and show no evidence of a compromised mast or instrument. Radiation shields have fallen off in some deployments, but this would appear as a constant bias that doesn't self-correct.

At this time, no lab experiments are proposed, as it's unknown how to replicate KEO's unique field conditions. A link to warm, sunny, humid environments was suggested, but several moorings meet all 3 criteria without experiencing LWR measurement issues. Without more information, reproducing the anomalous LWR in the lab is unlikely.

Further consultation with LWR experts will be pursued. Data collection issues seen by other scientists could help form new hypotheses or narrow down those presented above.

Until resolved, LWR post-processing will continue. Contemporary OCS data are quality controlled using thresholds on net LWR (> 0 W/m^2 flagged) and/or downwelling LWR (> 475 W/m^2 flagged), adapting as the anomaly presented. These thresholds will be adjusted if the true climatological signal inches upward.

References

Albrecht, B. and S. Cox, 1977: Procedures for Improving Pyrgeometer Performance. *Journal of Applied Meteorology (1962-1982), 16*(2), 188-197
http://www.jstor.org.offcampus.lib.washington.edu/stable/26178151

Eppley Pyranometer (PSP) Instruction Sheet:
ftp://soest.hawaii.edu/pibhmc/Calibration_Manuals/PIR%20Instructions.pdf

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