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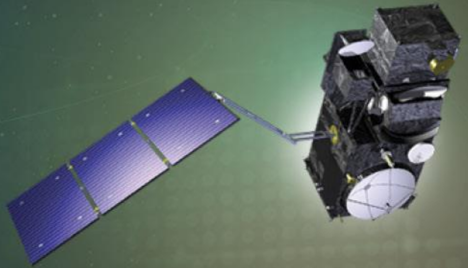

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The Feasibility of Using Radiometers on Saildrones for the Validation of Satellite-Derived Skin SST

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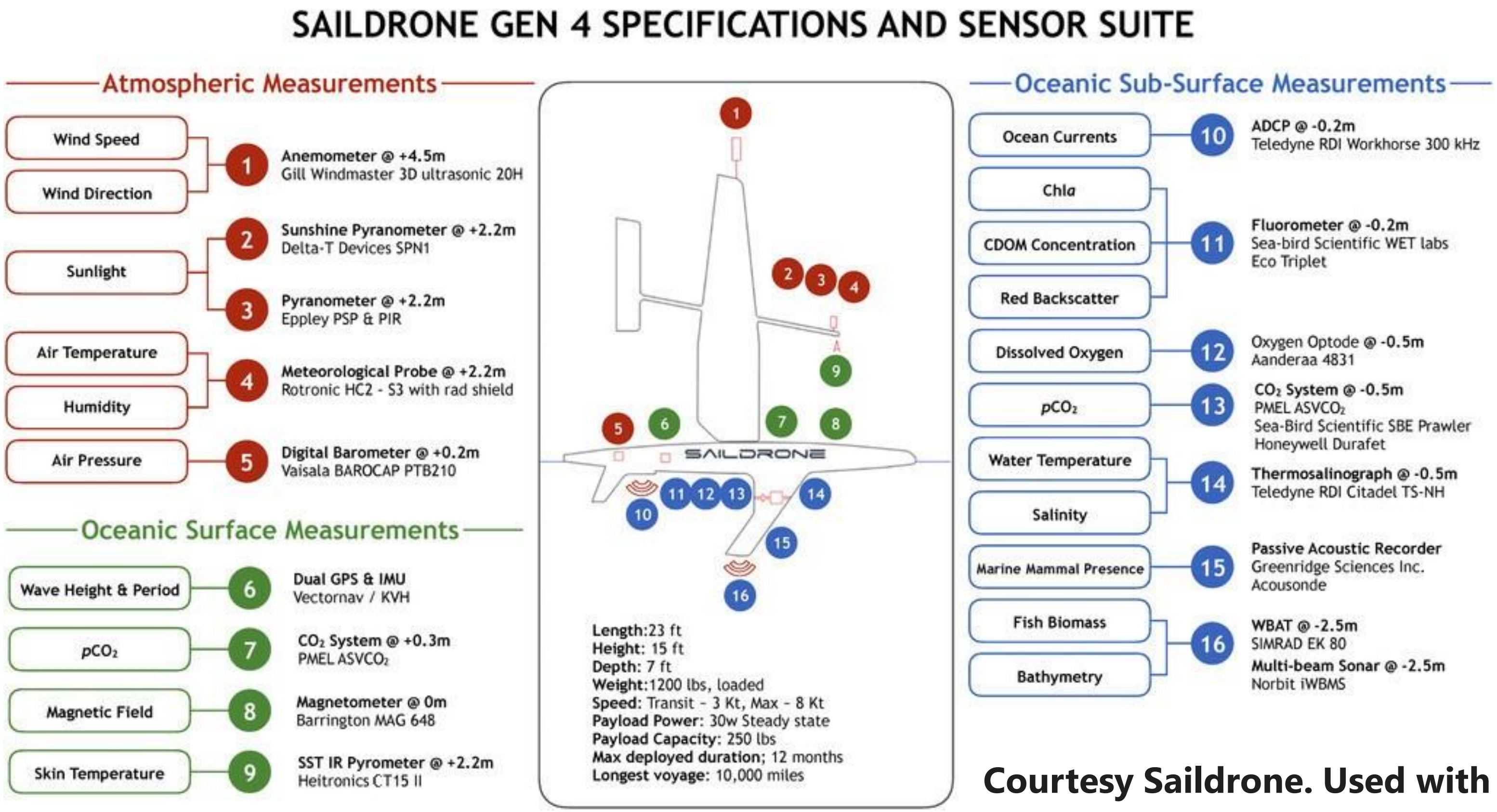
Contents

Introduction: Background

- **Infrared (IR) satellite remote sensing can provide frequent, long-term, global coverage of the sea surface skin temperature (skin SST).**
- **IR radiometers mounted on ships or other platforms have been recognized as providing appropriate, accurate skin SSTs for the satellite data validation.**
- **There are several ship-borne IR radiometer systems that have been proven to be successful in collecting skin SSTs, such as the SISTeR, the M-AERI, and the ISAR.**
- **The amount of available skin SST data is still limited in number and coverage, especially at high latitudes.**
- **Here we introduce a simple system with two IR radiation pyrometers carried on Saildrone uncrewed surface vehicles (USVs) deployed in the Arctic in 2019.**

Introduction: Saildrone USV



SAILDRONE GEN 4 SPECIFICATIONS AND SENSOR SUITE

Atmospheric Measurements

- Wind Speed, Wind Direction — 1 Anemometer @ +4.5m, Gill Windmaster 3D ultrasonic 20H
- Sunlight — 2 Sunshine Pyranometer @ +2.2m, Delta-T Devices SPN1; 3 Pyranometer @ +2.2m, Eppley PSP & PIR
- Air Temperature, Humidity — 4 Meteorological Probe @ +2.2m, Rotronic HC2 - S3 with rad shield
- Air Pressure — 5 Digital Barometer @ +0.2m, Vaisala BAROCAP PTB210

Oceanic Surface Measurements

- Wave Height & Period — 6 Dual GPS & IMU, Vectornav / KVH
- pCO_2 — 7 CO_2 System @ +0.3m, PMEL ASVCO$_2$
- Magnetic Field — 8 Magnetometer @ 0m, Barrington MAG 648
- Skin Temperature — 9 SST IR Pyrometer @ +2.2m, Heitronics CT15 II

Oceanic Sub-Surface Measurements

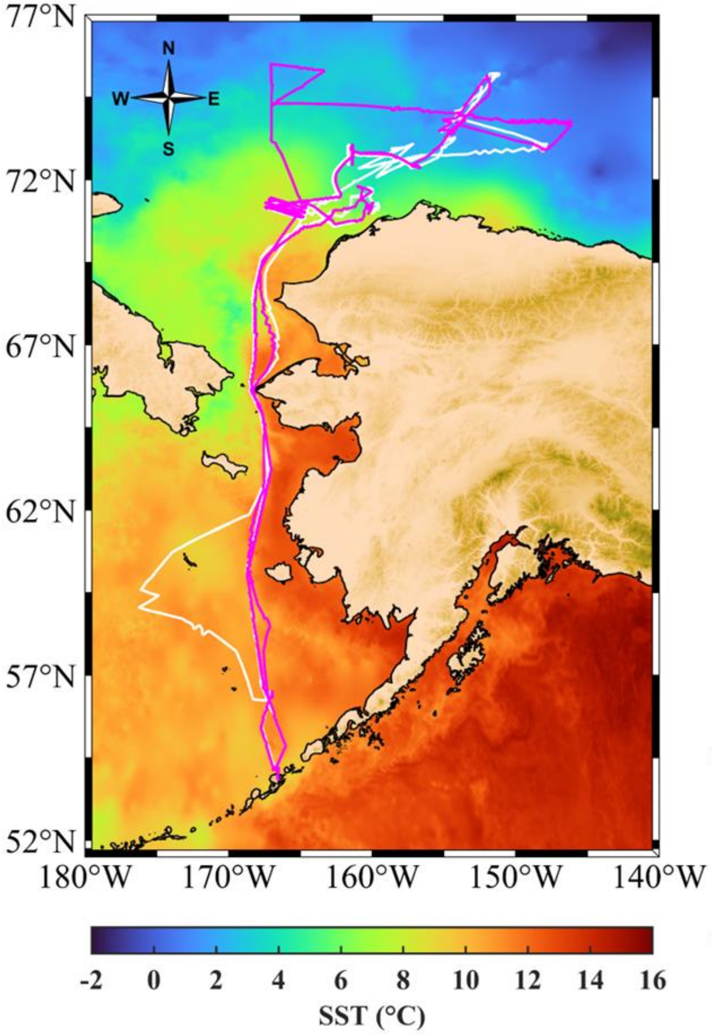
- Ocean Currents — 10 ADCP @ -0.2m, Teledyne RDI Workhorse 300 kHz
- Chla, CDOM Concentration, Red Backscatter — 11 Fluorometer @ -0.2m, Sea-bird Scientific WET labs Eco Triplet
- Dissolved Oxygen — 12 Oxygen Optode @ -0.5m, Aanderaa 4831
- pCO_2 — 13 CO_2 System @ -0.5m, PMEL ASVCO$_2$, Sea-Bird Scientific SBE Prawler, Honeywell Durafet
- Water Temperature, Salinity — 14 Thermosalinograph @ -0.5m, Teledyne RDI Citadel TS-NH
- Marine Mammal Presence — 15 Passive Acoustic Recorder, Greenridge Sciences Inc., Acousonde
- Fish Biomass, Bathymetry — 16 WBAT @ -2.5m, SIMRAD EK 80; Multi-beam Sonar @ -2.5m, Norbit iWBMS

Length: 23 ft
Height: 15 ft
Depth: 7 ft
Weight: 1200 lbs, loaded
Speed: Transit - 3 Kt, Max - 8 Kt
Payload Power: 30w Steady state
Payload Capacity: 250 lbs
Max deployed duration: 12 months
Longest voyage: 10,000 miles

Courtesy Saildrone. Used with express permission.

- **Wind-power for propulsion with a suite of solar-powered meteorological and oceanographic instruments.**
- **Deliver data in real time via satellite transmissions to ground stations.**

Introduction: 2019 Arctic Cruise (15th May to 11th October)



- Tracks for SD-1036 (white) and SD-1037 (magenta).
- Background SSTs are the MUR Level 4 data on 16 Sep 2019.

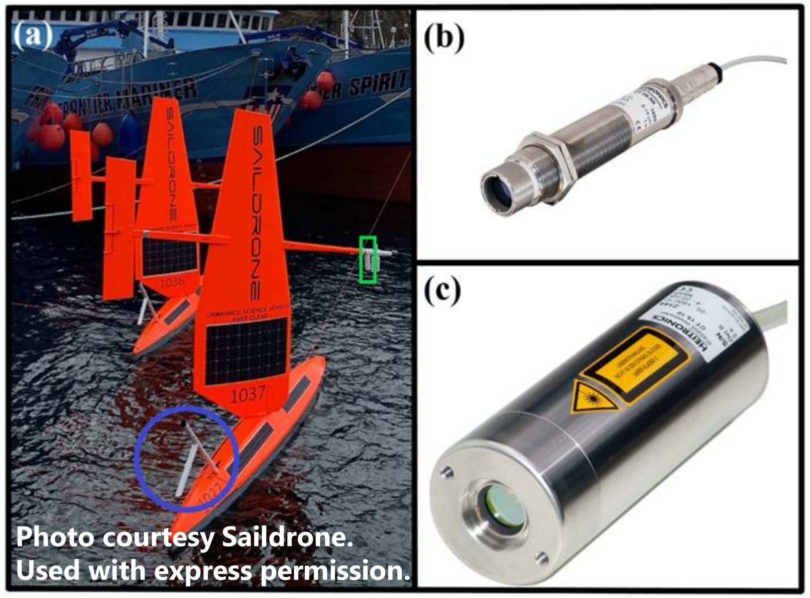
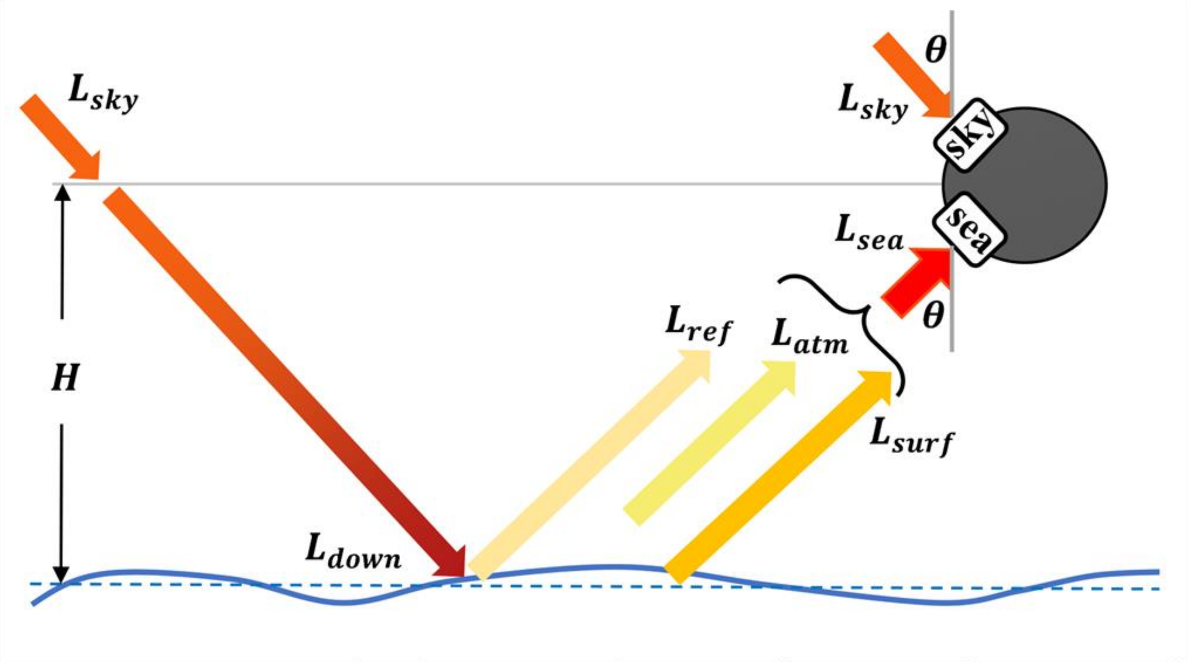


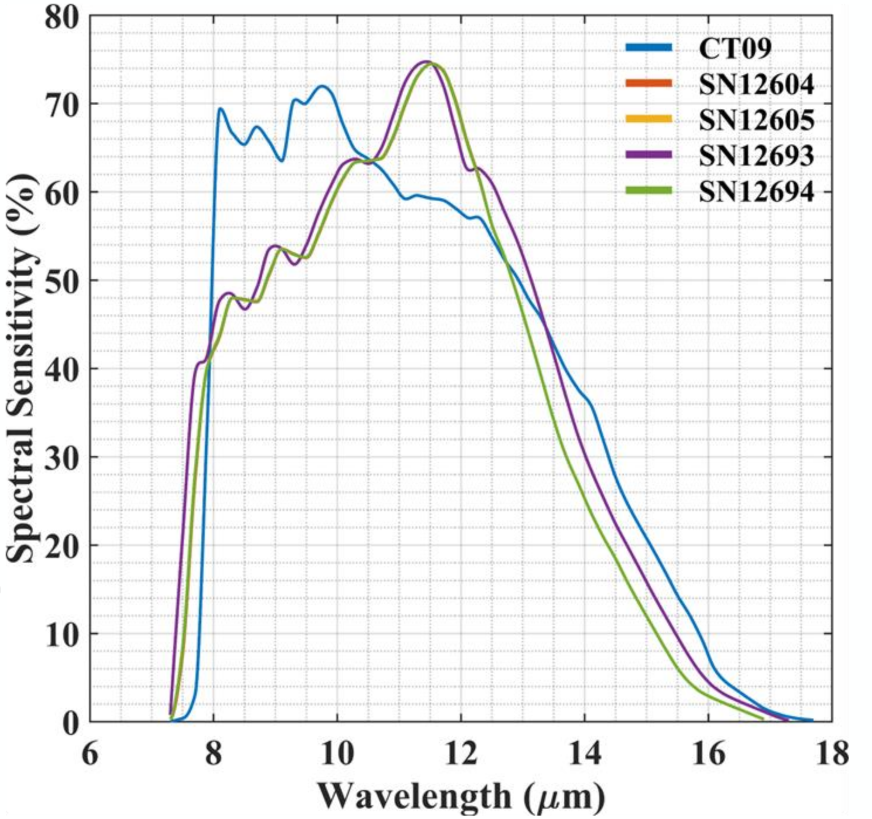
Photo courtesy Saildrone.
Used with express permission.

- A pair of IR pyrometers were near the bow on the deck at 0.8 m height (a; blue circle). An additional pyrometer was mounted on the spar of the sail at 2.25 m above the ocean surface (a; green box).
- Two sea-viewing sensors were CT15.10 (c), while the sky-viewing sensor was a CT09 (b).

Methodology: Saildrone Skin SST Derivation



Relative spectral response (RSR) function



Assume atmospheric transmittance from surface to radiometer of unity and consider the sea surface emissivity effect:

$$B(T_{sea},\lambda) \approx \varepsilon(\lambda,\theta)B(T_s,\lambda) + \left(1-\varepsilon(\lambda,\theta)\right)B\left(T_{sky},\lambda\right) \qquad (1)$$

Consider the spectral response function:

$$\int_{\lambda_0}^{\lambda_1}\sigma(\lambda)B(T_{sea},\lambda)\,d\lambda = \int_{\lambda_0}^{\lambda_1}\sigma(\lambda)\left[\varepsilon(\lambda,\theta)B(T_s,\lambda) + \left(1-\varepsilon(\lambda,\theta)\right)B\left(T_{sky},\lambda\right)\right]d\lambda \qquad (2)$$

Methodology: Viewing Geometry Determination

To derive the sea surface emissivity, we should determine the viewing geometry first.

Establish the three-dimensional rotation matrix:

$$R = \begin{bmatrix} \cos\gamma & -\sin\gamma & 0 \\ \sin\gamma & \cos\gamma & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos\beta & 0 & \sin\beta \\ 0 & 1 & 0 \\ -\sin\beta & 0 & \cos\beta \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha & -\sin\alpha \\ 0 & \sin\alpha & \cos\alpha \end{bmatrix} R' \qquad (1)$$

where γ is the angle rotating about the z-axis, the yaw angle; β is the angle rotating about the y-axis, the pitch angle; α is the angle rotating about the x-axis, the roll angle.

The unit vector with reference to the IR pyrometer itself:

$$R' = \begin{bmatrix} \cos\theta_0 & 0 & \sin\theta_0 \\ 0 & 1 & 0 \\ -\sin\theta_0 & 0 & \cos\theta_0 \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \qquad (2)$$

For the sensors mounted on the hull, θ_0 is -50° (down-looking) or 50° (up-looking); for the one at the spar of wing, θ_0 is -7°.

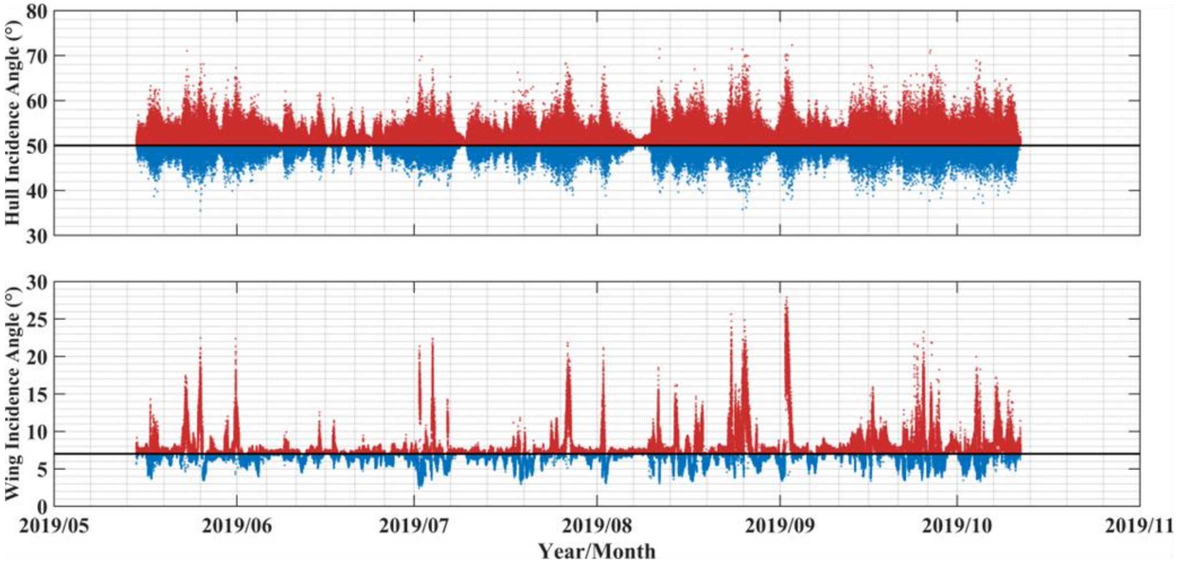
where θ_0 is the standard viewing angle of the sensors for an upright Saildrone.

The effective incidence angle:

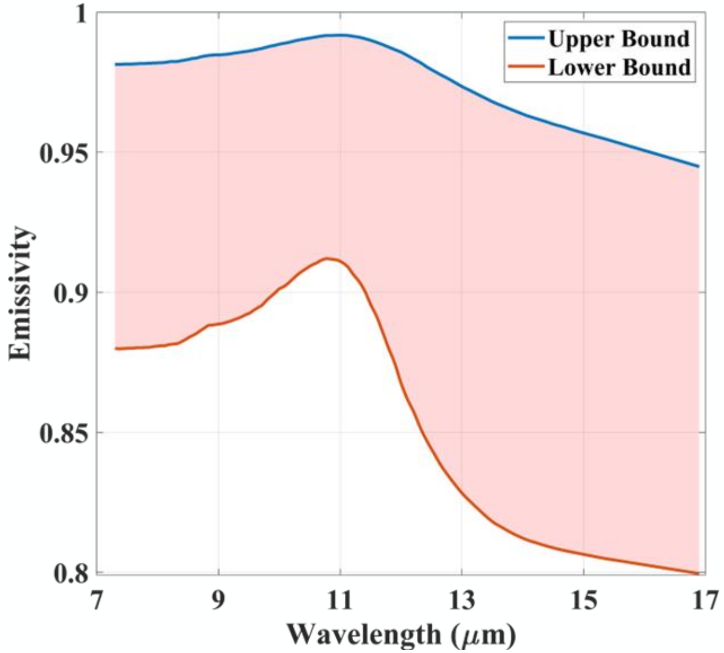
$$\theta_e = \arccos\left(R \cdot \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}\right) \qquad (3)$$

Methodology: Emissivity Calculation

Down-looking sensors on the hull and wing:



A built-in IR sea surface emissivity model (IREMIS) in RTTOV (Radiative Transfer for TOVS) model is used to determine the emissivity. This model includes the zenith angle and wind speed dependence, also the refractive indices depending on skin temperature in the 10-12 µm window.

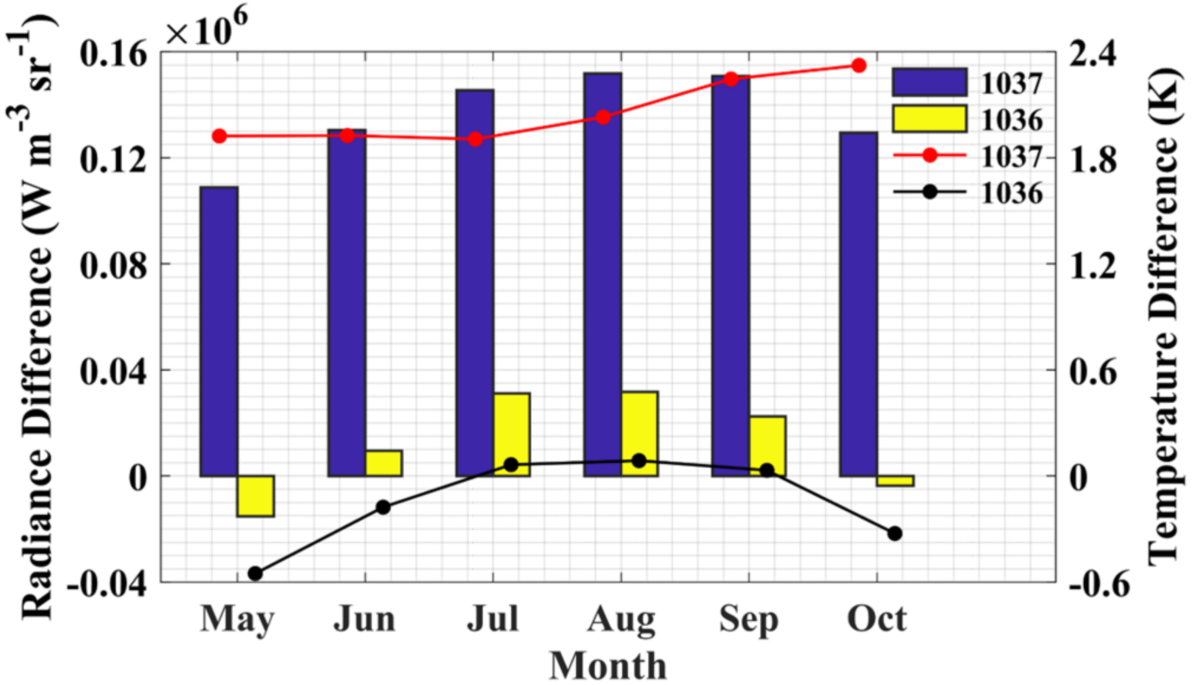


Before deriving the skin SST:

- **Different RSR functions**
- **Different viewing angles**

Resulting in inaccuracies of using the T_{sky} for the reflected sky radiance correction

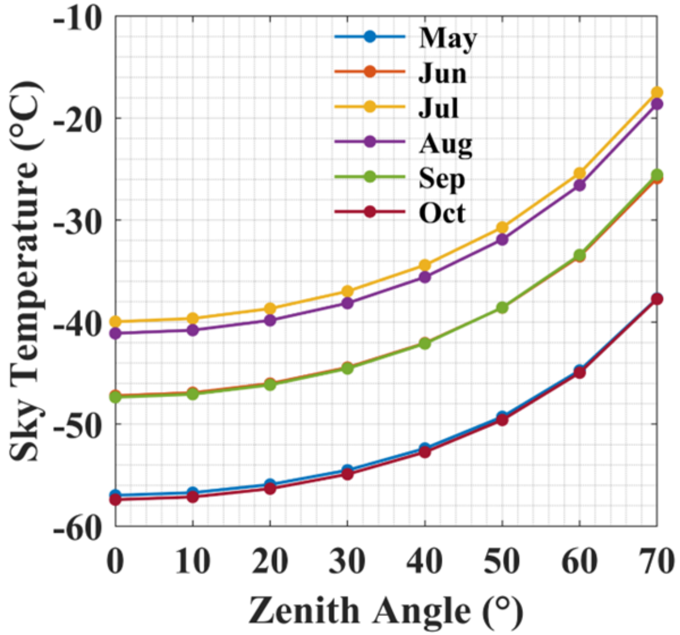
Methodology: Numerical Simulations — RSR Functions



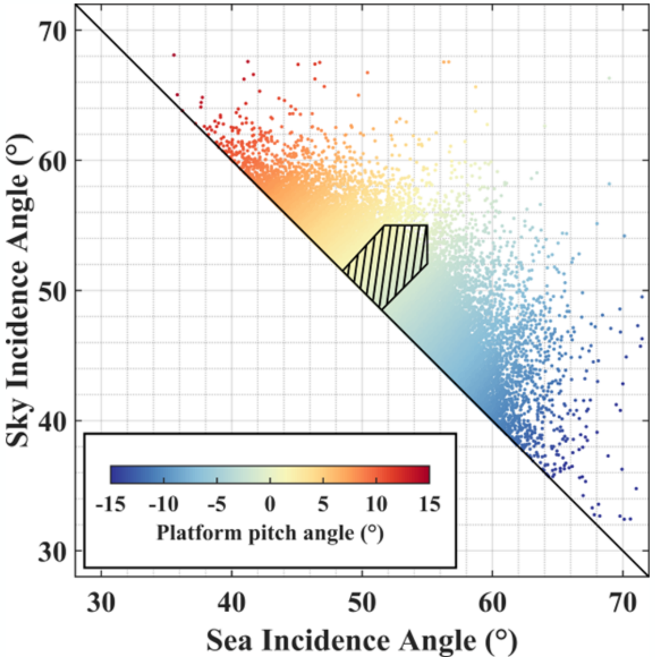
- Use the Line-By-Line Radiative Transfer Model (LBLRTM) to simulate the clear sky atmospheric downwelling radiance spectra at the surface.
- Then the radiance (and brightness temperature) measured by the IR pyrometers can be simulated based on the their RSR functions.
- MERRA-2 data, as model inputs for meteorological fields, have been averaged by month in the target area (50°N~75°N, 180°W~140°W) with land mask.

- The simulations of the sky radiance (bars) and corresponding temperature (dots and lines) differences measured by CT15 and CT09 at a zenith angle of 50° from May to October 2019.
- For SD-1036, CT09 would generally measure the T_{sky} 0.15 K warmer than that would have been measured by CT15 under clear skies (ignore), whereas for SD-1037, it reaches up to 2 K colder on average, causing a warm bias of 0.025 K error in skin SST.

Methodology: Numerical Simulations — Viewing Angles



- To further examine the effects of inconsistent sea- and sky-viewing angles due to the pitching of Saildrone, the input zenith angle was set from 0 to 70° in increments of 10° based on the LBLRTM simulation mentioned above.
- Both the ranges of the sea- and sky-viewing angles to be used are limited within 45° to 55°. Furthermore, the platform pitch angles are also limited within ±1.5°.



- Due to those limitations (shadow area), the angle discrepancies have been finally controlled within ±3°, and the resulting T_{sky} uncertainties are < ±1.5 K, which introduces an uncertainty of 0.02K in the derived skin SST under clear sky conditions.

Results and Analysis: Uncertainty Budget Analysis of Skin SST

Three main components of uncertainty:

- **Sea surface emissivity (assumed to be very small and negligible)**
- **Sea-viewing radiometer measurement (instrument)**
- **Sky-viewing radiometer measurement (instrument, viewing angle and RSR function)**

$$\epsilon_{skin}^2 = \epsilon_{sea}^2 + \epsilon_{sky}^2 + \epsilon_{angle}^2$$

	CT09 (Sky)	CT15 (Sea)
Manufacturer's stated uncertainty	± 1.0 K plus 0.6% of the difference between target and instrument temperature	± 0.5 K plus 0.7% of the difference between target and instrument temperature

- **The total uncertainty from the last two terms is no more than 0.024 K for SD-1036 and SD-1037.**
- **The accuracy of CT15 (0.5 K) given in the manufacturer's specifications is so large and not acceptable.**

Results and Analysis: Uncertainty Budget Analysis of Skin SST

To evaluate the skin SST uncertainty, compare skin SST difference with the subsurface SST difference measured by Sea-Bird SBE 56 temperature loggers at 0.3 m between SD-1036 and SD-1037 within small separations (10 km).

$$\Delta SST_{skin} = SST_{skin\_1036} - SST_{skin\_1037} = u_c + \delta(SST_{skin}) \qquad (1)$$

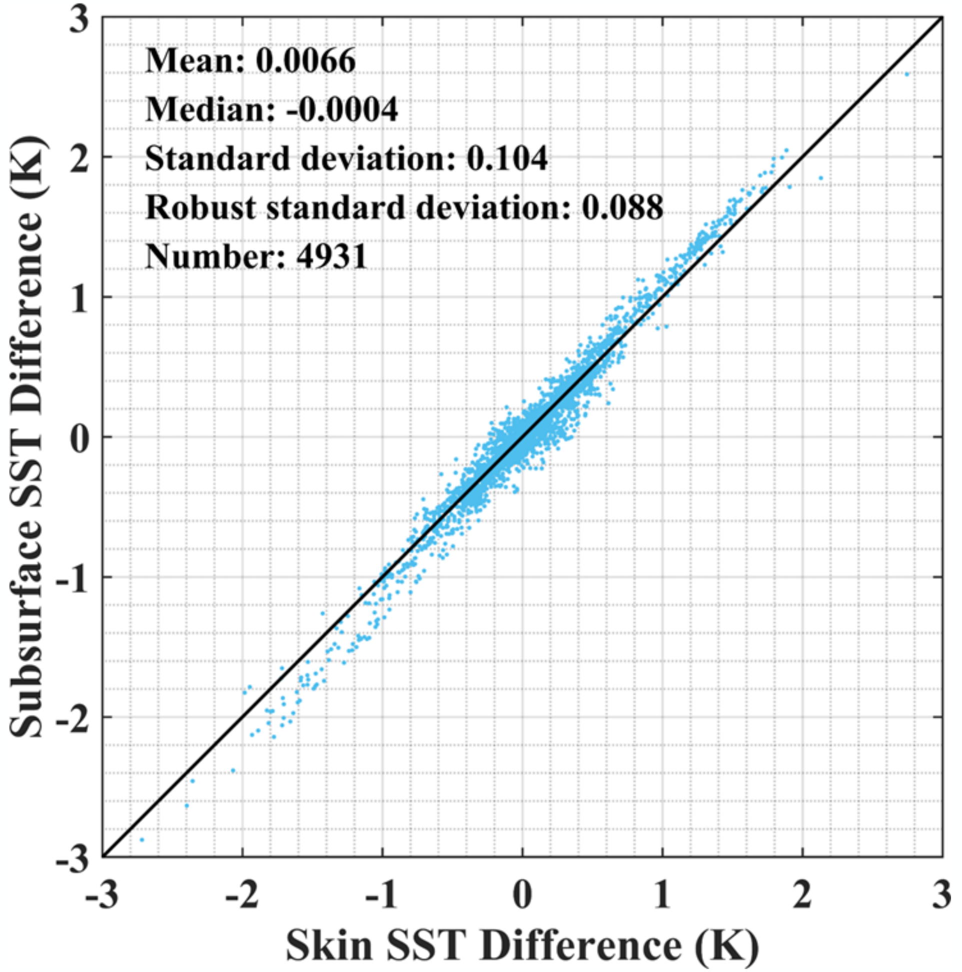
$$\Delta SST_{0.3\,m} = SST_{0.3\,m\_1036} - SST_{0.3\,m\_1037} = \delta(SST_{0.3\,m}) \qquad (2)$$

$$\delta(SST_{skin}) = \delta(SST_{0.3\,m}) \qquad (3)$$

Remove diurnal heating signals

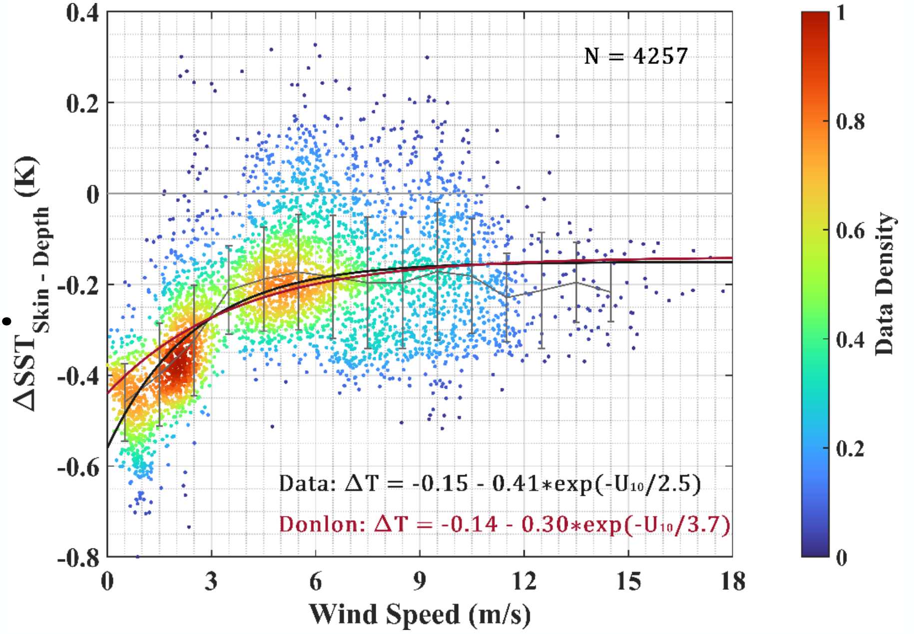
$$u_c = \sqrt{u_{1036}^2 + u_{1037}^2} = 1.96 * \mathrm{RSD}(\Delta SST_{skin} - \Delta SST_{0.3\,m}) \qquad (4)$$

$$u_{SST_{skin}} = u_{1036} = u_{1037} = 0.12\ \mathrm{K} \qquad (5)$$



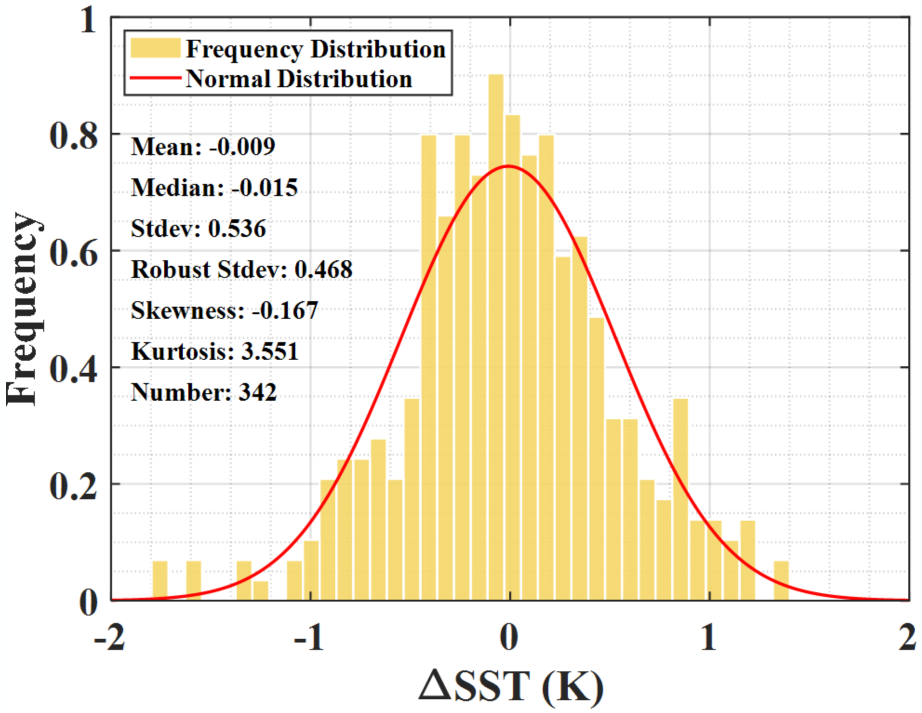
Results and Analysis: Systematic Error Analysis of Skin SST

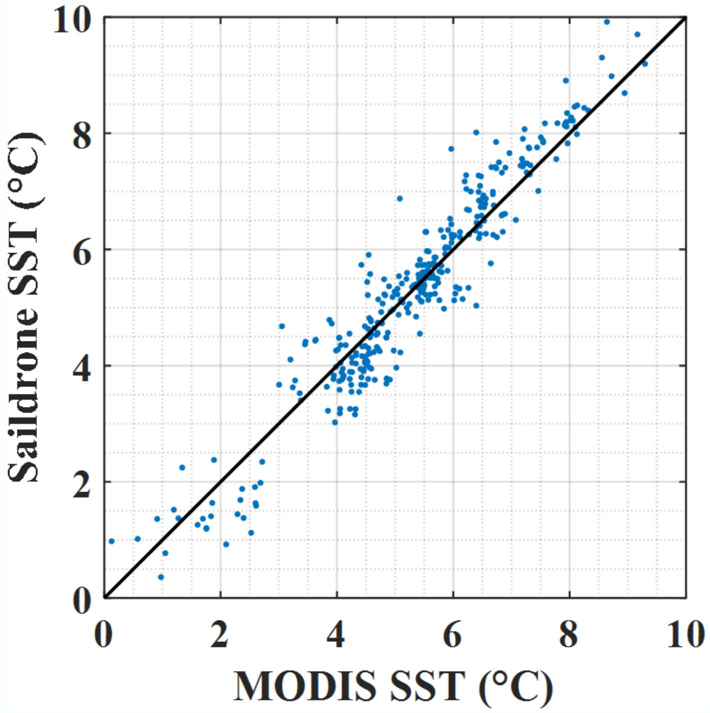
- **Wintronics Inc., the US agent for Heitronics, has calibrated the one CT15 (but not the sensor on SD-1036 or SD-1037) in 2022. The result at their blackbody target temperature of 1 °C was +0.09 K, and -0.07 K at 30 °C.**
- **Assuming a monotonic temperature dependence of the error, the measurement errors at temperatures experienced in the 2019 Saildrone deployments are ~0.06 K in average.**
- **Compared to SST at -1.7 m, the deepest SST taken by SBE 56 logger, during nighttime, as a function of 10 m wind speed, showing that the asymptotic value of the curve fitted to the Saildrone data only differs from Donlon et al., (2002) by 0.01 K.**



It would be very unlikely if there were a significant systematic error in the Saildrone-derived skin SST.

Future Work: Validation of Satellite-Derived Skin SST





Also for the SLSTR on the Sentinel-3 in the future!

The matchups for SD-1036/SD-1037 and MODIS on Aqua derived skin SST during the 2019 Arctic Cruise, with the temporal and spatial windows as 30 min and 1 km respectively.

Summary

- To obtain sufficiently accurate emissivity for skin SST derivations, the viewing geometry of sensors must be well established given the effects of the vehicle's pitching and rolling.
- The instrumental uncertainty of CT15 is much smaller than 0.5 K given in the manufacturer's specifications.
- The skin SSTs derived from the infrared pyrometers mounted on the hull of Saildrones have an estimated uncertainty of 0.12 K, with very small systematic errors.
- The Saildrone-derived skin SST is sufficiently accurate to be used in many scientific studies, such as the validation of Satellite-retrieved SST (MODIS, VIIRS, SLSTR, etc.).
- This presentation is mainly based on the work under second round review by IEEE TGRS.

Acknowledgements

We would like to especially appreciate the assistance from the following people:

Charles Hamel (Saildrone Inc.) for providing specifications of Saildrone as well as lending us the CT15 IR pyrometer for laboratory calibrations.

Bud Foran (Wintronics Inc.) for providing the specific RSR functions of pyrometers equipped on Saildrones, and for detailed discussions on how the Heitronics instruments function, and their behavior during calibration.

Dr. Andy Jessup and Dr. Chris Chickadel (University of Washington Applied Physics Laboratory) for discussions on the determination of the viewing geometry.

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Thank You!